CHAPTER 2
LITERATURE REVIEW ON FLOWMETERS

This chapter describes a selection of research works regarding CNG flowmeter technologies which covers momentum flowmeter; volumetric flowmeter; pressure-volume-temperature (PVT) based flowmeter and mass flowmeter. As with the choice of coverage, the reference are selected from a large number of sources but is not meant to provide a comprehensive review.

2.1 Introduction

CNG metering technologies require the determination of the quantity of CNG that passes through a check point, either a closed conduit or an open channel, in daily processing or operating condition such as CNG filling station. There are two types of CNG filling station: timed-fill and fast-fill filling systems, whilst the instrument to measure the CNG filling is called flowmeter. The quantity to be determined could be in the form of volume flowrate, mass flowrate, flow velocity or other quantities related to the previous three.

2.1.1 Timed-fill

Timed-fill systems refuel the NGV vehicle slowly, usually overnight while the vehicle is idle. They use a small compressor which directly fills the vehicle's on-board storage cylinder. These systems are usually dedicated to the supply of individual vehicles or very small fleets. A low-pressure meter, similar to the common household gas meter, is normally installed at the system inlet to record total fuel dispensed [1].

2.1.2 Fast-fill

Fast-fill systems are designed to refuel an NGV vehicle in a similar time to a liquid fuel station and are analogous to these stations in many aspects of their operation. A typical station is shown in the Figure 2.1 [1].

A report carried out by Advantica and National Weights and Measures Laboratory (NWML) shows that a typical fast-fill CNG filling station consists of a compressor, storage vessels and a dispenser [2].

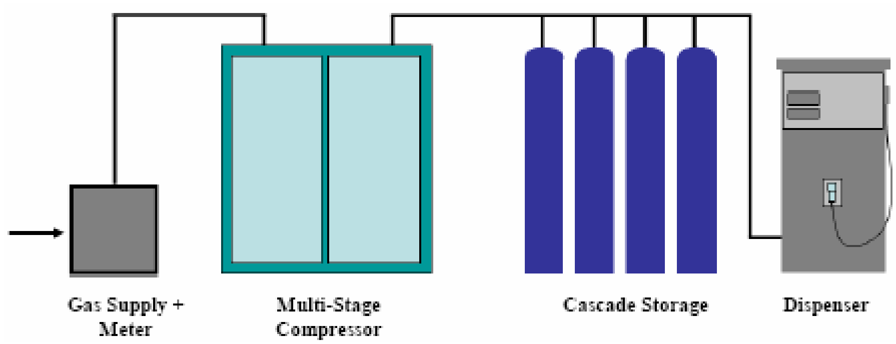


Figure 2.1: Fast-fill CNG filling station [2]

Gas from the distribution pipeline, usually at low pressure of 14.7 psig or medium pressure of 14.7-102 psig, is compressed using a large multi-stage compressor into a cascaded storage system as shown in Figure 2.1. This system is maintained at a pressure higher than that in the vehicle's on-board storage so that the gas flows to the vehicle under differential pressure. Typically, the cascaded storage will operate at 3600 psig, while the vehicle's maximum on board storage pressure is 3000 psig. In some countries, notably USA and Europe, higher cascade storage and vehicle pressures are used and are becoming more common for heavy-duty vehicle applications [11].

In order to make the utilization of the compressor and buffer storage more efficient, CNG stations usually operate using a three-stage cascaded storage system. The buffer storage is divided into three "banks" – termed as the low, medium and high pressure banks using valves controlled by the dispenser system. During refueling the vehicle is first connected to the low-pressure bank. As the pressure in the bank falls and that in the on-board storage rises, the flow of gas decreases. When the flow rate has declined to a pre-set level the system switches to the medium pressure bank, then finally to the high-pressure bank to complete the fill. The cascaded system results in a more complete "fill" rather than if the whole buffer storage was maintained at one pressure because it can utilize the compressor and storage with maximum efficiency [11].

In addition, when the compressor is automatically switched on to refill the banks; it will fill the high pressure bank first up to 3600 psig, before switching to the medium and the low banks. This is to ensure that the high-pressure bank which is used to complete the fill up to maximum storage pressure is maintained at highest possible pressure, thus ensuring that vehicles will always be supplied with the maximum amount of gas available. The cascade system, described above, results in a widely varying flow rate of gas to the NGV vehicle being refueled. This is shown by Figure 2.2, where the bank switching points is represented by the sharp curves [11].

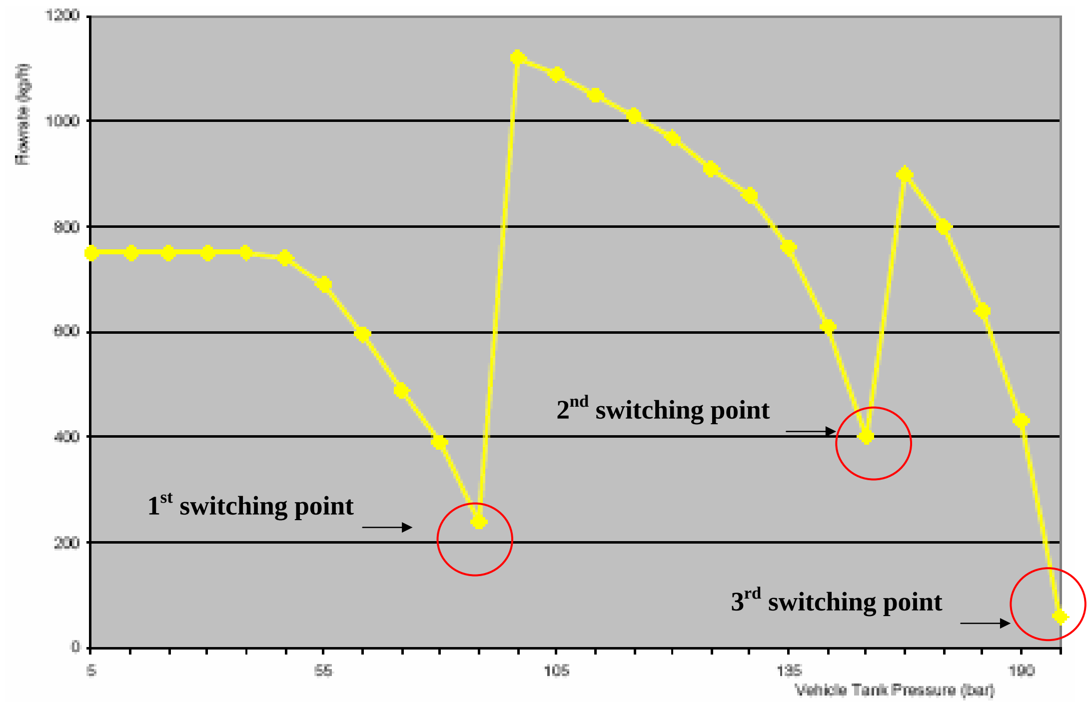


Figure 2.2: Mass flowrate during fast-filling for vehicle tank pressure (in bar) [2]

Based on Figure 2.2, any metering system used as part of the CNG dispenser must be able to measure and totalized the gas flow accurately under rapidly changing pressure and flow conditions over a relatively short refueling cycle (typically 4-5 minutes). As mentioned before, there are four types of metering technologies available for CNG: momentum flowmeter; volumetric flowmeter; pressure-volume-temperature (PVT) based flowmeter and mass flowmeter. The following section discusses the first metering technologies which are momentum flowmeter.

2.2 Previous works based on momentum flowmeter

Momentum flowmeters is also known as differential pressure flowmeter i.e., a device that employs Bernoulli equation to describe relationship between pressure and velocity of a flow. The device guides the flow into a section with different cross section areas that causes variation of velocity and pressure. Flow restriction in the line or between two measurements locations would create a differential pressure that would relate to flowrate value. There are various types of differential pressure flowmeters available for CNG such as orifice plate, venturi tube, nozzle, segmental wedge, v-cone, pitot tube, averaging pitot tube, elbow and dall tube [4].

2.2.1 Orifice plate

Figure 2.3 shows a plate with an opening is inserted into the pipe and placed perpendicular to the flow stream. As fluid passes through the orifice plate, the restricted cross section area causes an increase in velocity and decrease in pressure. The pressure difference before and after the orifice plate is used to calculate the flow velocity [4].

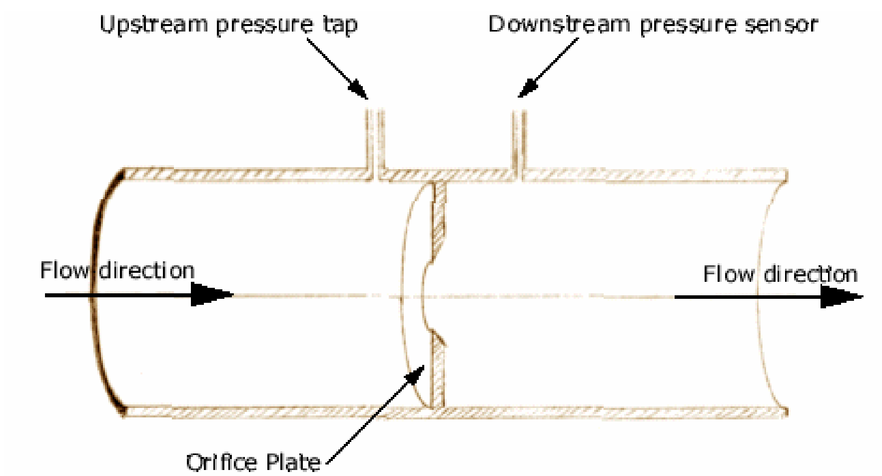


Figure 2.3: Orifice plate flowmeter [4]

2.2.2. Venturi tube

Figure 2.4 shows a section of tube which forms a relatively long passage with smooth entry and exit. A venturi tube is connected to the existing pipe, first narrowing down in diameter then opening up back to the original pipe diameter. The changes in cross section area cause changes in velocity and pressure of the flow [4].

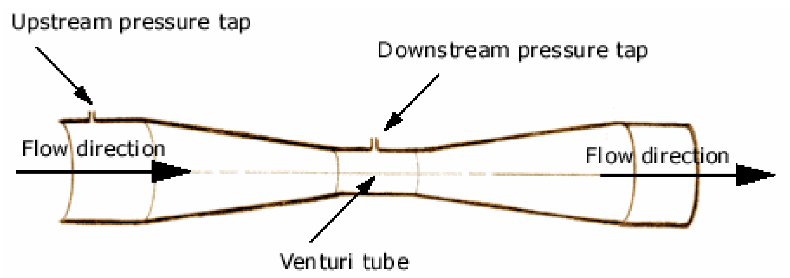


Figure 2.4: Venturi tube flowmeter [4]

2.2.3 Nozzle

Figure 2.5 shows a nozzle with a smooth guided entry. A sharp exit is placed in the pipe to change the flow field that would create a pressure drop that is used to calculate the flow velocity [4].

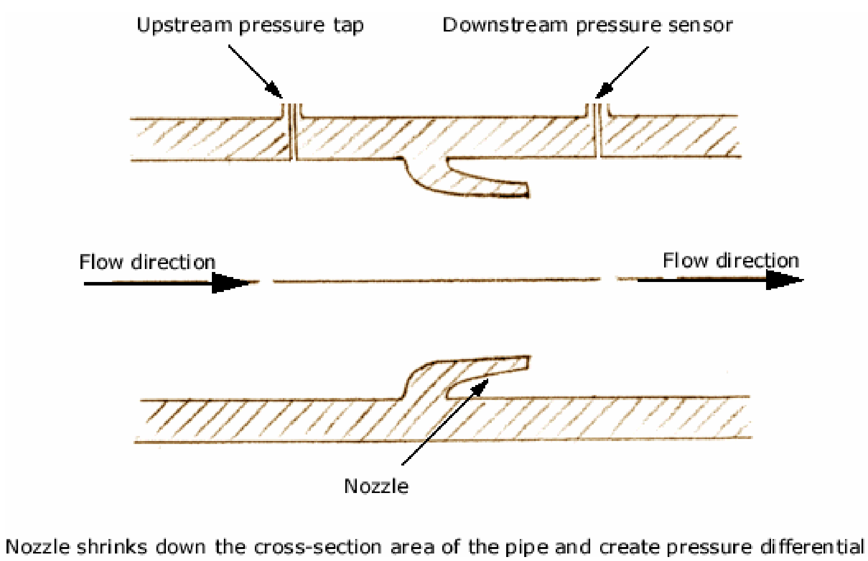


Figure 2.5: Nozzle flowmeter [4]

2.2.4 Segmental Wedge

Figure 2.6 shows a wedge-shaped segment is inserted perpendicularly, into one side of the pipe while the other side remains unrestricted. The change in cross section area of the flow path creates pressure drops used to calculate flow velocities [4].

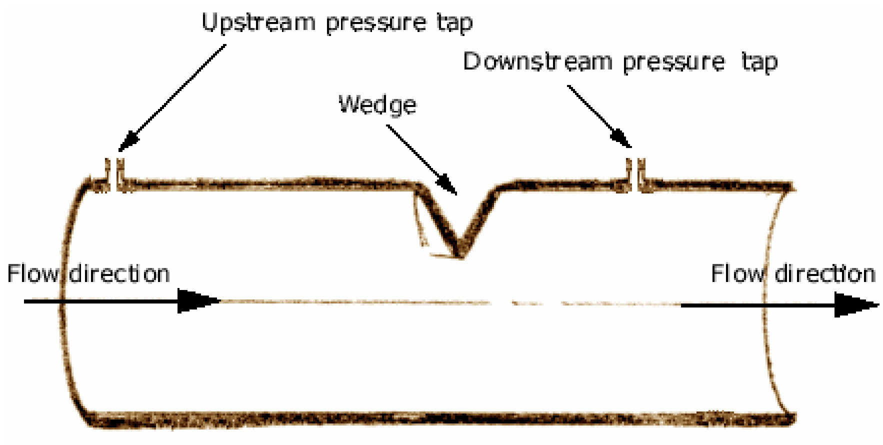


Figure 2.6: Segmental Wedge [4]

2.2.5 V-cone

Figure 2.7 shows a cone shaped obstructing element that serves as the cross section modifier. It is placed at the center of the pipe for calculating flow velocities by measuring the pressure differential [4].

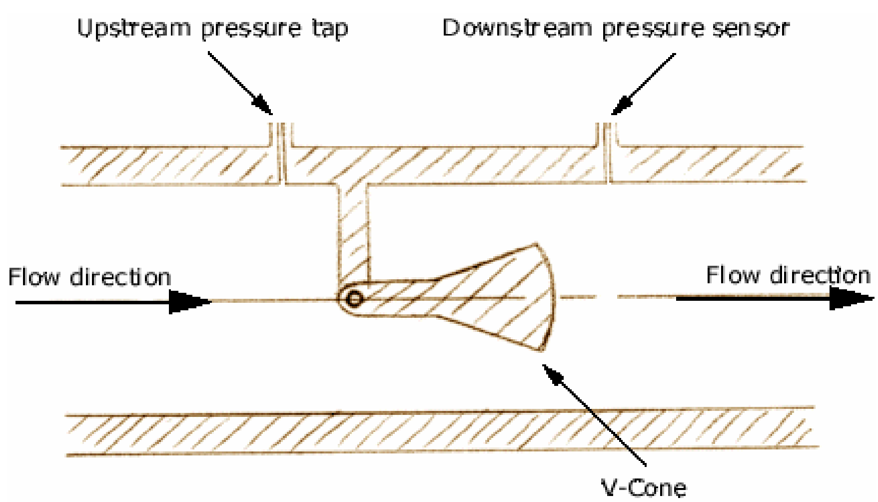


Figure 2.7: V-cone flowmeter [4]

2.2.6 Pitot tube

Figure 2.8 shows a probe with an open tip which a Pitot tube is inserted into the flow field. The tip is stationary (zero velocity) point of the flow, whilst its pressure is compared to this static pressure to calculate the flow velocity. Pitot tubes can measure flow velocity at the point of measurement [4].

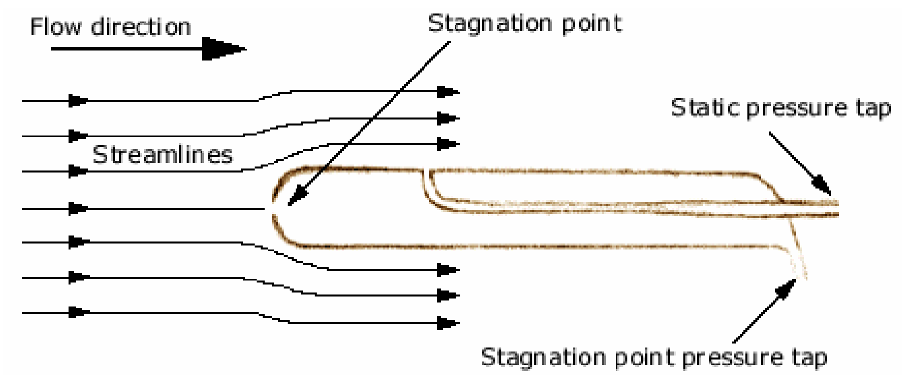


Figure 2.8: Pitot tube flowmeter [4]

2.2.7 Averaging pitot tube

Figure 2.9 shows a similarity to pitot tube but with multiple openings, averaging pitot tubes could take overall flow profile to provide better accuracy in pipe flows [4].

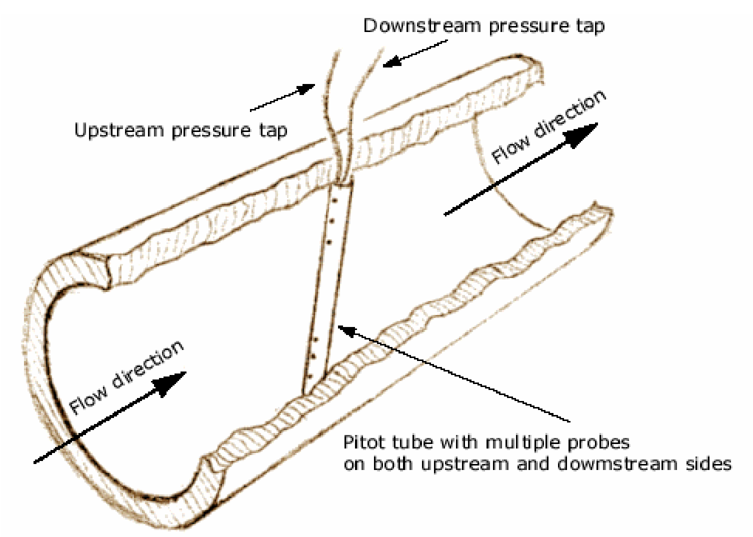


Figure 2.9: Averaging pitot tube flowmeter [4]

2.2.8 Elbow

Figure 2.10 shows when a fluid flows through an elbow, the centrifugal forces would cause a pressure difference between the outer and inner sides of the elbow. This pressure difference generated by an elbow flowmeter is used to calculate the flow velocity which has less obstruction to flow compared to other pressure differential flowmeters [4].

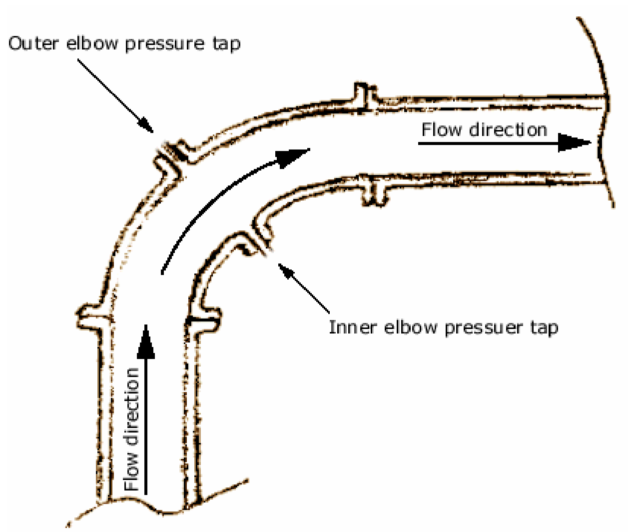


Figure 2.10: Elbow flowmeter [4]

2.2.9 Dall tube

Figure 2.11 shows a dall tube which features same tapering intake portion of a venturi tube but has a 'shoulder' similar to the orifice plate's exit part. This is to create a sharp pressure drop that could be used in applications with larger flow rates [4].

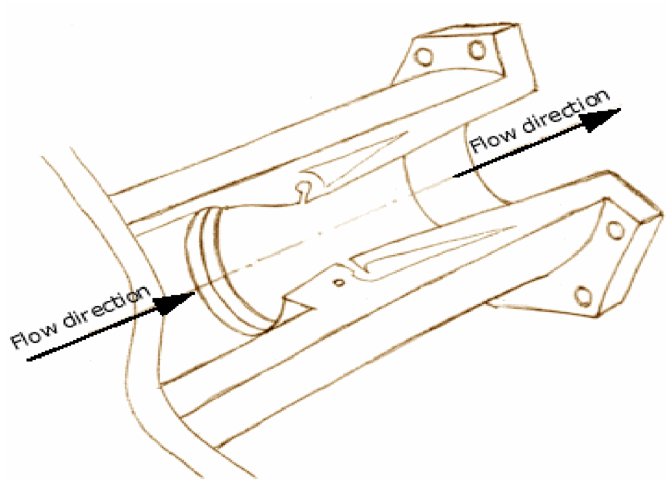


Figure 2.11: Dall tube flowmeter [4]

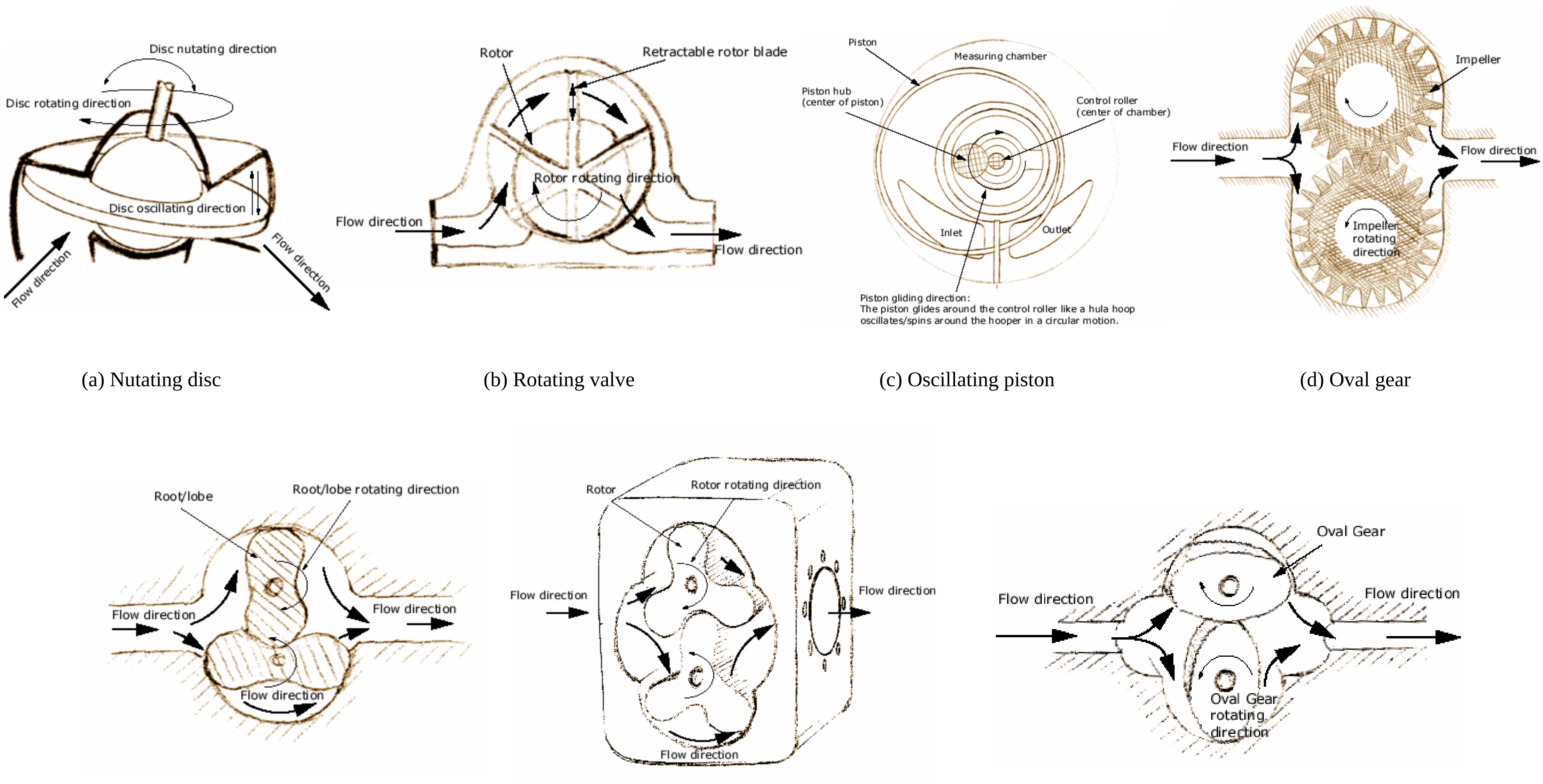
Although differential pressure flowmeters are simple in construction and widely used in industry, they have a common drawback: they always create medium to high amounts of pressure drop, which could not be tolerated in CNG metering application. To meet international standard of CNG custody transfer, other flowmeter technologies are applied such as volumetric flowmeter [4].

2.3 Previous works based on volumetric flowmeter

Volumetric flowrate is defined as the volume of fluid which passes through a given surface per unit time, for example cubic meters per second (m^3s^{-1}) or cubic feet per second (cu ft/s), and usually represented by symbol, Q. They are various types of volumetric flowmeters applicable for CNG measurement such as positive displacement flowmeter, turbine flowmeter, ultrasonic flowmeter, vortex flowmeter and magnetic flowmeter [33].

2.3.1 Positive displacement flowmeter

Positive displacement flowmeters are also known as PD meters, which measure volumes of fluid flowing through by counting repeatedly the filling and discharging of known fixed volumes. Typical designs actually comprise of chambers that obstruct the flow. A rotating (reciprocating) mechanical unit is placed inside the chamber to create fixed volume discrete parcels from the passing fluid. Hence, the volume of the fluid that passes the chamber can be obtained by counting the number of passing parcels or equivalently the number rounds of the rotating (reciprocating) mechanical device. Whilst, the volume flow rate can be calculated from the revolution rate of the mechanical device. Many types of positive displacement flowmeters are used in the industries which are named after the mechanical devices inside the chamber. In the following section, Figure 2.12 shows example of the mechanical devices such as nutating disc, rotating valve, oscillating piston, oval gear, roots (rotating lobe), birotor and rotating impeller. They share the same principle of operation which is based on volumetric flowrate, but the accuracy relies on the integrity of the capillary seal that separates the incoming fluid into the discrete parcels [34].



(a) Nutating disc (b) Rotating valve (c) Oscillating piston (d) Oval gear

(e) Roots (rotating lobe) (f) Birotor (f) Rotating impeller

Figure 2.12: Types of positive displacement flowmeters [34]

To ensure positive displacement flowmeter functions properly and to achieve measurement accuracy, a filtration system is required to remove particles larger than 100 μm as well as gas (bubbles) occurs from the fluid flow. Although it has a simple principle of operation, they also cause a considerable pressure drop which has to be considered in CNG metering application. As a result, other volumetric flowmeter is desired such as turbine flowmeter [5].

2.3.2 Turbine flowmeter

Figure 2.13 below shows a typical design of turbine flowmeter. It consists of a rotor mounted on a bearing and shaft located in housing. The fluid to be measured is passed through the housing, causing the rotor to spin with a rotational speed proportional to the velocity of the flowing fluid within the meter. The principle also is similar with windmill operation which utilizes angular velocity (rotation speed) to indicate the flow velocity. A good turbine flowmeter requires well designed and placed aerodynamic (hydrodynamic) blades that are suitable for the fluid and flow condition, and bearings that are both smooth and durable to survive the sustained high-speed rotation of the turbine. As mentioned by [5], advantages of applying turbine flowmeter in CNG application are medium initial set-up cost, reliable, and time tested proven technology, whilst disadvantage is clean fluid environment is needed with low to medium pressure drop. For that reasons, other volumetric flowmeter is proposed such as ultrasonic flowmeter [5].

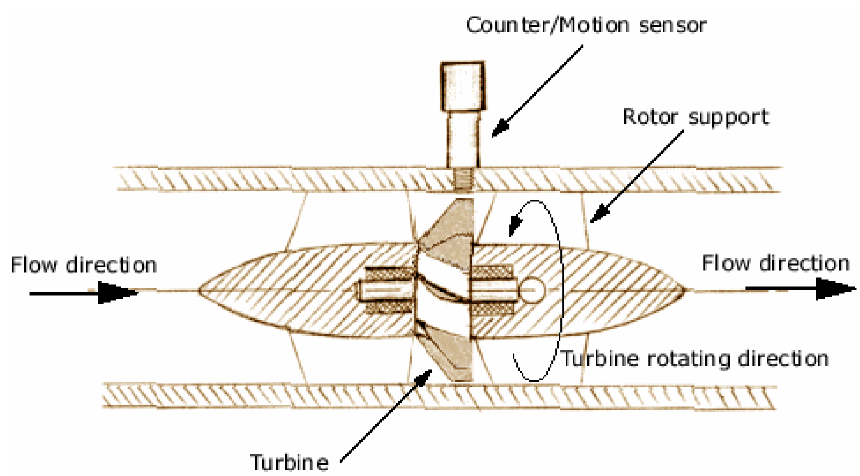


Figure 2.13: Turbine flowmeter [5]

2.3.3 Ultrasonic flowmeter

There are two types of ultrasonic flowmeters: transit time model and doppler model. To calculate flow velocity, transit time model measures traveling time, whilst doppler model measures frequency shift of ultrasonic wave in a preconfigured acoustic field [6].

2.3.3.1 Transit time ultrasonic flowmeter

As shown by Figure 2.14, the time for acoustic waves to travel from upstream transducer to downstream transducer, t_d is shorter than the time it requires for the same waves to travel from downstream to upstream, t_u. Therefore, if larger time difference between t_u and t_d is measured, higher flow velocity of CNG flow would be expected [35].

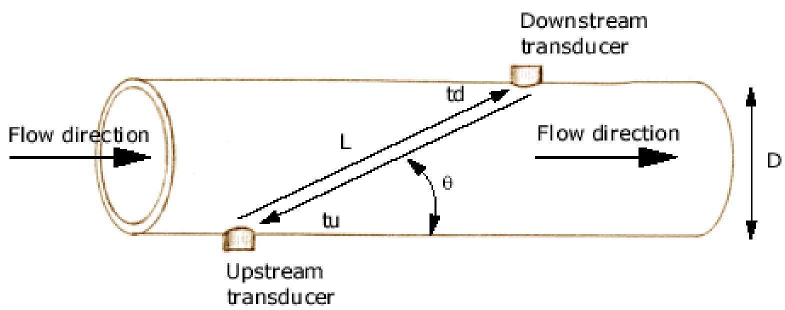


Figure 2.14: Transit time ultrasonic flowmeter [35]

2.3.3.2 Doppler ultrasonic flowmeter

As shown by Figure 2.15, it relies on doppler effect to relate frequency shifts of acoustic waves to flow velocity. Some particles are required in the fluid flow to reflect the signals; therefore "dirtier” CNG conditions is required if lower frequency transducer is used [36].

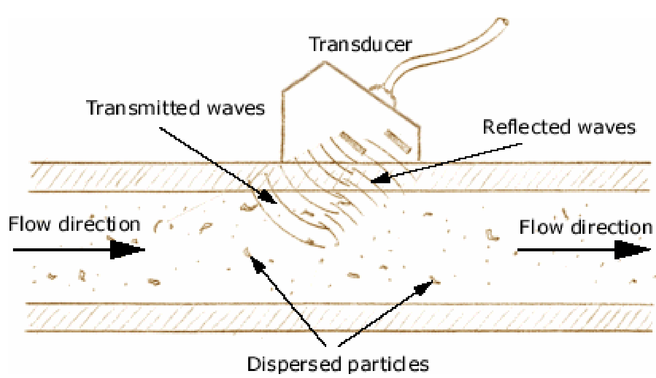


Figure 2.15: Doppler ultrasonic flowmeter [36]

Since there is no obstruction in ultrasonic flowmeters flow path, the advantages would be no pressure drop, no moving parts and potential to be applied in CNG dispenser. However, the only disadvantage is higher initial set-up cost needed, which requires cheaper volumetric flowmeter such as vortex flowmeter. Figure 2.16 below shows a typical design of vortex flowmeter [6].

2.3.4 Vortex flowmeter

Vortex flowmeter is also known as vortex shedding flowmeter or oscillatory flowmeter because it measures vibrations of downstream vortexes caused by the barrier placed in a moving stream. The vibrating frequency of vortex shedding can then be related to the velocity of flow. The advantages of vortex flowmeter are low to medium initial set-up cost and low maintenance is needed. However, the disadvantages are clean flow conditions are required and low pressure drop due to obstruction in the flow path. Therefore, other option for metering CNG such as magnetic flowmeter is seek [37].

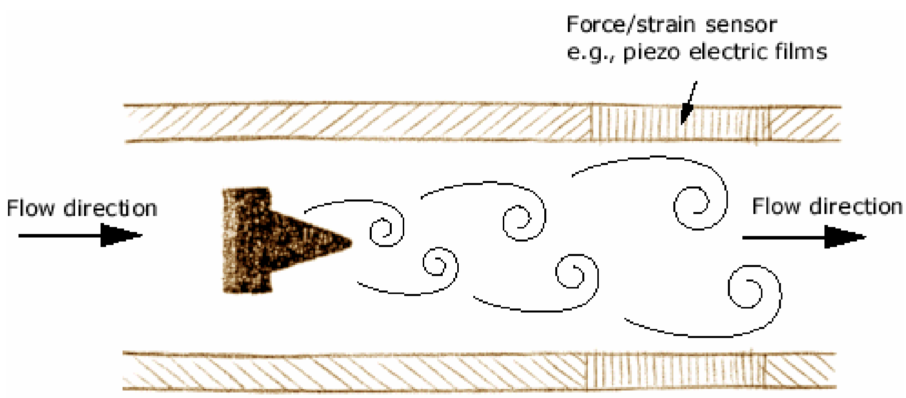


Figure 2.16: Vortex flowmeter [37]

2.3.5 Magnetic flowmeter

Magnetic flowmeter is also known as electromagnetic flowmeter or induction flowmeter which measures flow velocity based on changes of induced voltage from conductive fluid that passes across controlled magnetic field. There are two types of magnetic flowmeters available i.e., inline magnetic flowmeter and insertion magnetic flowmeter which are discussed in following section [38].

Figure 2.17 and Figure 2.18 below show typical designs for inline magnetic flowmeter and insertion magnetic flowmeter, respectively. For inline model, electric coils and electrodes are placed around and across the pipe wall, respectively, whilst, for insertion model, electric coils and electrodes are placed near and at the tip of the flowmeter, respectively. From both figures, if the fluid passes through the pipe is electrically conductive, the value of flow would be equal to value of conductor cutting across the magnetic field, which would induce voltage changes between the electrodes. Therefore, if the velocity of the fluid is higher, more induced voltage would be detected [38].

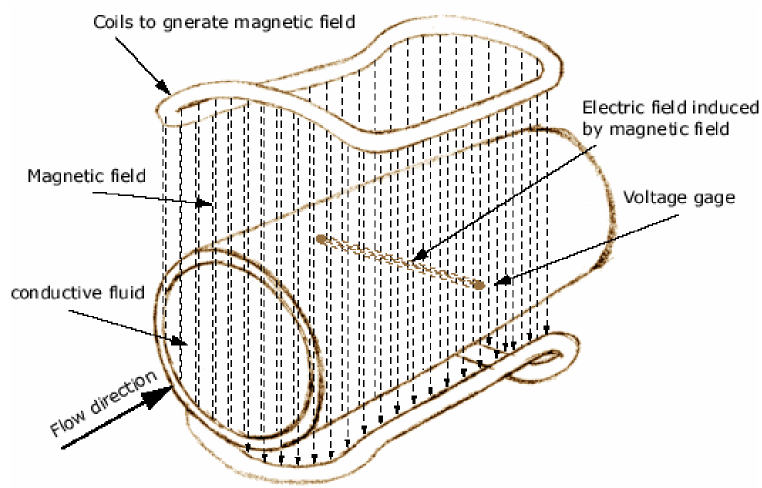


Figure 2.17: Inline magnetic flowmeter [38]

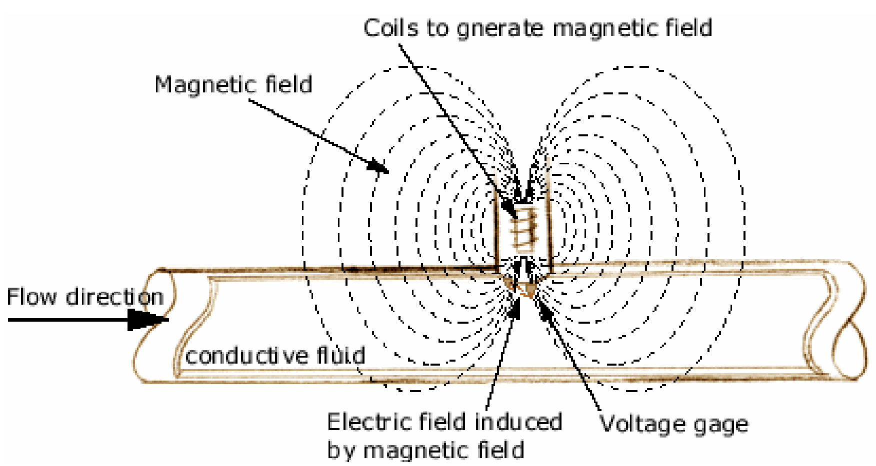


Figure 2.18: Insertion magnetic flowmeter [38]

Magnetic flowmeter has several advantages such as capability to measure highly flammable fluid such as CNG, low maintenance cost, no moving parts, higher linearity and minimum pressure drops are developed. However, the disadvantages are higher electrical conductivity of fluid is needed and zero drifting if it is lower flow. For that reason, other metering technologies are developed for CNG such as pressure-volume-temperature based flowmeter or also known as PVT [38].

2.4 Previous works based on pressure-volume-temperature (PVT) flowmeter

PVT is based on equation of state (EOS) i.e., a relation between state variables, more specifically, a thermodynamic equation describing the state of matter under a given set of physical conditions. It is a constitutive equation which provides a mathematical relationship between two or more state functions associated with the matter, such as its temperature, pressure, volume, or internal energy which are useful in describing the properties of fluids including CNG. Interesting works based on PVT for CNG could be reviewed from Radhakrishnan *et al* [13]. Some of the equations are classical ideal gas law, Van der Waals, Redlich-Kwong, Soave-Redlich-Kwong and Peng-Robinson.

Any consistent set of units may be used, although SI units are preferred. Absolute temperature is referred as the Kelvin, K or Rankine, $^{\circ}R$ temperature scales, with zero being absolute zero. The following describes the first PVT equation i.e., classical ideal gas law.

p	=	absolute pressure
V	=	volume
n	=	number
V_m	=	molar volume
T	=	absolute temperature
R	=	ideal gas constant
p_c	=	pressure at the critical point
V_c	=	molar volume at the critical point
T_c	=	absolute temperature at the critical point

2.4.1 Classical ideal gas law

The classical ideal gas law may be written as [39],

$$pV = nRT \tag{2.1}$$

The ideal gas law may also be expressed as follows

$$p = \rho(\gamma - 1)e \tag{2.2}$$

Where ρ is the density, $\gamma = C_p / C_v$ is the adiabatic index (ratio of specific heats), $e = C_v T$ is the internal energy per unit mass (the "specific internal energy"), C_v is the specific heat at constant volume, and C_p is the specific heat at constant pressure. The following describes the second PVT equation i.e., Van der Waals.

2.4.2 Van der Waals

The Van der Waals equation may be written as [39],

$$\left(p + \frac{a}{V_m^2}\right)(V_m - b) = RT \tag{2.3}$$

Where a and b are constants that depend on the specific material. They can be calculated from the critical properties p_c, T_c and V_c as,

$$a = 3 p_c V_c^2 \tag{2.4}$$

$$b = \frac{V_c}{3} \tag{2.5}$$

Which may be written as,

$$a = \frac{27(RT_c)^2}{64 p_c} \tag{2.6}$$

$$b = \frac{RT_c}{8 p_c} \tag{2.7}$$

The following describes the third PVT equation i.e., Redlich-Kwong.

2.4.3 Redlich-Kwong

The Redlich-Kwong equation may be written as [39],

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T} V_m (V_m + b)} \tag{2.8}$$

$$a = \frac{0.42748 R^2 T_c^{2.5}}{p_c} \tag{2.9}$$

$$b = \frac{0.08662 R T_c}{p_c} \tag{2.10}$$

However, the equation is adequate for calculation of gas phase properties when the ratio of the pressure to the critical pressure is less than about one-half of the ratio of the temperature to the critical temperature.

$$\frac{p}{p_c} < \frac{T}{2T_c} \tag{2.11}$$

2.4.4 Soave-Redlich-Kwong

The Soave-Redlich-Kwong equation may be written as [39],

$$p = \frac{RT}{V_m - b} - \frac{a\alpha}{V_m (V_m + b)} \tag{2.12}$$

$$a = \frac{0.42747 R^2 T_c^2}{P_c} \tag{2.13}$$

$$b = \frac{0.08664 R T_c}{P_c} \tag{2.14}$$

$$\alpha = \left(1 + (0.48508 + 1.55171\omega - 0.15613\omega^2 \left(1 - T_r^{0.5}\right)\right)^2 \tag{2.15}$$

$$T_r = \frac{T}{T_c} \tag{2.16}$$

Where ω is the acentric factor for the fluids.

2.4.5 Peng-Robinson

The Peng-Robinson equation may be written as [39],

$$p = \frac{RT}{V_m - b} - \frac{a\alpha}{V_m^2 + 2bV_m - b^2} \tag{2.17}$$

$$a = \frac{0.45724R^2T_c^2}{p_c} \tag{2.18}$$

$$b = \frac{0.07780RT_c}{p_c} \tag{2.19}$$

$$\alpha = \left(1 + \left(0.37464 + 1.54226\omega - 0.26992w^2\right)\left(1 - T_r^{0.5}\right)\right)^2 \tag{2.20}$$

$$T_r = \frac{T}{T_c} \tag{2.21}$$

Based on Figure 2.19, Radhakrishnan *et al* has compared these EOS measurements with weight scale system and found that only Peng-Robinson algorithm can measure accumulated mass in the CNG tank accurately. However, inaccuracy could still occur because at present, there is no single equation of state that could predict the properties of all substances under all conditions. Therefore, other flowmeters are desired compared to PVT based meter which can measure mass of CNG directly, provide accuracy with repeatability, minimum permissible error, maintenance free and cheaper operating cost ever. As a result, mass flowmeter is preferred which is discussed in following section.

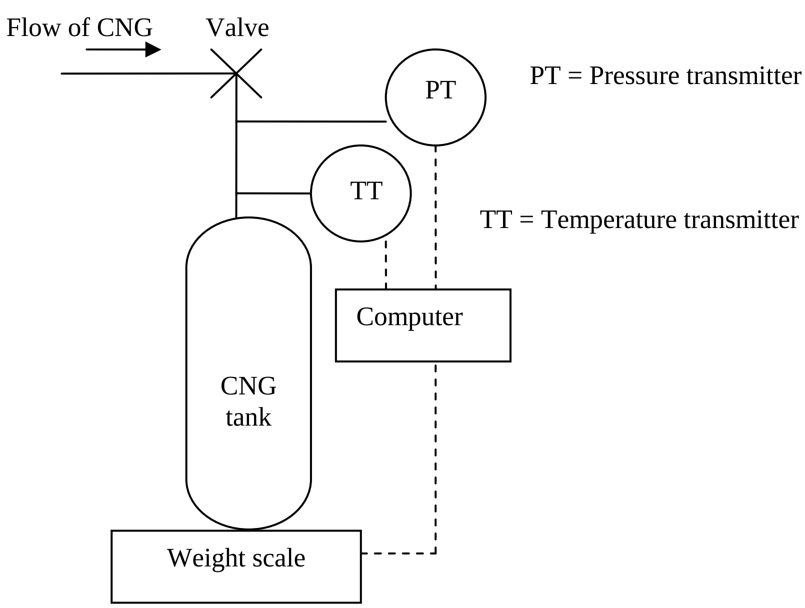


Figure 2.19: PVT based flowmeter [13]

2.5 Previous works based on mass flowmeter

There are two types of mass flowmeters: thermal mass flowmeter and coriolis mass flowmeter. To measure mass of fluids, thermal mass flowmeter measures the heat carried away by the fluid through a sensor, whilst coriolis mass flowmeter measures the vibration signal deformed by the coriolis force. Figure 2.20 below shows a typical design of thermal mass flowmeter [14], [15].

2.5.1 Thermal mass flowmeter

The primary sensor of a thermal flowmeter is a heated wire or film, typically a platinum or tungsten Resistance Temperature Detector (RTD) that is exposed in the flow. A second sensor, possibly another RTD, is used to measure the flow temperature. As the flow passes over the hot wire, it carries away heat. The heat loss depends on the mass flow rate, the heat capacity of the fluid, and the temperature difference between the wire and the fluid. Since the heat capacity of the fluid is known and the temperatures are monitored in real-time, the mass flow rate can be determined from the heat loss and the thermal expansion coefficient of the wire as discussed in the hot wire theory [40]. Although, it has advantages such medium initial set up cost and lower pressure drop, it still produces disadvantages such as fragile, higher repair cost and relies on heat transfer within the flow gas. Because the meter relies on measurement of temperature difference between two sensors, the response to step changes is relatively slow [14]. Therefore, other mass flowmeter is used in CNG metering which is coriolis mass flowmeter.

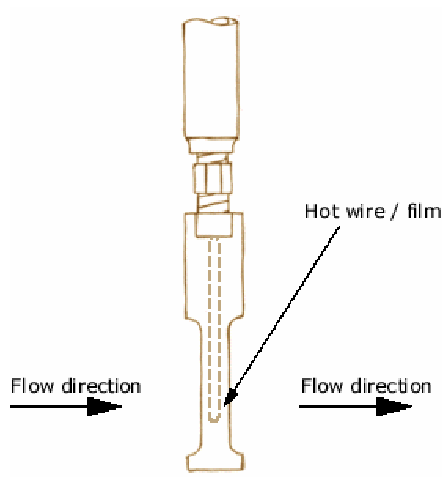


Figure 2.20: Thermal mass flowmeter [14]

Since coriolis is the main interest that motivates this research, the following section would brief in details of what are the principle behind its operations, the physical design and its mathematical model which forms fundamental basis in designing inferential coriolis. Figure 2.21 below shows a typical design of coriolis mass flowmeter.

2.5.2 Coriolis mass flowmeter

The coriolis effect is an apparent deflection of moving objects from a straight path when they are viewed from a rotating frame of reference. The effect is named after Gaspard-Gustave Coriolis, a French scientist who described it in 1835, though the mathematics had appeared previously in the tidal equations of Pierre-Simon Laplace in 1778. The coriolis effect is caused by the coriolis force, which appears in the equation of motion of an object in a rotating frame of reference. Sometimes this force is called a fictitious force (pseudo force), because it does not appear when the motion is expressed in an inertial frame of reference, in which the motion of an object is explained by the real impressed forces, together with inertia. In a rotating frame, the coriolis force, which depends on the velocity of the moving object, and centrifugal force, which does not, is needed in the equation to correctly describe the motion. Perhaps the most commonly encountered rotating reference frame is the earth. Freely moving objects on the surface of the earth experience a coriolis force, and appear to veer to the right in the northern hemisphere, and to the left in the southern., whilst, movements of air in the atmosphere and water in the ocean are notable examples of this behavior [246].

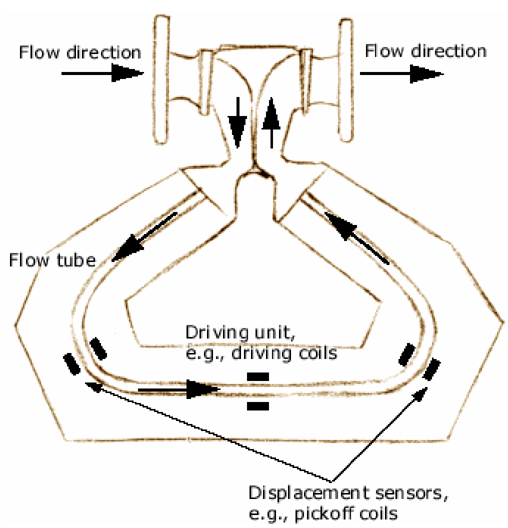


Figure 2.21: Coriolis mass flowmeter [237]

2.6 Defining coriolis

This section describes the coriolis force as discussed in [42]. As shown in Figure 2.22, when there is a fluid flowing at velocity, V in a rotating elastic tube, a deflection would occur from the tube.

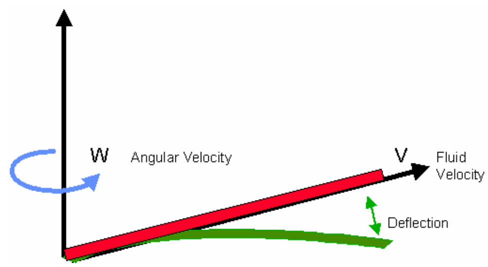


Figure 2.22: Deflection of tube [42]

Based on Figure 2.23 shown below, if there is a mass, M moving from the center to the edge of a rotating plate, this mass, M will take path B. If the mass, M is guided by a wall, A which is the tube, a coriolis force will be exerted on the wall, that could be derived as $Fc = -2MVW$, where Fc is the coriolis force.

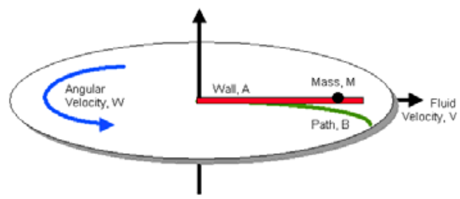


Figure 2.23: Coriolis force [42]

Many applications could be developed from coriolis force [42]. One of the applications is the mass flowmeter design as shown by Figure 2.24 i.e., a measuring instrument that uses tube walls to guide fluid in a U-tube pathway.

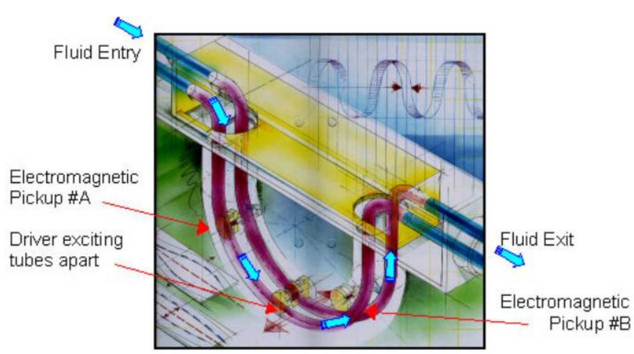


Figure 2.24: Coriolis in U-tube [42]

2.6.1 Defining coriolis flowmeter

Mass flowmeter is defined as a flowmeter that measure mass directly using the properties of mass, as opposed to those that measure volume or velocity [3]. The operating principle, introduced in 1977 by Micro Motion Inc., involves inducing a vibration of the tube through which the fluid passes. The vibration, though it is not completely circular, provides the rotating reference frame which gives rise to the coriolis force. While specific methods may vary according to the design of the flowmeter, sensors will monitor and analyze changes in frequency, phase shift, and amplitude of the vibrating flow tubes. The changes observed represent the mass flow rate and density of the fluid. Meters of this type were developed and commercialized in 1980s which is found to have wide application because the fluid measurement is virtually independent from any changing fluid parameters. Other flowmeters are affected by changes such as fluid density, viscosity, pressure and temperature. Meters that measure mass directly, in effect, weigh the fluid as it passes through the meter, yielding a highly accurate measurement that is virtually independent of varying process conditions that often occur. Because of this unique ability, it is possible to use a coriolis flowmeter on a wide variety of process fluids without need for recalibration or compensation to specific fluid parameters. It is also relatively easy to apply and size i.e., since it possesses no moving parts, it exhibits low maintenance requirements and does not require frequent calibration. Wetted parts that can be constructed from a variety of materials make it adaptable to many corrosive fluids as well as fluids containing solid or fibrous particles. Coriolis flowmeter can also measure the density of the process fluid, making it possible to infer volume of one component in a two-component flow stream. Figure 2.25 shows a coriolis flowmeter manufactured by Micro Motion [20].

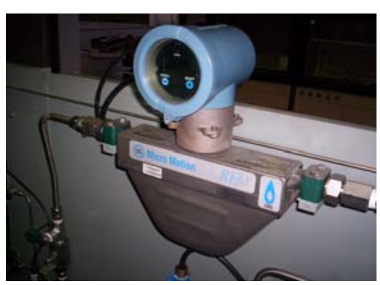


Figure 2.25: Micro Motion coriolis flowmeter

2.6.2 Principle operation of coriolis flowmeter

A coriolis meter operates on the basic principles of motion mechanics. The fluid in motion through a vibrating flow tube is forced to take on a transverse acceleration as it moves toward the point of peak amplitude of vibration. Conversely, the fluid decelerates as it moves away from the point of peak amplitude as it exits the tube. The moving fluid exerts a force on the inlet side of the tube in resistance to this acceleration, causing this side of the tube to lag behind its no-flow position. On the outlet side, the force exerted by the flowing fluid is in the opposite direction as the fluid resists the deceleration. This force causes the outlet side of the tube to lead ahead of its no-flow position. The result of these forces is a twisting reaction of the flow tube during flow conditions as it traverses each vibrational cycle [3]. This is demonstrated with a U-shaped tube shown in Figure 2.26.

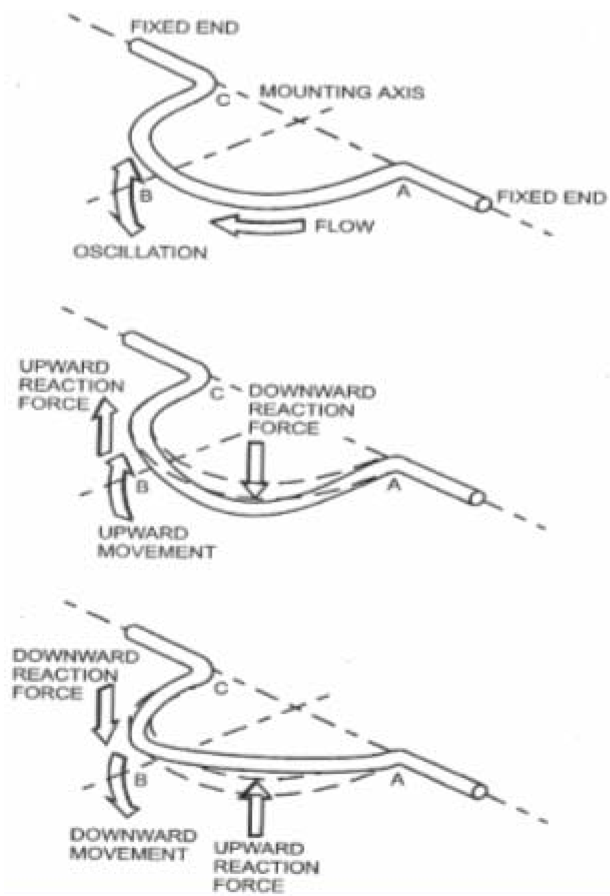


Figure 2.26: Coriolis principle [3]

As illustrated by Figure 2.26 previously, fluid at point B moves up and down faster than fluid at A or C. Fluid passing through the curved section must, therefore, change its overall velocity in space even though its speed relative to the tube may be constant. When the fluid moves away from the mounting axis, the tube motion lags behind point B. When the fluid moves toward the mounting axis, the tube motion leads ahead of point B.

The flow tube is vibrated at its natural frequency through the use of electromagnetic devices. The motion at any point on the tube represents a sine wave. With no flow through the tube, all points move in sequence or in phase with the driver as shown in Figure 2.27 (a). As mass flow through the tube occurs, the inlet side motion of the tube lags the driver phase, and the outlet side motion leads the driver phase as shown in Figure 2.27 (b). The time delay between S_1 and S_2 is directly proportional to the mass flow rate through the sensor.

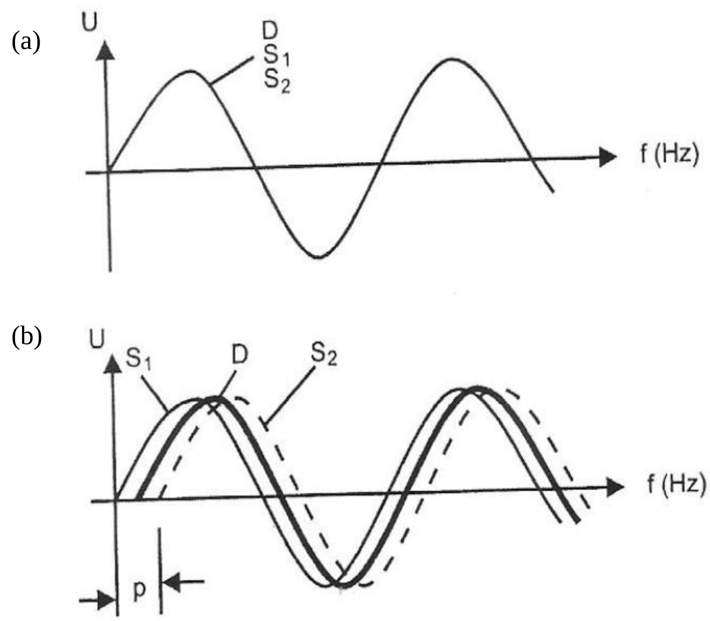


Figure 2.27: Sine waves (a) No Flow (b) Mass Flow [3]

Typically, the coriolis principle mass flowmeters are manufactured in a variety of shapes, sizes and materials of construction. All of these factors influence the sensitivity of the meter to flowrate; however, the basic principle of operations remains the same.

2.7 Mathematical derivation for mass flowrate

The basic equations for mass flowrate could be developed based on Figure 2.28, which represents fluid with mass, m, flowing with a velocity, $\bar{v}$, through a U-shaped tube oscillating with an angular velocity around axis, $o-o$.

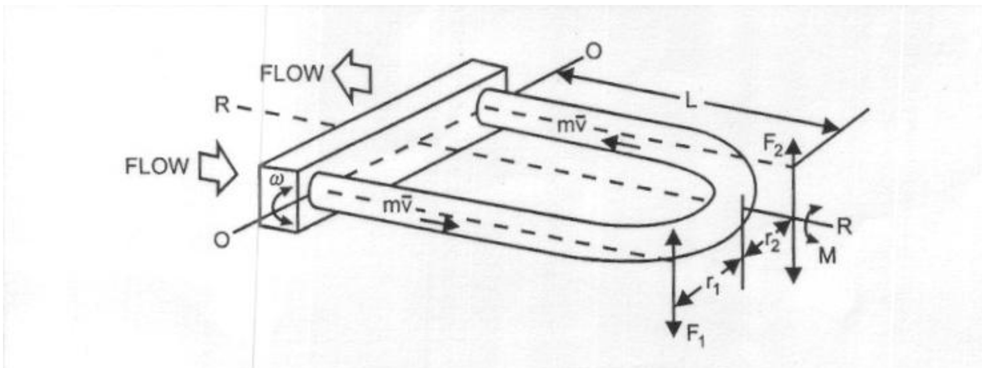


Figure 2.28: Oscillating U-tube [3]

The following mathematical analysis is derived based on [3], which has been greatly simplified to demonstrate the concept of coriolis flowmeter principle. According to [3], the coriolis force induced by the flow could be described by the following equation:

$$F = 2m\omega\bar{v} \tag{2.22}$$

In which, F (force), ω (its angular motion) and $\bar{v}$ (velocity) are vectors, and m, is the mass to be applied to a known point at a distance, L from the axis, $o-o$ of Figure 2.28. This equation is equivalent to $F = ma$ (Newton's Second Law for Rotational Motion). The vectors for the input and output velocities of the fluid are in opposite directions. Looking at the measuring tube along the axis, $R-R$, the forces F_1 and F_2 applied by the fluid to the input and output legs are in opposite directions but having the same amplitude. The mathematical derivation shown by Equation (2.22) describes the relationship between the mass flowrate and the behavior of the measuring element for a sensor with only one U-shaped tube. This equation applies as well to the implementation with two opposite measuring tubes.

Since the tube oscillates around the axis, $o-o$, the developed forces create an oscillating moment, M around the axis, $R-R$, with a radius, r. It is expressed as:

$$M = F_1 r_1 + F_2 r_2 \tag{2.23}$$

Since, $F_1 = F_2$ and, $r_1 = r_2$, it follows from Equation (2.22) and (2.23):

$$M = 2Fr = 4mv\omega r \tag{2.24}$$

The mass, m is defined as the product of the density, ρ the cross-sectional area, A and length, L of the measuring tube. The velocity is defined as unit of length L per unit of time, t. The mass flowrate W is defined as the mass, m that flows by a given point per unit of time. Therefore:

$$m = \rho AL \tag{2.25}$$

$$\bar{v} = \frac{L}{t} \tag{2.26}$$

$$W = \frac{m}{t} \tag{2.27}$$

Thus, by substituting, $W = \dfrac{m\bar{v}}{L}$, in which, L is the length of the tube, Equation (2.24) becomes:

$$M = 4\omega rWL \tag{2.28}$$

The moment, M would induce an angular deflection or twist, ϕ of the measuring tube around the axis, $R-R$. The twist would have the maximum value at half of the travel of the vibrating tube, as shown previously by Figure 2.28.

Nevertheless, the deflection caused by the moment is opposed by the force, K corresponding to the elastic modulus of the tube. In general, for a spring subjected to a twisting moment, the torque, T is defined as:

$$T = K\phi \tag{2.29}$$

Since, $T = M$, the mass flowrate W can now be related to the deflection angle, ϕ using Equation (2.28):

$$W = \frac{K\phi}{4\omega rL} \tag{2.30}$$

The mass flowrate can be derived by measuring the deflection angle with two magnetic position sensors as shown by Figure 2.29.

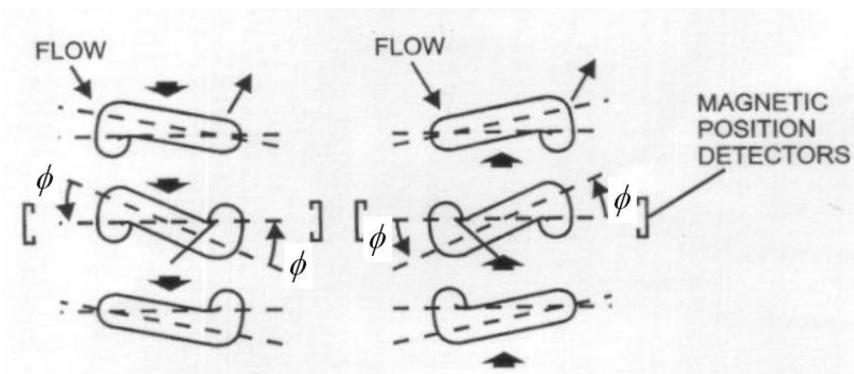


Figure 2.29: Deflection Angle Measurements [3]

A signal processing method is used at each sensor to measure, ϕ as a function of the time it takes for each leg of the tube to cross the middle point of the travel corresponding to the total deflection. The time differential between the two legs is zero in no-flow conditions. When a flow is established (increasing the angle, ϕ), the time differential between the signals corresponding to the high and low travels of the tube legs also increases. These time differentials are interpreted as pulses of different lengths by the digital logic circuit [3].

The velocity, v_t of the tube in the middle of its travel, multiplied by the time interval Δt, is related to ϕ by the following equation:

$$\sin\phi = \frac{v_t \Delta t}{2r} \tag{2.31}$$

If ϕ is small, it is almost equal to its sine. And, for a small angular rotation, v_t is equal to the product of ω by the length L of the tube.

Thus if $\sin\phi = \phi$ and $v_t = \omega L$, Equation (2.31) becomes:

$$\phi = \frac{\omega L \Delta t}{2r} \tag{2.32}$$

Combining Equations (2.30) and (2.32), it follows that:

$$W = \frac{K\omega L \Delta t}{8r^2 \omega L} = K\Delta t \tag{2.33}$$

Therefore, the mass flowrate, W is proportional to the time interval, Δt and some geometric constants, K. W is independent of ω, and thus, independent of vibrating frequency of the measuring tube. The term, K in the equations above represents the elastic modulus of the tube. The elastic modulus of all metals varies as a function of temperature. Since K is a constant of proportionality, it must be compensated for temperature changes that occur in the process. The surface temperature of the flow tube is monitored using platinum RTD. As temperature changes, the signal processing electronics will continuously adjust the constant of proportionality, which scales, Δt to obtain the corrected mass flowrate measurement [3].

2.8 Mathematical derivation for density

Since the mass flow measurement is not affected by the frequency of vibration of the tube, it is possible to allow the tube to be vibrated at its fundamental natural frequency. This has two advantages. Firstly, by vibrating the tube at its natural frequency, a least amount of energy delivered to the drive coil is required to keep the tube vibrating. Secondly, the natural frequency of the vibrating tube depends on the mass of the material contained within the tube. Therefore, it is possible to measure the density of the process fluid with the same sensor used for mass flow. The following equations govern the density measurement implemented with a coriolis flow sensor. For a vibrating spring mass system, the governing equation is

$$\omega = 2\pi f = \sqrt{\frac{K}{m}} \tag{2.34}$$

Where w, angular frequency of oscillation, K spring constant, f frequency of oscillation and m, mass of fluid. The mass is comprised with the mass of vibrating structure plus the mass of its contained liquid, which is

$$m = m_{tube} + m_{liquid} \tag{2.35}$$

The mass of the liquid is equal to density multiplied by volume, as shown below

$$m_{liquid} = \rho V \tag{2.36}$$

By substituting equation (2.35) and (2.36) into (2.34), the resulting equation is

$$\omega = \sqrt{\frac{K}{m_{tube} + \rho V}} \tag{2.37}$$

Since, period is $T = \frac{1}{f}$. By equating (2.34) to (2.37), the process fluid density ρ could be derived as

$$\rho = \frac{\frac{KT^2}{(2\pi)^2} - m_{tube}}{V} \tag{2.38}$$

Therefore, by measuring the natural period of vibration and compensating for the change in spring constant with temperature, the process fluid density, ρ could be calculated.

2.9 Practical implementation of coriolis flowmeter

In the practical implementation of coriolis principles to mass flow measurement, most manufacturers use two parallel flow tubes vibrated in opposition to each other to neutralize the vibration induced into the piping and mounting system, as shown in Figure 2.30.

The flow is split between the two tubes at the inlet to the meter and recombined at the outlet i.e., the meter is plumbed for flow to pass through the two tubes one after the other. This allows one tube's coriolis twist signal to be measured with respect to the other tube's twist signal while rejecting piping vibration. The amplitude of vibration of the tube is controlled to a level that keeps the bending stress in the tubing well below the elastic limits of the tube material.

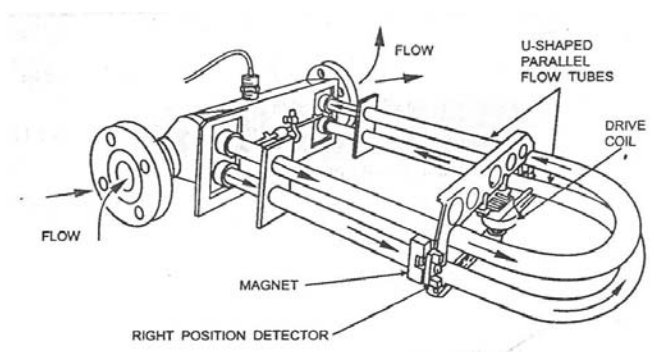
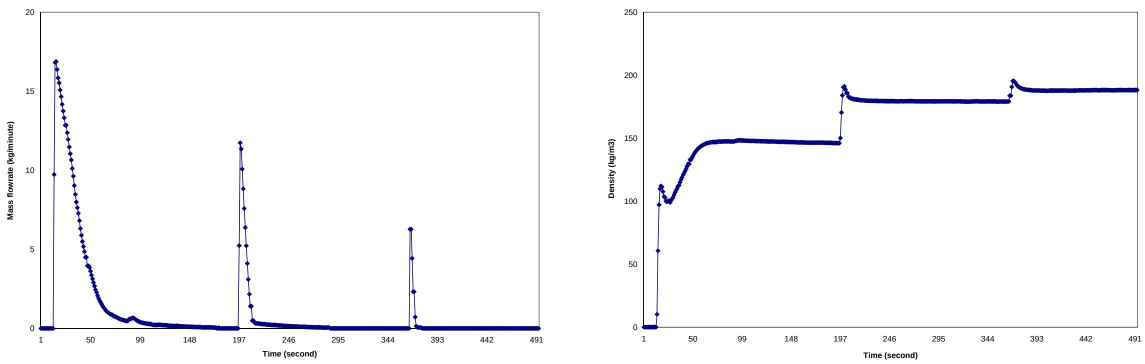


Figure 2.30: Typical construction of coriolis flowmeter [3]

The primary measurement section is made of highly corrosion-resistant metal tubing. The most common material used is seamless 316L stainless steel, whilst they are also tubing available in titanium, Hastelloy®, and tantalum for chemical compatibility with process fluids that are corrosive. The amount of coriolis twist induced by the mass flow is very small. One manufacturer claims that for a 0.040 inch amplitude of vibration, the tube only twist a maximum of 0.0014 inch at rated full scale flow. Therefore, the design for electronics that detect these small signals is equally critical. The Δt signal, which is the basis of mass flow measurement, needs to be resolved to nanosecond range. For that reason, both analog and digital signal processing and filtering techniques are used in state-of-the-art of the coriolis flowmeter [3].

A typical example of actual mass flowrate and density measurements using micro motion coriolis flowmeter are shown in Figure 2.31 (a) and Figure 2.31 (b), respectively.



(a) Mass flowrate measurement (b) Density measurement

Figure 2.31: Coriolis measurements using Micro Motion flowmeter

In many applications, the coriolis is considered the most accurate to be used as a mass flowmeter and density measurements. Considering that most of this technology user is concerned on the investment and reliability of the system, a suitable substitute that is able to perform similar measurements and directly read into a computer is very useful. Alternatively, the “device” would serve as a ‘redundant’ to the coriolis, or as a complete replacement of other flowmeters.

As shown by Figure 2.31 (a) and Figure 2.31 (b) respectively, both graphs of mass flowrate and density measurements are nonlinear, which could not be represented using a typical linear regression method. In this research a method known as SYSID would be applied for determining discrete transfer function of coriolis mass flowrate (CMF). Notably, only the transfer function of mass flowrate would be determined in this research since a similar approach could be applied to determine transfer function of density. The major difference is only in the sampled output data used in the SYSID i.e., if transfer function to be determined is mass flowrate, then data of mass flowrate should be used as the output, whilst, if transfer function to be determined is density, then data of density should be used as the output. The SYSID would be discussed further in Chapter 3.

2.10 Summary

This chapter introduces a selection of research works regarding CNG filling systems and flowmeter technologies which covers momentum flowmeter; volumetric flowmeter; pressure-volume-temperature (PVT) based flowmeter and mass flowmeter. As with the choice of coverage, the reference are selected from a large number of sources but is not meant to provide a comprehensive review. Since coriolis is the main interest, the principle behind its operations, the physical design and its mathematical model is described in details which form the fundamental basis in designing inferential coriolis. The coriolis effect is an apparent deflection of moving objects from a straight path when they are viewed from a rotating frame of reference. One of the applications could be seen from a mass flowmeter that measure mass of fluid directly, using the properties of mass as opposed to other flowmeters that measure volume or velocity which is based on fluid viscosity, pressure, temperature, etc. Mathematical equation of mass flowrate has been derived based on a U-shaped tube flowmeter. However, the problems lies on determining the right value of elastic modulus of tube, K since coriolis flowmeter uses signal processing electronics to compensate K for an accurate mass flowrate measurement automatically. Hence, a method is introduced in this research known as SYSID, to determine the coriolis mass flowrate (CMF) transfer function which is a nonlinear system problem.

Considering the benefits of modeling and implementing the inferential coriolis as measuring tool for CNG, the motivation to embark on this work is based on the potential for improving the gas mass flowrate measuring technique using the methodology to be presented in Chapter 3.