| KLM Technology Group
#03-12 Block Aronia,
Jalan Sri Perkasa 2
Taman Tampoi Utama
81200 Johor Bahru
Malaysia | Process Equipment Design Guidelines

Chapter Four

Instrumentation Selection and Sizing

(Engineering Design Guidelines) | Co Author

Rev 01 - A L Ling
Rev 02 - Viska Mulyandasari
Rev 03 – K Kolmetz
Rev 04- Mochamad Adha Firdaus

Karl Kolmetz |

TABLE OF CONTENT

INTRODUCTION

Scope 6

General Instrumentation Consideration 7

Pneumatic Power Supplies 8

Important of Instrumentation Control for Unit Operation 9

Process Variable Measurement Instrument 10

DEFINITIONS 12

NOMENCLATURE 14

THEORY

A) Pressure Measurement 16

Height of a Liquid Column 16

Elastic-Element – Bourdon Tube, Bellows and Diaphragm 18

i) Bourdon Tubes 19

ii) Bellows 20

iii) Diaphragm 22

Electrical Method -Electrical Pressure Transducers 23

i) Strain Gauges 23

B) Level Measurement 24

Gauge Glass 25

Chain or Tape Float Gauges 26

Lever and Shaft Float Gauges (Ball Gauge) 27

Displacer 29

Pressure Gauge 32

Electrical Level Gauges 35

Magnetic Gauge 36

C) Temperature Measurement 37

Thermocouples 37

i) Thermocouples Sensor 40

Resistance Thermometers (RTD) 41

Bimetal Thermometers 42

D) Signal Transmitter 43

E) Recorders and Indicators 44

F) Control System 44

G) Control Modes and Controllers 45

On-off Controller 45

Proportional Controller 46

Proportional Plus Integral (PI) 47

Proportional Plus Derivative Mode (PD) 48

Proportional Plus Integral Plus Derivative (PID) 48

H) Installation, Troubleshooting, and Calibration 52

Failed Systems 52

Poorly Commisioned Systems 53

Poor Performance 54

Calibration 55

Pressure Transmitters 55

Differential pressure transmitters 55

Temperatures transmitters 56

I) Computer Systems 57

Analog Computers 57

Digital Computers 57

i) Microcomputers 57

ii) Minicomputers 58

iii) Process Input / Output Equipment 58

J) Digital First-Level Control Systems 58

Individual Controllers 58

Direct Digital Controllers (DDC) 59

Distributed Control Systems (DCS) 59

Fieldbus 59

K) Analytical Instruments 60

Cyclic Analyzers 60

Continuous Analyzers 60

System Control Diagram 62

L) Fire, Gas and Smoke Detector 62

Flammable Gas Detectors 63

Oil Mist Detectors 64

Very toxic compounds Detectors 64

Fire and Smoke Detectors 64

APPLICATION

Example Case 1: Level Control Schematic Drawing for Fractionation Tower Bottom. 66

Example Case 2: Pressure Control Schematic Drawing for Fractionation Overhead Drum. 67

Example Case 3: Temperature Control Schematic for Bottom Fractionation Tower 68

REFEREENCES 69

SPECIFICATION DATA SHEET

Instrument Specification Data Sheet Revision 01 70

LIST OF TABLE

Table 1: Properties of Typical Type of Thermocouples. 39

Table 2: Metals Properties for RTDs. 42

Table 3 : Common Measurement Problems 54

Table 4 : Square Root Input / Output Relaionship 56

Table 5 : Continuous Analysis Instruments 61

LIST OF FIGURE

Figure 1: Simple Instrument Model 7

Figure 2: U- Shape Tube Manometer 17

Figure 3: Inclined U-Tube Manometer 18

Figure 4: C-spring Bourdon-Tube Pressure Gauge 20

Figure 5: Spring-Loaded Bellows 21

Figure 6: Unopposed Bellows 21

Figure 7: Beam Balance Sensor Bellows 22

Figure 8: Diaphragm Pressure Elements 23

Figure 9: The Wheatstone bridge 24

Figure 10: Reflex Gauge Glass 26

Figure 11: Transparent Gauge Glass 26

Figure 12: Chain and Tape Float Gauge 27

Figure 13: External Ball Float Level Device for Emergency and Alarm Services 28

Figure 14: Internal Ball Float Level Device 29

Figure 15: Displacer Level Measuring Device 30

Figure 16: Quantities of a solid body immersed into a liquid 30

Figure 17: Typical pressure gauge level measurement system 33

Figure 18: HTG Level Measurement System 33

Figure 19: Bubble Tube Level Measurement 34

Figure 20: Conductivity Level Device – Low and High Level Alarm Indication 35

Figure 21: Magnetic Gauge Level Measurement Device 36

Figure 22: Thermal EMF, E, of Commonly Used Thermocouples as a Function of Temperature 38

Figure 23: Typical Thermocouple circuit 39

Figure 24: Industrial Thermocouple Assembly 40

Figure 25: Ceramic Platinum RTD. 41

Figure 26: Flat Strip Bimetal Thermometer 42

Figure 27: Controller Modeling Diagram 46

Figure 28: Response of Step Change in Disturbance with Tuned P, PI, PID, and Non-controlled. 49

Figure 29 : Typical Chromatograph System 61

KLM Technology Group is providing the introduction to this guideline for free on the internet. Please go to our website to order the complete document.

www.klmtechgroup.com

INTRODUCTION

Scope

Instrumentation is a term that is commonly used in engineering, which means measurement and control for industrial process systems. Various processes in petrochemical industries need to be maintained at controlled levels to get the desired product. It is commonly done by controlling such process variables as pressure, temperature, and liquid level by using measurement devices (instruments) with control systems. Control instrumentation plays a significant role in both gathering information from the field and changing the field parameters.

This design guideline covers the selection of measurement devices and control systems which are commonly used in the processing industries. Measurement devices could be classified into various types based on their function.

In this guideline, three types of commonly used measurement devices are explained in detail; such as pressure, level, and temperature measurement devices. Some devices, such as signal transmitter, recorder, and indicator, are generally also networked together to support the measurement device. Those supporting equipments are also explained as well in this guideline.

The selection of measurement device is mostly based on necessity, which variables need to be controlled. But their accuracy, installation cost, and maintenance should be considered as well. Comparing several measurement devices might be important to obtain the most suitable one.

Besides deciding the measurement device to be used in a process, it is also important to put them in a right order. Hence, the control system and control mode explanation are also included in this guideline.

The control system decides how to cope the disturbances in process system by managing behavior of other devices in a system. Generally a controller could be classified into several types based on its characteristics. Each type of controller has their own disadvantages; hence they are commonly combined in industrial process system. No one control system and controller can be utilized for all petrochemical industrial applications. This guideline gives the basic information as a guide to be applied in the process industries.

Some sample calculations based on the real industrial samples are included in this guideline. Calculation spreadsheet for manometer, level measurement using pressure gauge devices and Bimetal thermometers are attached as well and to aid user to understand how to apply the theory for calculations.

General Concept of Instrumentation

An instrument is a device that transforms a physical variable (temperature, length, pressure, velocity, capacity, etc) of interest (the measurand) into a form that is suitable for recording (the measurement). In order for the measurement to have broad and consistent meaning, it is common to employ a standard system of units by which the measurement from one instrument can be compared with the measurement of another. An example of a basic instrument is a ruler. In this case the measurand is the length of some object and the measurement is the number of units (meters, inches, etc.) that represent the length. [4]

Simple instrument model (Figure 1), physical measurement variable is measure by measurand as input to sensor; sensor has a function to convert the input to signal variable; signal variables have the property that they can be manipulated in a transmission system, the signal is transmitted to a display or recording device where the measurement can be read by a human observer.

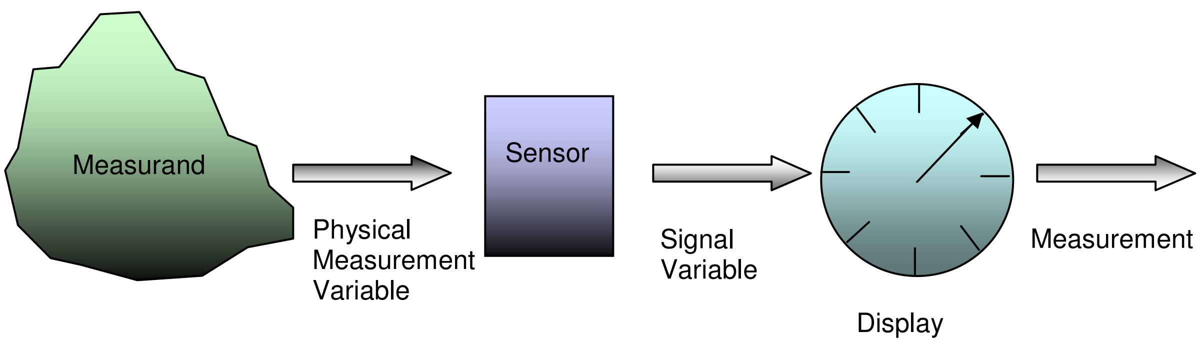

Figure 1: Simple Instrument Model

Instruments are important for control of process variables (temperature, pressure, level, flow and etc). Objectives of process control are to achieve safe production, lowest cost of process, improving product quality, lowering labor costs, reducing or eliminating human error, reducing energy consumption, elimination of product giveaway, and reducing products off-spec.

Instrumentation in industrial sites today normally are equipped with a distributed control system (DCS) that provides advanced control capabilities and interfaces to other systems, including management information and accounting systems and read-only interface to protective systems.

Function of the process control can be class into basic functions and corollary functions. Generally basic functions are needed for plant operability and corollary functions come after plant operability is established.

Basic functions consist of maintaining stability of operating conditions at key points in the process and providing the operator with information of suitable operating condition and the means for adjusting them.

The corollary functions are automating operations which reduce the demand for continuous operator attention as dictated by economics; insuring that operations are safe for personnel and equipment to met all regulatory requirements; and maintaining product quality while minimizing operating costs.

Instrumentation is usually comprised of a system of pneumatic or electronic devices for measurement and control of all the process variables. Both type of the pneumatic or electronic instrumentation have advantages and disadvantages.

Generally advantage of pneumatic system is intrinsically safe (no electrical circuits), compatible with valves, reliable during power outage for short period of time. The disadvantage are subject to air contaminants, air leaks, mechanical part failure due to dirt or water, subject to freezing with moisture present and control speed is limited to velocity of sound.

Advantages of electronic systems are greater accuracy, more compatible with computer, fast signal transit time, no signal integrity loss if current loop is used. The disadvantages are contacts subject to corrosion, must be air purged, explosion proof, or intrinsically safe to be used in hazardous areas, subject to electrical interference, and more difficult to provide for positive fail-safe operation.

Pneumatic Power Supplies

Usually known also know as instrument air system, main consideration of the system are

i) Adequate Capacity of the air supply to all instruments in the system. Normally the capacity should maintain at sum of the individual requirements of each instrument in the system plus supplemental volume for purges, leaks, additions and etc. It estimated consumption volume of volume of 3.7 US gallons per minute for each air-consuming device is usually adequate. The air storage tank should have sufficient capacity to maintain that flow rate for five minutes or more as is considered adequate to perform an emergency shut-down of plant.

ii) Filtering is requiring for instrument air since the contamination such as oil, water, and any hazardous or corrosive gases is not allowed. Non-lubricated compressors should be used if possible, because present of oil in compressors system may cause air contamination and may create a combustible mixture. After the compressing process instrument air will be cooled to remove the contained water. A drying system must be installed to maintain the water dew point at least 6^{o}C below the ambient temperature at line pressure. An after filter is required to remove particulate carryover from the dehydrators.

iii) Safety Regulation is practiced since the instrument air system is designed for high pressure (up to 59.5 psig) this means relief valve should be installed to protect the system.

iv) The air distribution system should be free of any “pocket” which liquid could accumulate. If the “pocket” could not be eliminated drain valve should be installed.

Important of Instrumentation Control for Unit Operation

When establishing a control system for a unit operation (reactor, fractionators, and fired heaters), it is very important to ensure that control of each equipment item and circuit provides the ability to maintain material balance, maintain heat balance and allow the control of product quality to the necessary degree.

Material balance control is to prevent build-up or depletion of material for continuous processes. Material balance is easily obtained in piping circuits system, since there is no place in which to store material and no storage from which to withdraw it.

In the feed circuits as in fractionation tower, material balance is obtained without automatic control. This is because whatever material is pumped into the circuit exits into the tower and the separately pressure-controlled tower acts as a pressure sink for the feed circuit. For situations in which the circuit pressure must be held higher than would be required merely because of pipe friction pressure drop, material balance is maintained through the use of a pressure controller and valve.

With this arrangement, pressure is used as a measure of material balance. Controlling the balance of material may be more difficult when variable holdup of material is possible. In these situations, a level measurement monitors buildup or depletion of liquid and is therefore the basis for control of material balance. Buildup or depletion of vapor in a tower is commonly based on pressure measurement, with many possibilities for valve location. Material balance are achieved when the pressure and bottom level are maintained in the tower.

Heat balance control is achieved when the temperature in the unit operation is maintained. In contrast to material balance, heat balance in piping circuits can become quite complex. Heat balance in the fractionation tower can be achieved by maintain of bottom temperature in towers with control the heat supply (normally steam flow rate) from a boiler. In this cascade control of heat balance, the success only can be achieve when level in the bottom tower is maintain, that means a material balance is achieved.

By maintaining material and heat balance in the circuits or unit operation, the product quality control can be achieved and maintained. The means of stability of the operating conditions at key points in the process will lead to successful product quality control.

The measurement of product quality is made either directly (i.e., continuously with an on-line analyzer) or indirectly (i.e., by means of a correlation). The end point of the overhead liquid product from the tower is an example. This end point may be measured directly with a boiling point device, or it may be inferred from a over head vapor line temperature measurement. The essential point is that when laying out a control system, the basic measurement information and means for making an adjustment must be made available to the operator.

Process Variable Measurement Instrument

Process variable such as pressure, level, temperature, flow rate and etc, can be measure with the specific measurement instrument and control with specific control valve / control system.

Pressure measurement instruments utilized in today's market can be classified as manometer, Bourdon tubes, Bellows, diaphragm and electrical pressure transducers.

Level measurement instruments used in today's industrial processes can be classified as gauge glass, chain and tape float gauges, lever and shaft float gauges, displacer level measuring device, head-pressure level gauges, electrical type level gauges and magnetic gauge.

Temperature measurement instruments can be classified into thermocouples, resistance thermometers (RTD), and bimetallic thermometers.

The flow rate measurement instruments can obtained by referring to “Flow Measurement Selection and Sizing Engineering Design Guideline” and for the Control valve instrumentation can be obtained by referring to “Control Valve Selection and Sizing Engineering Design Guidelines”. Both guidelines have discussed in detail of the respective instrumentation selection and included sizing as well.

Each type of the difference process variable measurement instruments have difference design and suitability for differences process. That means the knowledge of the selection process is very important for the suitable measurement instrument for a specific process.

DEFINITION

Amplifier- A device which draws power from a source other than the input signal and which produces as an output an enlarged reproduction of the essential features of its input.

Adaptive Control - Method of control whereby tuning (response) of the control system is varied with the process condition, unlike other control where tuning is manual and remains constant.

Bourdon Tube – It uses a coiled tube which as it expands due to pressure increase causes a rotation of an arm connected to the tube.

Capacity - Is the water handling capability of a pump commonly expressed as either gallon per minute (gal/min) or cubic meter per minute (m^3/min).

Cascade Control – Controllers arranged such that the output of one controller manipulates the set point input of a second controller instead of manipulating a process variable directly.

Control Action, Derivatives (Rate)- Control action with the controller output proportional to the rate of change of the input.

Control Action Integral (Reset) – Control action with the controller output proportional to the time integral of the error signal.

Control Action, Proportional – Control action with the controller output has a linear relationship to the error signal.

Controller - A device which receives a measurement of the process variable, compares that measurement with a set point representing the desired control point, and adjusts its output based on the selected control algorithm to minimize the error between the measurement and the set point. If an increase in the measured process variable above the set point causes an increase in the magnitude of the controller output, the controller is said to be “direct acting”. If a process variable increase above the set point causes a decrease in the magnitude of the controller output, the controller is “reverse acting”.

Displacer – Is a level measurement devices, displacer density will be greater than the liquid and will act as an immersed body. Operation of the displacer is based on the measurement of the change in buoyancy of the displacer as the level changes over its length.

Distribution Control System (DCS) – Is a system consists of some number of microprocessor-based nodes that are interconnected by a digital communications network, often called a data highway. It is type of computer process control system.

Manometer – Is a device to measure pressures. A common simple manometer consists of a *U* shaped tube of glass filled with some liquid. Typically the liquid is mercury because of its high density.

PD Controller- A controller with proportional plus derivatives (rate) control action.

PI Controller – A controller with proportional plus integral (reset) control action.

PID Controller – A controller with proportional plus integral plus derivative control action.

RTD (Resistance Temperature Detector) - A resistance temperature detector operates on the principle of the change in electrical resistance in wire as a function of temperature.

RTD Element -Sensing portion of the RTD which can be made most commonly of platinum, nickel, or copper.

Set Point – The desired value at which a process variable is to be controlled.

Transmitter – A device that converts a process measurement variable into an electrical or pneumatic signal suitable for use by an indicating or control system.

Thermocouple Thermometer – Is a temperature measuring system comprising a temperature sensing element called a *thermocouple* which produces an electromotive force (emf), a device for sensing emf which includes a printed scale for converting -emf to equivalent temperature units, and *electrical conductors* for operatively connecting the two.

Thermistor Thermometer - Is a special type of resistor 'comprised of a mixture of metallic oxides known as semiconductors which are substances whose electrical conductivity at or near room temperature is less than that of metals but greater than that of typical insulators, Semiconductors have a high negative temperature coefficient in contrast with most metals which have a positive coefficient.

NOMENCLATURE

A	Cross section area of body displacer, ft^2
b	Length of displacer body, ft
C	Controlled Variable
c	Output bias or Manual reset
d	Thickness of flat strip, mm
E	Error = PV –SP
F_B	Buoyant force, lbm.ft/s^2
F_G	Weight force, lbm.ft/s^2
F_R	Net force F_B –F_G, lbm.ft/s^2
f	Movement of flat strip, mm
g	Acceleration of gravity, SI unit or 32.2 ft/s^2
Δh	Difference height of the liquid level in manometer, SI unit
k	Specific bending coefficient, 1/^oC
K_i	Integral mode gain constant
K_p	Proportional gain, (pure number)
L	Fluid level in tank, ft
L_d	Dipped length, ft
ℓ	Height distance between points of measure P_1 and P_2 , ft
$\int$	Length of flat strip, mm
m	Mass of the displacer body immersed in liquid, lbm
P	Absolute pressure, SI unit or Hydrostatic pressure at bottom tank, psig
P_1	Absolute pressure at location 1 in tank, psig
P_2	Absolute pressure at location 2 in tank, psig
P_0	Atmospheric pressure, psia
P_{ref}	Absolute pressure reference, SI unit
PB	Proportional band in percent, %
SP	Set – Point
T_i	Integral mode time constant
ΔT	Temperature change, ^{o}C
K_d	Derivative mode gain constant
T_d	Derivative mode time constant

Greek letters

ρ_A	Density of gas or atmospheric, lbm/ft^3
ρ_B	Weight density of fluid in manometer, SI unit
ρ_D	Density of the displacer, lbm/ft^3
ρ_L	Density of liquid, lbm/ft^3
θ	Angle of column relative the horizontal plane
μ	Absolute (dynamic) viscosity, cp
υ_1	Velocity for upstream, ft/s
υ_2	Velocity for downstream, ft/s

THEORY

A) Pressure Measurement

Pressure defined as force per unit area exerted by a fluid (liquid or gas) on any surface. Usually is expressed in terms of units of weight-force and area (lb/ft^2) or the height of a column of liquid (ft) that produces a like pressure at its base.

Absolute pressure ($P_{absolute}$) is the pressure difference between the point of measurement and a perfect vacuum where pressure is zero ($P_{absolute} = P_{gauge} + P_{atm}$). Gauge pressure ($P_{gauge}$) is the pressure difference between the point of measurement and the ambient. In reality, the atmospheric pressure (P_{atm}) can vary, but only the pressure difference is of interest in gauge pressure measurements.

The most direct way of measuring pressure is to isolate an area on an elastic mechanical element for the force to act on. The deformation of the sensing element produces displacements and strains that can be precisely sensed to give a calibrated measurement of the pressure. This is the basis method of measurement of pressure for all commercially available pressure sensors today.

Process pressure measuring devices may be divided into three groups: (1) based on the measurement of the height of a liquid column, (2) based on the measurement of the distortion of an elastic pressure chamber, and (3) electrical sensing devices.

Height of a Liquid Column

Manometers common consists of a *U* shaped tube of glass filled with some liquid (either water or mercury). Typically the liquid is mercury because of its high density. Manometers measurement methods are based on the measurement of the height of liquid-column, which the pressure being measured is balanced against the pressure exerted by a column of liquid. If the density of the liquid is known, the height of the liquid column is a measure of the pressure.

The height of the liquid column may be measured in length units or be calibrated in pressure units. Depending on the pressure range, water and mercury are the liquids most frequently used for manometer. Since the density of the liquid used varies with temperature, the temperature must be taken into account for accurate pressure measurements.

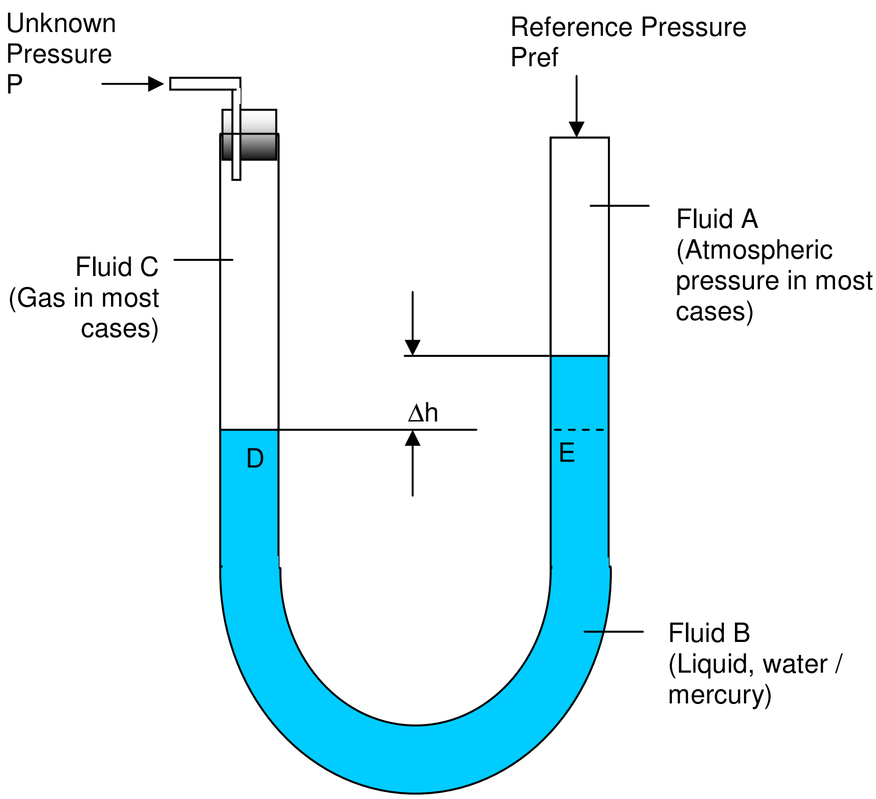

Figure 2: U- Shape Tube Manometer

The difference of the level of the liquid on both sides of the U tube, the unknown pressure P for gas fluid C can be determine with fluid statics formula as below,

$$P = P_{ref} + \rho_B g \Delta h \qquad \text{Eq (1)}$$

The gauge pressure of P can be determinate with

$$P_{gauge} = P - P_{ref} = \rho_B g \Delta h \qquad \text{Eq (2)}$$

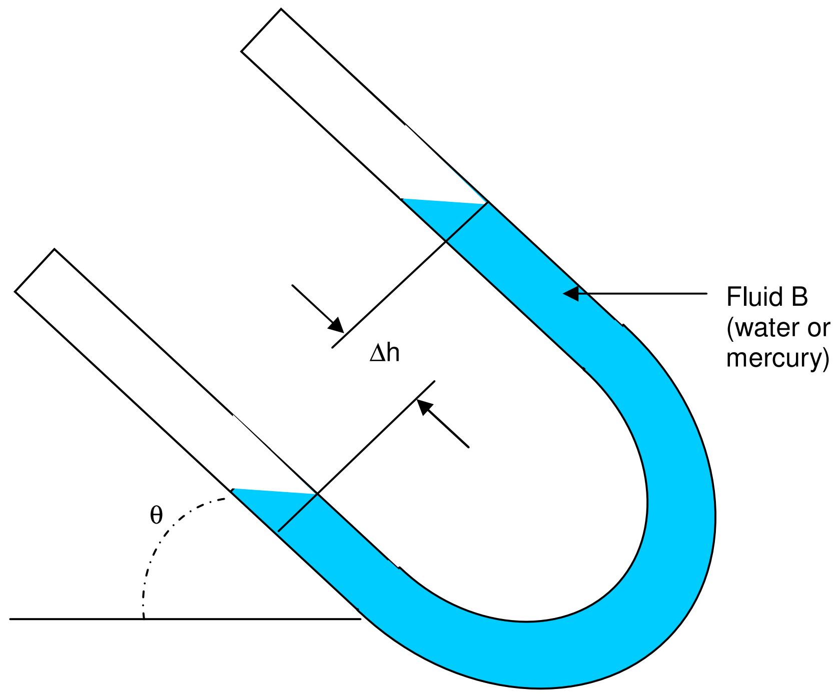

Figure 3: Inclined U-Tube Manometer

The pressure difference in a inclined u-tube can be expressed as

$$\Delta P = \rho_B g h \sin(\theta) \qquad \text{Eq (3)}$$

where

θ = angle of column relative the horizontal plane

Elastic-Element – Bourdon Tube, Bellows and Diaphragm

These measuring devices are base on method which the measured pressure deforms some elastic material (metallic) within its elastic limit, the magnitude of the deformation being approximately proportional to the applied pressure.

i) Bourdon Tubes

A Bourdon tube was discovered in year 1849 in France by Eugene Bourdon. It is the most widely used instruments for measuring the pressure of liquids and gases and measure up to pressures of 100,000 pounds per square inch. Bourdon tubes general are designed used for measuring high pressures application.

Structure of Bourdon tube is form of tube which is curved or twisted along its length and has an oval cross-section. The tube is sealed at one end and tends to unwind or straighten when it is subjected to a pressure applied to the inside.

The most frequently used process pressure-indicating device is the C-spring Bourdon-tube pressure gauge. General types are available in a wide variety of pressure ranges and materials of construction. Materials of construction are selected base on the basis pressure range, resistance to corrosion by the process materials, and effect of temperature on calibration.

A typical C-spring Bourdon tube contains a curved tube that is open to external pressure input on one end and is coupled mechanically to an indicating needle on the other end, Figure 4. The external pressure is guided into the tube and causes it to flex, resulting in a change in curvature of the tube. These curvature changes are linked to the dial indicator for a number readout.

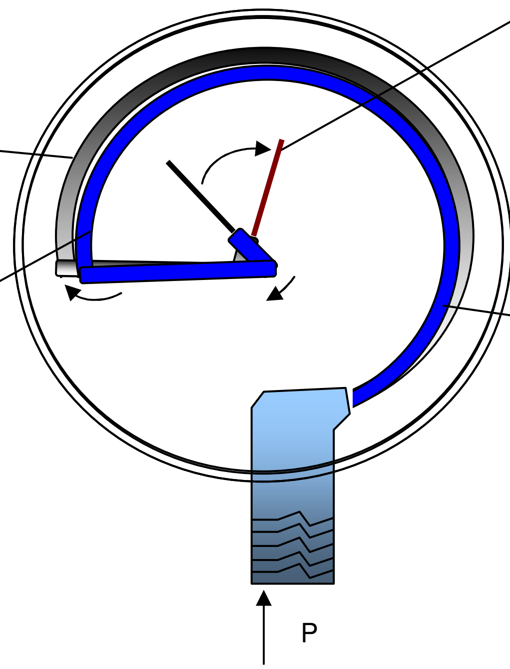

Figure 4: C-spring Bourdon-Tube Pressure Gauge

ii) Bellows

The bellows element is an axially elastic cylinder with deep folds or convolutions. Types of bellows may classify as unopposed, spring-loaded and beam balance sensor. The pressure to be measured may be applied either to the inside or to the space outside the bellows, with the other side exposed to atmospheric pressure. For measurement of absolute pressure either the inside or the space outside of the bellows can be evacuated and sealed. Differential pressures may be measured by applying the pressures to opposite sides of a single bellows or to two opposing bellows.

Bellows is usually for measuring low pressures or vacuum services, but types are available for use with high pressures as well. Typical diameters of bellow are range from 10 to 300 mm. As per Bourdon tube, it indicates pressures as gauge or relative to its surroundings.