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METROLOGY APPLICATIONS IN CHEMICAL ENGINEERING: A BRIEF REVIEW

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ABSTRACT

Metrology, while often confused with the science of measuring weather (meteorology), is a very widely used field. Metrology is mainly concerned with (i) establishing the units of measurements, reproducing these units in the form of standards, and ensuring the uniformity of measurements, (ii) developing methods of measurement, analysing the accuracy of methods of measurement, establishing uncertainty of measurement, researching into the causes of measuring errors, and eliminating these. Although as engineers and scientists, we make use of measurement to quantify the physical and chemical properties of objects, and design systems to conform to standards based on unit of measurement, the principles of measurement science (metrology) is not too familiar to most engineers and scientists. The focus of this brief review is to bring to fore the (i) meaning and definitions of metrology, (ii) importance of measurement, and (iii) the importance of metrology applications in chemical engineering and engineering in general.

***Key words**: Metrology, measurement, process control, process development, engineering design.*

1. INTRODUCTION

1.1 Metrology: Meaning and Definitions

The word "**Metrology**" may appear strange to many people. At best, most people assume it to mean the same as "**Meteorology**" or another way of writing "**Meteorology**". The two words are quite different in eamning. Meteorology is the study of the Earth's atmosphere and the variations in temperature and moisture patterns that produce different weather conditions. It is a branch of the atmospheric sciences with a major focus on weather forecasting; whereas Metrology is the study of measurement.

The study of measurement is a basic requirement in any field of science and technology, most importantly in engineering and manufacturing. Since metrology is the study of measurement, it is expected to enforce, validate and verify predefined standards for traceability, accuracy, reliability, and precision. All of these are factors that would affect the validity of measurement.

The word metrology indeed has a long tradition and is derived from the Greek word for measure. It is well-known saying that the knowledge about anything is complete only when it can be expressed in numbers. Thus for every kind of quantity measured, there must be a unit to measure it and express it in numbers of that unit. Furthermore, in order that this unit is followed by all and not just the one who is taking the measurements, there must be a universal standard; and the various units for various parameters of importance must be standardised (*WikiHow, 2019*).

Metrology is basic to the economic and social development of a country. It is concerned with providing accurate measurements which impact our economy, health, safety and general well-being. Trade and currency exchanges are possible because there are units of measurements.

Metrology also includes ways of establishing and maintaining the accuracy of measurement devices, such as by comparing them with more accurate standards.

1.2 Three sub-field of Metrology

Metrology is divided into three basic overlapping activities. The first being the definition of units of measurement, second the realisation of these units of measurement in practice, and last traceability, which is linking measurements made in practice to the reference standards. These overlapping activities are used in varying degrees by the three basic sub-fields of Metrology. The sub-fields are scientific or fundamental metrology, which is concerned with the establishment of

units of measurement, Applied, technical or industrial metrology, the application of measurement to manufacturing and other processes in society, and Legal metrology, which covers the regulation and statutory requirements for measuring instruments and the methods of measurement *(Wikipedia, 2021*).

As a further explanation, Scientific Metrology deals with the organization and development of measurement standards and with their maintenance. As you might expect, scientific metrology is deeply involved with research and new technologies for industries concerning government, healthcare, and research for commercial products.

Industrial metrology's purpose is to ensure that instruments, used in a wide variety of industries, are functioning properly. An example of this type of metrology might be seen in the production of products for the commercial industry, the testing and designing of aircraft, the functioning of large machinery, or even in factories using rotating equipment during the manufacturing of their products.

Legal Metrology is concerned with the measurements that influence economic transactions. This field does not use physical tools as the other fields of metrology use. Instead it focuses on the buying and selling of materials for economic studies and law enforcements.

The focus in this review is on the metrology applications in engineering and with chemical engineering as the main focus. (*Wikipedia, 2021, Jaychris, 2019*)

1.3 Importance of Measurement

Measurement is a quantitative comparison between a known quantity and an unknown quantity. Therefore, a measurement is the process of determining quantity of something (say size or length). Measurement is part of our daily life. It is used in all our movement, in our research work, our industry. How does one know the distance, the time, the height and the width of any geometrical shape? How does one know his size to buy clothes? How does one differentiate between cm, inch, foot, meter, mile and km? How could we deal with studying the universe without measurement? How do chemical engineers compare quality of products and ascertain their safety for use? So, measurement is an important part of human beings' lives and endeavours.

Indeed, without the ability to measure, it would be difficult for scientists to conduct experiments or form theories. Not only is measurement important in science and the chemical industry, it is also essential in engineering, farming, construction, manufacturing, commerce, and numerous other occupations and activities.

It is impossible to describe anything without measuring it. Measurement provides a standard for everyday things and processes. From weight, temperature, length even time is a measurement and it does play a very important role in our lives. The money or currency we use is also a measurement. And think of the rumble that can be caused if it was not there.

Scientists and engineers use many skills as they investigate the world around them. They make observations by gathering information with their senses. Some observations are simple. For example, a simple observation would be figuring out the color or texture of an object. However, if scientists want to know more about a substance, they may need to take measurements. Indeed, measurement is perhaps one of the most fundamental concepts in science. (*The Importance of Measurement*). A standard measurement system is important because it allows scientists and engineers to compare data and communicate with each other about their results. Indeed, one of the activities of engineers is to generate data from the experimental models and using it for betterment of people by generalising the results. Data like properties of materials, stresses, forces, etc must be done with maximum precision possible. As your precision increases you would have better design than previous. Measurement is comparison of available data with set standards or specimen which are agreed upon globally. Therefore, you cannot have data or information without any reference to compare it.

The international today's society relies on a proper measurement infrastructure, which in much extent depends on the properly trained people. There is no doubt that quality of measurements is an important issue in modern society influencing quality of life and border-crossing trade. Most important decisions are based on data obtained from measurement (*Bulska & Taylor, 2003*).

2.0 THE IMPORTANCE OF METROLOGY APPLICATIONS IN CHEMICAL ENGINEERING

The role of metrology in the various phases of a products lifecycle is very important (*ASQ, 2019*). Chemical engineers should have a proper understanding

of metrology concepts, basic statistics, reliability statistics and measurement uncertainty.

A quantitative analysis of design based on sound metrology principles will help engineers and scientists to design better products and services. In order to evaluate multiple solutions to the design, physical measurements are made and the data analyzed. Predictions need to be made on how well the design will perform to its specifications before full scale production begins. Tests are performed using prototype models, computer simulation, designed experiments, destructive and non-destructive tests, scale models and stress tests among the many other methods of evaluation.

In the broader sense, metrology is not limited to length measurement but is also concerned with the industrial inspection and its various techniques. Due to big industrial revolution and great advancement, industrial inspection does not simply mean the fulfilling of the specifications laid down by the manufacturers. Rather inspection in real sense is concerned with the checking of a product at various stages in its manufacture right from the raw material form to the finished products and even assembled parts in the form of machine also *(WikiHow, 2019).*

Let us discuss in brief how metrology plays a role in some critical areas of chemical engineering operations.

2.1 In Manufacturing and Chemical Analysis

Anything that has to do with manufacturing is the main domain of a chemical engineer. Chemical engineers design chemical plant equipment and devices and troubleshoot processes for manufacturing chemicals and products, such as gasoline, synthetic rubber, plastics, detergents, cement, paper, pulp just to name a few by applying principles and technology of chemistry, physics, and engineering. They are most often employed by large-scale manufacturing plants to maximize productivity and product quality while minimizing costs. Chemical engineers therefore must design systems that led themselves to ease and accurate measurements at all times. In design you must have idea of measurement.

Chemical engineering has its offshoot in science and particularly in chemistry which involves the use of various precision measuring machines. Chemical engineers use chemistry and engineering to turn raw materials into usable products on a large-scale, industrial setting.. In all of these processes, both physical and chemical measurement are critical to compare data obtained with international standards in helping to determining safety and quality of products to human life. Therefore, they work with a lot of experimental method and instrumentation to analyse processes and products quality.

2.2 In Process Control

Process control, for example, is all about controlling a chemical process or running machinery. Process Control can be manual or automatic, continuous or discrete. It is all about monitoring and controlling certain set of process variables (i.e. temperature, flow, level, pressure, etc) that leads to control of the whole process. If we can't measure then we can never control. Almost all control method works on the basis of the error of the process variable. For example in PID (proportional–integral–derivative controller**)** control, *Error=set point - measured value*. We can't get error without measuring process variables. We called it feedback. So measurement is most important parameter for controlling of any process. For in controlling any process it is necessary to know the current amount or the quantity of the controlled variable. Thus, we need to sense that variable (Pressure, temperature, flow, level, etc). For this purpose measuring instruments are necessary in process control. The measuring instrument measures, converts it to Electrical signals and gives it to controller for taking proper action of the final control element to control the process the way we want. And unless we measure the value to a precision needed in our control system, we cannot change the output of the system manually or in automatic, as required to keep the process in the required state. *(James E. Potzick, 2010).* Similarly, the conformance of parts and assemblies to geometrical specifications is assessed by physical measurements (*NRC, 1995*).

2.3 In Product Development

Chemical engineers do not really use much of chemical laboratory equipment in the industry. It should be stressed that, even in the university, chemical engineering laboratory equipment often consists of pilot scale systems where potential chemical engineers learn about unit operations and chemical process steps such as distillation, separation, crystallization, evaporation, filtration, polymerization, mixing, homogenization, cooling, heating, polymerization and chemical reactions. Practicing chemical engineers generally work with larger scale equipment in a pilot facility or in a production plant where they can evaluate how equipment and system changes impact physical and chemical transformations. Chemical engineers receive

training and develop understanding of fluid flow, heat transfer, mass transfer, thermodynamics, chemistry, physics, advanced mathematics and control theory, which they use to optimize and design chemical processes. (*Gary Kardys, 2017*)

Although chemical engineers evaluate processes on pilot scale equipment, bench top chemical laboratories are necessary when chemical engineers are involved in product development and in research activities. Every stage of a chemical process involves checking on safety, product quality, level of effluents emission in solid, liquid and gaseous form, etc. To ensure compliance, there are needs for measurements, either analytically and otherwise; and may involve developing methods of measurement and analysing the accuracy of the methods of measurement. The need for compliance to standards in process and product manufacturing industries, places upon a chemical engineer a burden to design unit operations and processes that strictly adhere to standards.

For an example, for product formulation, characterization and quality testing, the chemical engineers use analytical testing machines. Analytical testing, which is also referred to as materials testing, is a broad term used to describe various techniques that are used to identify the chemical makeup or characteristics of a particular sample. Chemical analysis equipment is used to determine, characterize, and quantify chemical components in gas, liquid, and solid samples. Bioanalysis, nanotechnology, clinical chemistry, environmental and materials analysis, and forensics represent a few of the many areas of use for chemical analysis instruments.

Examples of such analytical instruments include mass spectrometers, chromatographs (e.g. GC and HPLC), titrators, spectrometers (e.g. AAS, X-ray, and fluorescence), particle size analyzers, rheometers, Refractometers, viscometers, evaporators and calorimeters, elemental analyzers (e.g. salt analyzers, CHN analyzers), thermal analyzers, and more. In the chemical laboratory, you will have also basic measuring equipment like graduated cylinders, volumetric flasks, Pipettes, Burets, Thermometers, balances, and many more.

2.4 Equipment categories of interest to chemical engineers

Gary (2017) provides a list of equipment categories and their descriptions (shown in Appendix 1) that are of interest to chemical engineers. These serve as process components and equipment required for process engineering projects, and sometimes helps to determine quality of products. The list included the following: Equipment for

- Instrumentation and equipment used to control the properties and degree of purity of air;
- Remediation of environmental factors equipment;
- Processing equipment such as centrifuges, clarifiers, and several filter technologies used to filter or separate media of different materials or sizes;
- Flow measurement instruments used to determine flow rate;
- Materials Processing Equipment.

Alpha (2016) gave description of some of the Chemical Testing Equipment. These include:

- **Abrasion Testers** - widely used for testing abrasion resistance of plastic materials
- **Adhesion Tester** - to determine the flexibility and adhesion of coatings to painted metallic surface.
- **Automatic Pigment Muller** - widely used for accurate and fast evaluation of color strength, color matching, dispersion, particle hardness and particle size, color comparison, tint and tone of paints.
- **Corrosion Cabinet** - to determine their resistance to environmental elements
- **Density Measuring Equipment** – for determining the mass per unit volume of a substance
- **Dew Point Apparatus** - is commonly used for determining vapor content of gaseous fuels by measuring their dew point temperature.
- **Existent Gum Steam Generator** - used for measuring evaporation residue in aviation fuels, motor gasolines and other volatile distillates on the basis of standard test procedures
- **Flash Point Apparatus** - apparatus is a petroleum testing equipment for determining the flash point of fuels, lube oils, solvents and other liquids
- **Flexural Strength Tester** - to determine the flexure or bending properties of plastic materials.
- **Freezing Point Apparatus** - used to determine the temperature below which solid hydrocarbon crystals are formed in case of **aviation fuels**.
- **Impact Testing Equipment** - used in the plastic industry evaluates the effect of varying degrees of impact on plastic materials and components.
- **Liquid Bath** - **Liquid Bath** is an instrument commonly used in petroleum industry to determine the tendency of aviation fuels and gasoline to form

gum in storage conditions. It is also used to measure the oxidation stability of fuels.

- **Mandrel Bend Testers** - This equipment is used to determine elasticity, elongation and adhesion properties of paint on sheet metal.
- **Melting Point Tester** - **Melting point** is defined as the temperature at which a substance changes into liquid state from solid state.
- **Oxygen Index Apparatus** - **Oxygen index apparatus** is used to determine the oxygen index of plastic materials.

A chemical engineer may not be involved directly in the design and manufacture of these measuring equipment, but must be conversant with their use in analyzing his results; and should be able to detect when the system malfunction giving wrong results.

Because of the growing importance of metrology in chemical engineering, some Chemical Engineering departments of Universities have research units dealing with issues of design of measuring equipment. For example, the Department of Chemical Engineering and Biotechnology of the University of Cambridge (*University of Cambridge, 2019*) has a metrology research group whose research focus is addressing challenges of measurement and quantitative analysis of chemical and biochemical systems. In their website, it stays "Challenges in healthcare require new solutions in imaging and measurement and our skills are also central to investigations into structure-function relationships for catalysis and reaction engineering, and build on core understanding of chemical reactions and physical phenomena in designing sustainable new processes. The Department is home to the Measurement and Image Analysis Centre, the Laser Analytics Group and Cambridge Analytical Biotechnology and also the Magnetic Resonance Research Centre (MRRC). It leads 'Cam-bridge-Sens', the University strategic Network that brings together sensing activities across the University and it is active in promoting a sustainable healthcare model where the primary point of care will move towards the home, powered by technology for remote diagnosis and monitoring." Some of their current research include: Development of novel data acquisition techniques, Microstructural and composition data derived from MRI, Terahetz, X-ray and atomic force microscopy, Electrochemical, optical and acoustic sensors and biosensors, Development of high resolution microscopy techniques, Diagnosis through biomarker discovery, Analytical recognition ligand design and synthesis, Smart material design, etc.

2.5 Use of metrology in Nanotechnology.

The growing interest in applying nanomaterials to societal needs is now urging that increasing attention be given to the development of scientific and applied metrology to address nanomaterials as the newly developing field of nanometrology. This multidisciplinary field spans many disciplinary fields, such as chemistry, physics, materials science, biology, and engineering, chemical engineering in particular. Nanomaterials embrace the full range of traditional materials classes. The distinction between metrology in general and metrology on the nanoscale stems from the different properties of materials on the nanoscale as compared to their bulk counterparts. Of course, new ideas need new measurements and this is where the novel class of materials, the nanomaterials, is playing an important role. (*Jorio & Dresselhaus, 2010*)

3.0 MEASUREMENT IN ENGINEERING DESIGN

As stated above, *measurement* is a quantitative comparison between a known quantity and an unknown quantity. *Measurement* helps an engineer and indeed a chemical engineer to quantify the physical and chemical properties of objects and systems. In *engineering*, it can help you with manufacture of various parts thereby ensuring proper fit between components. An engineering designer must be conversant with measurement principles.

In Reverse Engineering, which is the ability to replicate the machine designs, construct, testing and publication of a manufacturing layout thereby developing requisite skills and technology in its manufacture and mass production, requires accurate measurement of components parts that are taken apart for study and replication. Chemical engineers also used the concept of Reverse Engineering to design and manufacture equipment components/parts from the existing one. Because in a manufacturing plant there will be need to replace a particular unit/parts of an equipment that may no longer be supported by the Original Equipment Manufacturer (OEM) due to its obsolesce. There will then the need for Reverse Engineering of such components. Measurement equipment like the following are very useful in giving accurate measurement of the parts. . (*Sanja , 2013*).

i. **Coordinate Measuring Machines, CMM** - A coordinate measuring machine (CMM) is a device used in the measurement of the physical geometrical characteristics of an object. These machines can be manually controlled by an operator

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or they may be computer controlled. Measurements are defined by a probe attached to the third moving axis of this machine.

ii. **Contour graph**. A contour plot is a graphical technique for representing a 3-dimensional surface by plotting constant z slices, called **contours**, on a 2-dimensional format. That is, given a value for z, lines are drawn for connecting the (x,y) coordinates where that z value occurs.

iii. **Surface texture examination machine**. Surface finish, also known as surface texture or surface topography for examining the roughness of a surface.

iv. **VMM (Vision System)** – Vision Measuring Machine, VMM are non-contact type of measuring machines which use Optics as source of inspection.

4. CONCLUSION

Measurements have been carried out for as long as civilization has existed. Metrology is basic to the economic and social development of a country. It is concerned with providing accurate measurements which impact our economy, health, safety and general well-being. Without accurate measurement, important decisions may be faulty.

Even though we have been applying the concept in our day to day practice as engineers, some of us still lack the

basic understanding of the concept of Metrology and its role in engineering. This brief review is able to bridge this gap by reviewing what metrology is all about and its uses in chemical engineering in particular and engineering in general.

Indeed, without the ability to measure, it would be difficult for scientists to conduct experiments or form theories. Not only is measurement important in science and the chemical industry, it is also essential in farming, engineering, construction, manufacturing, commerce, and numerous other occupations and activities. Indeed in all human endeavour.

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APPENDIX 1: LIST OF EQUIPMENT CATEGORIES (SHOWN IN APPENDIX 1) OF INTEREST TO CHEMICAL ENGINEERS AND THEIR DESCRIPTIONS (Gary, (2017))

Chemical Process Equipment Category	Description
Air Quality (3,093 suppliers)	Instrumentation and equipment used to control the properties and degree of purity of air. These types of equipment include dust collectors, oxidizers, scrubbers and adsorption equipment.
Environmental Equipment (5,544 suppliers)	Equipment involved in the remediation of environmental factors. Specific aspects covered include water and wastewater treatment, air and groundwater quality analysis, waste processing, and pollution control.
Filtration and Separation Products (5,092 suppliers)	Processing equipment such as centrifuges, clarifiers, and several filter technologies used to filter or separate media of different materials or sizes.
Flow Sensing (2,642 suppliers)	Flow measurement instruments are used to determine flow rate by monitoring the amount of media passing during a specific time. Devices within this category can monitor liquids, gases or solids, and measure in units of mass, velocity or volume.
Fluid Processing Equipment (3,351 suppliers)	Any piece of equipment used to monitor, distribute and store process and industrial fluids.
Gas Handling Equipment (1,008 suppliers)	Any piece of equipment used to monitor, distribute, generate, compress and store process and industrial gases.
Heating and Cooling Equipment (13,466 suppliers)	Ovens, furnaces, induction heaters, welding equipment, heat exchangers, fans, blowers, refrigerators, baths and other equipment for heating or cooling materials.
Hose, Pipe and Tubing (4,820 suppliers)	Hose, pipe and tubing covers the broad spectrum of fluid transfer lines.
Hose, Pipe, and Tubing Accessories (4,518 suppliers)	Hose, pipe, and tubing accessories make up the infrastructure necessary to convey all manner of materials in a process line.
Industrial Heaters and Heating Elements (2,520 suppliers)	Electrical resistance heaters or their internal elements; designed to provide an integrated thermal source for products or systems.
Industrial Machine Safeguarding (1,510 suppliers)	Components or systems that protect industrial machinery, operators or moving parts from injury or damage from electrical, mechanical or other potential hazards.
Materials Processing Equipment (3,617 suppliers)	Extruding, casting, forging, compacting, heat treating, molding, rolling or other processing machines and components used for metals, polymers or other materials.
Pressure Regulators (1,249 suppliers)	Pressure regulators are used to maintain a constant outlet pressure or flow.
Process Controllers (4,849 suppliers)	Instruments for monitoring and automatically revising process parameters such as temperature, pressure, force, humidity, level and flow.
Pumps (5,243 suppliers)	Machines and devices used for the raising, compression or transference of a variety of materials.
Safety and Personal Protective Equipment (3,655 suppliers)	Safety equipment guards personnel or areas from hazardous conditions or mitigates damage. Personal protective equipment protects individuals from personal injury.
Safety Sensors and Switches (733 suppliers)	Safety sensors and switches are used in machines and other industrial applications to safeguard equipment and prevent personal injury.
Tanks and Vessels (2,241	Equipment used to contain or store materials prior to, during, and after their processing.

Chemical Process Equipment Category	Description
suppliers)	
Vacuum Equipment (2,530 suppliers)	Vacuum equipment is used for degassing, welding, and the manufacturing of thin films, semiconductors, optics and specialty materials.
Valve Actuators and Positioners (946 suppliers)	Devices designed to automatically control and monitor the position of valves, in relation to their open or closed positions.
Valves (6,133 suppliers)	Devices that regulate the flow of gases, liquids, or loose materials through piping by opening, closing, or obstructing ports or passageways.
Viscosity Sensing (210 suppliers)	Instruments and sensors for measuring the viscosity (resistance to flow) or viscoelastic properties of liquid or molten glass and plastic.
Web Handling and Processing Equipment (1,157 suppliers)	Equipment for handling, processing and converting continuous webs of textiles, paper, plastic films, metal sheet or other materials.