Sudan University of Science and Technology

College of Graduate Studies

The Calibration of Pressure Gauges Using Pressure Balance and Direct Methods

(A Comparative Study)

معايرة عدادات الضغط بإستخدام طريقتي ميزان الضغط والطرق المباشرة

(دراسة مقارنة)

A Thesis Submitted as Partial Fulfillment of the Requirements for Degree of Master Science in Physics

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الآيـة

قال تعالى

بسم الله الرحمن الرحيم

﴿ قَالُواْ سُبۡحَٰنَكَ لَا عِلۡمَ لَنَآ إِلَّا مَا عَلَّمۡتَنَآ إِنَّكَ أَنتَ ٱلۡعَلِيمُ ٱلۡحَكِيمُ)

صدق الله العظيم

سورة البقرة ، الآية (32)

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Dedication

To my beloved family, friends & teachers who have provided any kind of support

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I owe a lot of thanks to a great many people who helped and supported me during the writing of this thesis.

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Abstract

The calibration is defines as set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards.

The main objective of this research is to make a comparison of calibrate of pressure gauge by using two methods, the pressure balance method and the direct comparison method. The experimental work has been carried out in pressure calibration laboratory at Sudanese Standard & Metrology Organization, calibration of pressure gauge was studied first by pressure balance method as a primary standard method and then by the direct comparison method as a secondary standard of calibration pressure indicators. Four pressure gauges were calibrated by the two methods in which each one has been measured in various measurement points and then the error value was calculated. In the first method (pressure balance method) the pressure measured after it's generated from the weights placed on the pressure balance and correspondingly the error was evaluated with comparison to standard value, in the second method the error of the pressure gauge measurement calculated after being measured from direct pressure generation of pressure pump. The first method was found to be more accurate than the second one and that's owing to many parameters affecting the measurement are taken into account in calculating pressure value so that the error value is more precise, therefore the pressure balance method is the primary calibration method.

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المستخلص

تعرف المعايرة بأنها مجموع العمليات التي تأسس في ظل ظروف محددة، العلاقة بين الكميات المتحصل عليها بواسطة أداة قياس أو نظام قياس أو القيم المتمثلة في القياس المادي أو مادة مرجعية، وتحقق القيم المقابلة بواسطة النظام المرجعي.

الهدف الرئيسي من هذا البحث هو القيام بمقارنة لمعايرة عدادات الضغط بإستخدام طريقتين هما طريقة ميزان الضغط وطريقة المقارنة المباشرة. وقد تمت التجارب العملية في معمل معايرة الضغط في هيئة المواصفات والمقاييس السودانية. عُيِّرَت عداد الضغط أولاً بطريقة ميزان الضغط باعتبارها طريقة القياس الأولية ثم بعد ذلك بواسطة المقارنة المباشرة باعتبارها طريقة ثانوية لمعايرة عدادات الضغط.

ثم عُيِّرَت أربعة أجهزة ضغط بإستخدام الطريقتين حيث أخِذت القراءات عند عدة نقاط قياس وحُسِبت قيمة الخطأ. في الطريقة الاولى (طريقة ميزان الضغط) قِيس الضغط الناتج بعد وضع الأوزان على ميزان الضغط وعليه قُدِّر الخطأ بعد المقارنة بالقيمة المرجعية. في الطريقة الثانية حُسِب الخطأ في قياسات عداد الضغط بعد مقارنته مباشرة مع الضغط الناتج من مضخة الضغط.

وأثبتت النتائج أن الطريقة الأولى أكثر دقة من الطريقة الثانية وذلك نسبة لوجود مجموعة من العوامل التي تؤثر على عملية القياس حيث تم أخذها في الحسبان مما أدي إلى تقييم الخطأ بدقة أكثر. وعليه نستخلص أن طريقة ميزان الضغط هي الطريقة الأولية في المعايرة.

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Chapter One

Introduction

1.1 Background

The actual term "calibration" was first used when describing the exact division of linear distance and angles – using a dividing engine and the calculation of gravitational mass using weighing scales. These measurement types were used for practically all technology developments and commerce – from the first fledgling civilizations until approximately 1800AD [1].

With the dawn of the Industrial Revolution, indirect measurement techniques were used much more frequently. During this period, recorded instances of the measurement of pressure can provide us with a good example of how indirect measurement processes were used. Previously, the hydrostatic manometer was a more commonly used pressure measurement device – a device that was less than ideal when measuring high pressures. The need for high pressure measurement was practically addressed by Eugene Bourdon with the Bourdon tube pressure gauge [2].

Moving forward in time – direct measurement techniques were still being used to verify the validity of measurements. A great instance of this can be found in the earliest days of US automobiles. When people purchased gasoline, they wanted to see it in a large glass pitcher – this was a direct way of measuring the volume and quality of a substance using appearance verification [2].

By around 1930, indirect measurement techniques also became widely accepted, with the implementation of rotary flow meters. Using a hemispheric viewing window, the consumer was able to see the blade of the flow meter turn as their gasoline was being pumped. As the 1970's arrived, the windows had been removed and all measurements were then completely indirect [3].

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However, although indirect measurement processes are now common place (most modern-day measurement techniques are indirect), they always involve conversion or linkages in one form or another. Because of this – the need for calibration is greater than ever [2].

Modern metrological concepts increasingly link the topics of measurement traceability (a term which a number of contracting and regulatory agencies have invoked to specify the standards used in the calibration of instruments.), laboratory accreditation, and quality assurance programs to the topic of measurement uncertainty. An essential component of all uncertainty budgets is the employment of calibrated gauges, standards, or instruments. It is the calibration process that transfers a reference value, usually an International System (SI) unit, to the artifact or instrument under calibration and hence establishes the "unbroken chain of comparisons" required for traceability [3]. The ISO International Vocabulary of Basic and General Terms in Metrology (VIM) [4] defines calibration as follows: Calibration (VIM-1993)—set of operations that establish, under specified conditions, the relationship between values of quantities indicated by a measuring instrument or measuring system, or values represented by a material measure or a reference material, and the corresponding values realized by standards [1].

SI allows all countries to synchronize to the same universal standards to ensure consistent measures worldwide Figure (1.1). In this way, calibration to the most reliable and accurate standards is passed down through an unbroken chain to help assure the accurate and reliable production of products, services, and technologies around the world [2].

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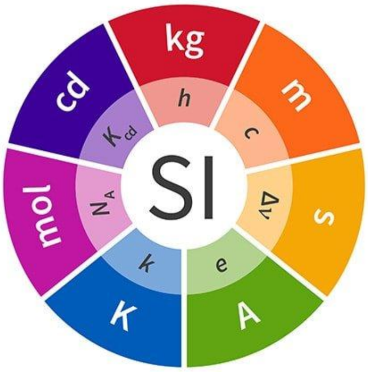

Figure (1.1): The SI (The International System of Units

The SI (The International System of Units) are the ultimate measurement reference standards that help assure accurate measurements in the production of millions of products and services we rely on every day

The **SI base units** are the standard units of measurement defined by the International System of Units (SI) for the seven base quantities of what is now known as the International System of Quantities, Figure (1.1): they are notably a basic set from which all other SI units can be derived. The units and their physical quantities are the second for time, the metre for measurement of length, the kilogram for mass, the ampere for electric current, the kelvin for temperature, the mole for amount of substance, and the candela for luminous intensity. The SI base units are a fundamental part of modern metrology, and thus part of the foundation of modern science and technology [2].

From 20 May 2019 all SI units are defined in terms of constants that describe the natural world. This assures the future stability of the SI and opens the opportunity for the use of new technologies, including quantum technologies, to implement the definitions [2].

The SI is the system of units in which:

- the unperturbed ground state hyperfine transition frequency of the caesium-133 atom $\Delta\nu_{Cs}$ is 9 192 631 770 Hz
- the speed of light in vacuum *c* is 299 792 458 m/s
- the Planck constant *h* is 6.626 070 15 x 10^{-34} J s

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- the elementary charge e is 1.602 176 634 x 10^{-19} C
- the Boltzmann constant k is 1.380 649 x 10^{-23} J/K
- the Avogadro constant N_A is 6.022 140 76 x 10^{23} mol^{-1}
- the luminous efficacy of monochromatic radiation of frequency 540 x 10^{12} Hz, K_{cd}, is 683 lm/W

where the hertz (Hz), joule (J), coulomb (C), lumen (lm), and watt (W), are related to the units second (s), metre (m), kilogram (kg), ampere (A), kelvin (K), mole (mol), and candela (cd), according to Hz = s^{-1}, J = kg m^2 s^{-2}, C = A s, lm = cd m^2 m^{-2} = cd sr, and W = kg m^2 s^{-3} [2].

1.2 The Problem of Study

The measurement of pressure plays an extensive and important role in the modern world, the applications are found in industries as diverse as nuclear, power, gas, petro-chemical, biological, pharmaceutical, meteorological, automotive, environmental, semi-conductor, optical, aerospace, defense. The Industrial Revolution was largely powered by the pressure System and they need to measure pressure over wider ranges and with increasing accuracy, pressure measurement has expanded ever since and has major effect on the quality of the products, validity of the measurement result, energy efficiency, so lack of measuring pressure will lead to various consequences concern un safe operational process in industries, un accurate measurement in some diagnostic instrument such as blood pressure measurement, un safe environment. For these reasons wide research concern pressure measurement is conducted to give attention to it.

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1.3 The Objectives of Present Study

Considering the common use of pressure gauges in the process industry, as with any measurement device, pressure gauges need to be calibrated at regular intervals to assure they are accurate. This research work is aimed to develop a study on calibration of pressure gauge using pressure balance and direct method comparison with the following objectives:

1- Calibrating 4 pressure gauges using pressure balance (primary standard) through adding weights to a platform on a dead weight tester. The weights put a known force on to a piston. The piston has a known area; then the pressure is calculated. Thereafter, calculating the correction from various parameters which would affect the measurement.

2- Calibrating 4 pressure gauges through a direct comparison method, in which the pressure gauge to be calibrate disconnected to a master gauge. Pressure is applied to the pressure gauge at predetermined pressure increments over its full operating range. The value indicated by the pressure gauge is compared to the corresponding value indicated by the master gauge at each pressure increment then the percent error between the two values is calculated.

3- Make a comparison of the two methods and stating out the differences.

1.4 The Previous Studies

There are various studies that have been undergone in the calibration topic regarding the pressure gauges and sensors with different approaches, some of these studies are stated as follow:

The first study has been done by A. A. Eltawil (2017) [4]. He studied the propagation of uncertainty from SI units through primary standard piston cylinder assembly (PCA) up to 500 MPa. The hierarchy of pressure measurements at NIS is based on using large effective area PCA in defining the pressure of 1 MPa. Primary

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standard PCA characterization and evaluation are presented then transferring the obtained results to other pressure traceability level is described. Calculation and propagation of uncertainty starting from primary standard to digital pressure gauges, digital pressure calibrators, pressure sensors and pressure transducers were investigated.

The other study has been done by T. Kobata, H. Kajikawa, and K. Ide, (2012) [5]. They calibrated pressure gauges including strain-gauge transducers and Manganin gauges and characterized it in the pressure range up to 1 GPa. For the calibration and characterization, the pressure generating system using a pressure balance and a precise pressure multiplier has been developed as a pressure standard. In this study, the pressure generating system, the method for calibrating the pressure gauges by using the system and the results obtained are presented. The temperature coefficients of Manganin gauges are also evaluated in the pressure range.

1.5 Research Layout

The present thesis has been divided into five chapters. All of these chapters will be described briefly as follow. Chapter one is begins with the introduction of calibration and the International System of Quantities (SI), Objectives of the present study, problem of the study, previous studies, and the research layout. In the second chapter (Chapter two) this study describes the science of metrology and measurement along with the different parameters that correlate with. While the third chapter (Chapter three) introduce the parameter of pressure with its various types, then the different methods of calibrations that are used to calibrate the pressure equipment; the further chapter (Chapter four) is describes the experimental details for the calibration of the pressure gauges with the pressure balance and direct method comparison. In addition to the results of

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calibration of the pressure gauges with the pressure balance and direct method comparison are outlined; thereafter, the discussions of the results are described as well. The final chapter (Chapter five) comes out with the conclusion for all previous discussions along with further recommendations. Lastly, the used references listed and supported pictures for the used devices attached at the end of research as appendices.

Chapter Two

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Metrology

2.1 Introduction

Metrology is defined by the International Bureau of Weights and Measures (BIPM) as "the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology"[14]. It establishes a common understanding of units, crucial to human activity [3]. Metrology is a wide reaching field, but can be summarized through three basic activities: the definition of internationally accepted units of measurement, the realisation of these units of measurement in practice, and the application of chains of traceability (linking measurements to reference standards) [3][6]. These concepts apply in different degrees to metrology's three main fields: scientific metrology; applied, technical or industrial metrology, and legal metrology [6].

2.1.1 Scientific Metrology

Scientific metrology is concerned with the establishment of units of measurement, the development of new measurement methods, the realisation of measurement standards, and the transfer of traceability from these standards to users in a society [1][3]. This type of metrology is considered the top level of metrology which strives for the highest degree of accuracy [3]. BIPM maintains a database of the metrological calibration and measurement capabilities of institutes around the world. These institutes, whose activities are peer-reviewed, provide the fundamental reference points for metrological traceability. In the area of measurement, BIPM has identified nine metrology areas, which are acoustics, electricity and magnetism, length, mass and related quantities, photometry and radiometry, ionizing radiation, time and frequency, thermometry, and chemistry [15].

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As of May 2019 no physical objects define the base units [16]. The motivation in the change of the base units is to make the entire system derivable from physical constants, which required the removal of the prototype kilogram as it is the last artefact the unit definitions depend on [17]. Scientific metrology plays an important role in this redefinition of the units as precise measurements of the physical constants is required to have accurate definitions of the base units. To redefine the value of a kilogram without an artefact the value of the Planck constant must be known to twenty parts per billion [18]. Scientific metrology, through the development of the Kibble balance and the Avogadro project, has produced a value of Planck constant with low enough uncertainty to allow for a redefinition of the kilogram [17].

2.1.2 Applied, Technical or Industrial Metrology

Applied, technical or industrial metrology is concerned with the application of measurement to manufacturing and other processes and their use in society, ensuring the suitability of measurement instruments, their calibration and quality control [3]. Producing good measurements is important in industry as it has an impact on the value and quality of the end product, and a 10–15% impact on production costs [6]. Although the emphasis in this area of metrology is on the measurements themselves, traceability of the measuring-device calibration is necessary to ensure confidence in the measurement. Recognition of the metrological competence in industry can be achieved through mutual recognition agreements, accreditation, or peer review [6]. Industrial metrology is important to a country's economic and industrial development, and the condition of a country's industrial-metrology program can indicate its economic status [19].

2.1.3 Legal Metrology

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Legal metrology "concerns activities which result from statutory requirements and concern measurement, units of measurement, measuring instruments and methods of measurement and which are performed by competent bodies" [20]. Such statutory requirements may arise from the need for protection of health, public safety, the environment, enabling taxation, protection of consumers and fair trade. The International Organization for Legal Metrology (OIML) was established to assist in harmonising regulations across national boundaries to ensure that legal requirements do not inhibit trade [21]. This harmonisation ensures that certification of measuring devices in one country is compatible with another country's certification process, allowing the trade of the measuring devices and the products that rely on them. WELMEC was established in 1990 to promote cooperation in the field of legal metrology in the European Union and among European Free Trade Association (EFTA) member states [22]. In the United States legal metrology is under the authority of the Office of Weights and Measures of National Institute of Standards and Technology (NIST), enforced by the individual states [21].

2.2 Standardization in Metrology

Standards are considered as measurement references. The basic standards about metrology are the basis of the traceability which is defined as a measurement whereby the result can be related to a reference through an unbroken chain of calibrations. Using internationally standardized systems of units, Vocabulary of Metrology (VIM), Guide to the International Uncertainty Measurements (GUM), or Internationally Standardized Measurement Management Systems [1] helps to improve the reliability of the results.

2.2.1 Measurement Units

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The very first measurement units were those used in barter trade to quantify the amounts being exchanged and to establish clear rules about the relative values of different commodities. Such early systems of measurement were based on whatever was available as a measuring unit. For purposes of measuring length, the human torso was a convenient tool and gave us units of the hand, the foot, and the cubit. Although generally adequate for barter trade systems, such measurement units are, of course, imprecise, varying as they do from one person to the next. Therefore, there has been a progressive movement toward measurement units that are defined much more accurately. The first improved measurement unit was a unit of length (the meter) defined as 10^{-7} times the polar quadrant of the earth. A platinum bar made to this length was established as a standard of length in the early part of the 19th century. This was superseded by a superior quality standard bar in 1889, manufactured from a platinum–iridium alloy. Since that time, technological research has enabled further improvements to be made in the standard used for defining length. First, in 1960, a standard meter was redefined in terms of 1.65076373_106 wavelengths of the radiation from krypton-86 in vacuum. More recently, in 1983, the meter was redefined yet again as the length of path travelled by light in an interval of 1/299,792,458 seconds. In a similar fashion, standard units for the measurement of other physical quantities have been defined and progressively improved over the years. The latest standards for defining the units used for measuring a range of physical variables are given in Table (2.1).

Table (2.1): Definitions of Standard Units

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Physical Quantity	Standard Unit	Definition
Length	Meter	Length of path travelled by light in an interval of 1/299,792,458 seconds
Mass	Kg	Mass of a platinum–iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
Time	Second	9.192631770 _ 109 cycles of radiation from vaporized Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K 133 (an accuracy of 1 in 1012 or one second in 36,000 years)
Temperature	Degree	Temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K
Current	Ampere	One ampere is the current flowing through two infinitely long parallel conductors of negligible cross section placed 1 meter apart in vacuum and producing a force of $2*10^{-7}$ newtons per meter length of conductor
Luminous intensity	Candela	One candela is the luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 terahertz (Hz _ 1012) and with a radiant density in that direction of 1.4641 mW/steradian (1 steradian is the solid angle, which, having its vertex at the centre of a sphere, cuts off an area of the sphere surface equal to that of a square with sides of length equal to the sphere radius)
Matter	Mole	Number of atoms in a 0.012-kg mass of carbon 12

The early establishment of standards for the measurement of physical quantities proceeded in several countries at broadly parallel times; in consequence, several sets of units emerged for measuring the same physical variable. For instance, length can be measured in yards, meters, or several other units. A part from the major units of length, subdivisions of standard units exist such as feet, inches, centimetres, and millimetres, with a fixed relationship between each fundamental unit and its subdivisions. Yards, feet, and inches belong to the Imperial system of units, which is characterized by having varying and cumbersome multiplication factors relating fundamental units to subdivisions such as 1760 (miles to yards), 3 (yards to feet), and 12 (feet to inches). The metric system is an alternative set of

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units, which includes, for instance, the unit of the meter and its centimetre and millimetre subdivisions for measuring length. All multiples and subdivisions of basic metric units are related to the base by factors of 10 and such units are therefore much easier to use than Imperial units. However, in the case of derived units such as velocity, the number of alternative ways in which these can be expressed in the metric system can lead to confusion. As a result of this, an internationally agreed set of standard units (SI units or Syste`mes internationales d'unite´s) has been defined, and strong efforts are being made to encourage the adoption of this system throughout the world. In support of this effort, the SI system of units is used exclusively in this book. However, it should be noted that the Imperial system is still widely used in the engineering industry, particularly in the United States.

2.2.2 Experimental Errors

No physical quantity can be measured with perfect certainty; there are always errors in any measurement. This means that if we measure some quantity and, then, repeat the measurement, we will almost certainly measure a different value the second time. How, then, can we know the true value of a physical quantity? The short answer is that we cannot. However, as we take greater care in our measurements and apply ever more refined experimental methods, we can reduce the errors and, thereby, gain greater confidence that our measurements approximate ever more closely the true value.

2.2.2.1 Types and Sources of Experimental Errors

When scientists refer to experimental errors, they are not referring to what are commonly called mistakes, blunders, or miscalculations. Sometimes also referred to as illegitimate, inhuman or personal errors, these types of errors can result from measuring a width when the length should have been measured, or measuring the voltage across the wrong portion of an electrical circuit, or

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misreading the scale on an instrument, or forgetting to divide the diameter by2 before calculating the area of a circle with the formula $A = \pi r^2$. Such errors are surely significant, but they can be eliminated by performing the experiment again C correctly the next time. Experimental errors, on the other hand, are inherent in the measurement process and cannot be eliminated simply by repeating the experiment no matter how carefully. There are two types of experimental errors: systematic errors and random errors.

Systematic Errors

Systematic errors are errors that affect the accuracy of a measurement. Systematic errors are one-sided errors, because, in the absence of other types of errors, repeated measurements yield results that differ from the true or accepted value by the same amount. The accuracy of measurements subject to systematic errors cannot be improved by repeating those measurements. Systematic errors cannot easily be analysed by statistical analysis. Systematic errors can be difficult to detect, but once detected can be reduced only by refining the measurement method or technique.

Common sources of systematic errors are faulty calibration of measuring instruments, poorly maintained instruments, or faulty reading of instruments by the user. A common form of this last source of systematic error is called "parallax error" which results from the user reading an instrument at an angle resulting in a reading which is consistently high or consistently low.

2.2.2.1.1 Random Errors

Random errors are errors that affect the precision of a measurement. Random errors are "two-sided" errors, because, in the absence of other types of errors, repeated measurements yield results that fluctuate above and below the true or accepted value. Measurements subject to random errors differ from each other due to random, unpredictable variations in the measurement process. The precision of measurements subject to random errors can be improved by repeating those measurements. Random errors are easily analysed by statistical

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analysis. Random errors can be easily detected, but can be reduced by repeating the measurement or by refining the measurement method or technique. Common sources of random errors are problems estimating a quantity that lies between the graduations (the lines) on an instrument and the inability to read an instrument because the reading fluctuates during the measurement

2.2.2.2 Calculating Experimental Error

When a scientist reports the results of an experiment, the report must describe the accuracy and precision of the experimental measurements. Some common ways to describe accuracy and precision are described below:

2.2.2.2.1 Significant Figures

The least significant digit in a measurement depends on the smallest unit which can be measured using the measuring instrument. The precision of a measurement can then be estimated by the number of significant digits with which the measurement is reported. In general, any measurement is reported to a precision equal to 1/10 of the smallest graduation on the measuring instrument, and the precision of the measurement is said to be 1/10 of the smallest graduation. For example, a measurement of length using a meterstick with 1-mm graduations will be reported with a precision of ±0.1 mm. A measurement of volume using a graduated cylinder with 1-ml graduations will be reported with a precision of ±0.1 ml. Digital instruments are treated differently. Unless the instrument manufacturer indicates otherwise, the precision of measurement made with digital instruments are reported with a precision of ±Ω of the smallest unit of the instrument. For example, a digital voltmeter reads 1.493 volts; the precision of the voltage measurement is ±Ω of 0.001 volts or ±0.0005 volt.

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2.2.2.2.2 Percent Error

The percent error (sometimes referred to as fractional difference) measures the accuracy of measurement by the difference between a measured or experimental value E and a true or accepted value A. The percent error is calculated from the following equation:

$$\%\ Error = \frac{|E - A|}{A}$$

2.2.2.2.3 Mean and Standard Deviation

When a measurement is repeated several times, we see the measured values are grouped around some central value. This grouping or distribution can be described with two numbers: the mean, which measures the central value, and the standard deviation which describes the spreader deviation of the measured values about the mean for a set of N measured values for some quantity x, the mean of x is represented by the symbol <x> and is calculated by the following formula:

$$\langle x \rangle = \frac{1}{N}\sum_{i=1}^{N} x_i = \frac{1}{N}\left(x_1 + x_2 + x_3 + \cdots + x_{N-1} + x_N\right)$$

where xi is the measured value of x. The mean is simply the sum of the measured values divided by the number of measured values. The standard deviation of the measured values is represented by the symbol σ_x and is given by the formula:

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$$\sigma_x = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(x_i - \langle x\rangle\right)^2}$$

The standard deviation is sometimes referred to as the mean square deviation and measures how widely spread the measured values are on either side of the mean. The meaning of the standard deviation can be seen from Figure (2.1), which is a plot of data with a mean of 0.5. SD represents the standard deviation. As seen in Figure (2.1), the larger the standard deviation, the more widely spread the data is about the mean. For measurements which have only random errors, the standard deviation means that 68% of the measured values are within σx from the mean, 95% are within 2σx from mean, and 99% are within 3σx from the mean.

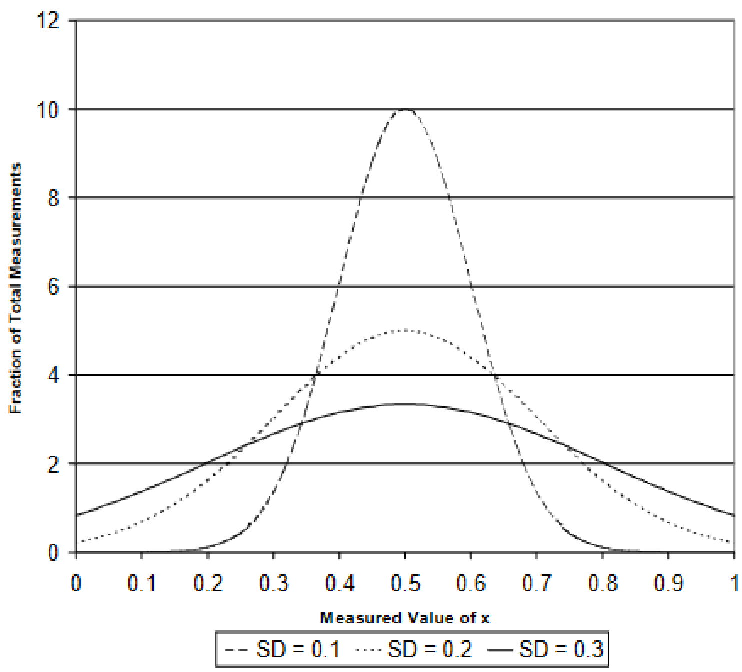

Figure (2.1): Measured Values of x

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2.3 Uncertainty of Measurement

The uncertainty of a measurement is a predicament that characterizes the range of values, including the true value of the measure. *Measurement uncertainty* is an important topic for all measurement fields. All measurements have error. The error of a measurement is unknowable because one cannot know the error without knowing the true value of the quantity being measured. The *Evaluation of Measurement Data: Guide to the Expression of Uncertainty in Measurement* (GUM) provides general rules for evaluating and expressing uncertainty in measurement. The uncertainty of measurement generally includes many components. Some of these components can be estimated on the basis of the statistical distribution of series measurement results and can be characterized by empirical standard deviations. The estimates of the other components are based solely on the main information or experiences. The uncertainty of measurements should be evaluated and reported according to the related international standards.

2.4 Calibration

The purpose of calibration is to determine and document how much of the equipment is in error with the actual value. The correct value is obtained by considering the amount of error in the result. Calibration is the process of determining the relationship between the value read in a gauge and the gauge size. Calibration and control of measuring, inspection, and control equipment ensure the appropriateness of measurements made during manufacturing. The continuity of this safety is ensured by the regular and identifiable calibration of the equipment in question. Calibration is performed by comparison with a measurement of normality known to the measurement magnitude. To sum up, calibration is explained in the related standard: under specified conditions, the

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series of operations in which the relationship between the values indicated by a measuring instrument or device and the values indicated by a material measurement or reference material is established [1]. In order to supply traceability in measurements, calibration hierarchy in Figure (2.2) should be followed up carefully.

Figure (2.2): Hierarchy of Calibration/Traceability Pyramid.

2.5 Data Evaluation

Metrology and inspection together serve as the control function of the quality of conformance. Inspection helps to evaluate the degree of conformance or non-conformance to specifications, provides for reporting of deficiencies early in the production process, and helps to assure that desired quality requirements have been met. The field of knowledge concerned with measurement. Metrology includes all aspects of both theoretical and practical with reference to measurements, whatever their level of accuracy, and in whatever fields of science or technology they occur. Since quality performance decisions are based on inspection and measurement, undesirable consequences may result if these tasks

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are not performed properly. Not only incorrect measurements lead to wrong decisions, which can have serious consequences, but also improper data evaluations can cause undesirable consequences. Since Statistical Process Control is the utilization of statistical tools and methods to acquisite and to analyse data in order to monitor process capabilities, it is widely used in data evaluation. Quality control charts and the other statistical tools are used to analyse processes enabling appropriate actions to achieve improved or stabilized processes. They help to ensure that the process operates efficiently and allow organizations to understand variation in their processes, differentiating common causes from special or assignable causes of variation.

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Chapter Three

Pressure

3.1 Introduction

The standard terminology used to describe the physical characteristic in a pressurized system can be a little confusing to someone new to pressure measurement. Knowing the standard terminology provides a common language that will ensure what you want is what you get when purchasing a pressure gauge, pressure controller or calibrator and pressure transmitter, transducer or sensor. It will also eliminate mismatch between the calibrated and the calibrator.

Pressure is a force applied perpendicular to the surface of an object per unit area. Mathematically it is P = F/A, where P is pressure, F is force, and A is area. Pressure is a scalar quantity, one that only has magnitude and no other characteristics. In a practical sense we can think of it as a force that acts equally on all surfaces it is exposed to, and results from the combined energy of the gas or liquid touching that surface. There are two basic pressure types: absolute and gauge, distinguished by what pressure they are compared to, which is called the reference pressure.

Gauge pressure's reference is ambient atmospheric pressure. Absolute pressure's reference is an absolute vacuum. So, both, in a sense, are reading the difference between the reference pressure and the pressure applied. However, with gauge pressure, the reference pressure may vary depending on the current atmospheric pressure.

3.2 Units:

The SI unit for pressure is the pascal (Pa), equal to one newton per square metre (N/m^2, or $kg{\cdot}m{-}1{\cdot}s^{-2}$). This name for the unit was added in 1971[5]; before that, pressure in SI was expressed simply in newtons per square metre.

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Other units of pressure, such as pounds per square inch (Ibf/in^2) and bar, are also in common use. The CGS unit of pressure is the barye (Ba), equal to 1 dyn·cm^{-2}, or 0.1 Pa. Pressure is sometimes expressed in grams-force or kilograms-force per square centimetre (g/cm^2 or kg/cm^2) and the like without properly identifying the force units. But using the names kilogram, gram, kilogram-force, or gram-force (or their symbols) as units of force is expressly forbidden in SI. The technical atmosphere (symbol: at) is 1 kgf/cm^2 (98.0665 kPa, or 14.223 psi).

Some meteorologists prefer the hectopascal (hPa) for atmospheric air pressure, which is equivalent to the older unit millibar (mbar). Similar pressures are given in kilopascals (kPa) in most other fields, where the hecto- prefix is rarely used. The inch of mercury is still used in the United States. Oceanographers usually measure underwater pressure in decibars (dbar) because pressure in the ocean increases by approximately one decibar per metre depth.

The standard atmosphere (atm) is an established constant. It is approximately equal to typical air pressure at Earth mean sea level and is defined as 101.325 Pa.

Because pressure is commonly measured by its ability to displace a column of liquid in a manometer, pressures are often expressed as a depth of a particular fluid (e.g., centimetres of water, millimetres of mercury or inches of mercury). The most common choices are mercury (Hg) and water; water is nontoxic and readily available, while mercury's high density allows a shorter column (and so a smaller manometer) to be used to measure a given pressure. The pressure exerted by a column of liquid of height h and density ρ is given by the hydrostatic pressure equation $p = \rho gh$, where g is the gravitational acceleration. Fluid density and local gravity can vary from one reading to another depending on local factors, so the height of a fluid column does not define pressure precisely. When millimetres of mercury or inches of mercury are quoted today, these units are not based on a physical column of mercury; rather, they have been given precise definitions that can be expressed in terms of SI units. One millimetre of mercury is

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approximately equal to one torr. The water-based units still depend on the density of water, a measured, rather than defined, quantity. These manometric units are still encountered in many fields. Blood pressure is measured in millimetres of mercury in most of the world, and lung pressures in centimetres of water are still common.

Gauge pressure is often given in units with "g" appended, e.g. "kPag", "barg" or "psig", and units for measurements of absolute pressure are sometimes given a suffix of "a", to avoid confusion, for example "kPaa", "psia". However, the US National Institute of Standards and Technology recommends that, to avoid confusion, any modifiers be instead applied to the quantity being measured rather than the unit of measure.[7] For example, "pg = 100 psi" rather than "p = 100 psig".

Differential pressure is expressed in units with "d" appended; this type of measurement is useful when considering sealing performance or whether a valve will open or close.

Presently or formerly popular pressure units include the following:

- Atmosphere (atm)
- Manometric units:
  - Centimetre, inch, millimetre (torr) and micrometre (mTorr, micron) of mercury,
  - Height of equivalent column of water, including millimetre (mm H_2O), centimetre (cm H_2O), metre, inch, and foot of water;
- Imperial and customary units:
  - kip, short ton-force, long ton-force, pound-force, ounce-force, and poundal per square inch,
  - short ton-force and long ton-force per square inch,
  - fsw (feet sea water) used in underwater diving, particularly in connection with diving pressure exposure and decompression;

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- Non-SI metric units:
  - Bar, decibar, millibar,
- msw (metres sea water), used in underwater diving, particularly in connection with diving pressure exposure and decompression,
  - Kilogram-force, or kilopond, per square centimetre (technical atmosphere),
  - Gram-force and tonne-force (metric ton-force) per square centimetre,
  - Barye (dyne per square centimetre),
  - Kilogram-force and tonne-force per square metre,
  - sthene per square metre (pieze).

3.3 Types of Pressure

There are different types (sometimes also referred as "modes") available for pressure: Figure (3.1)

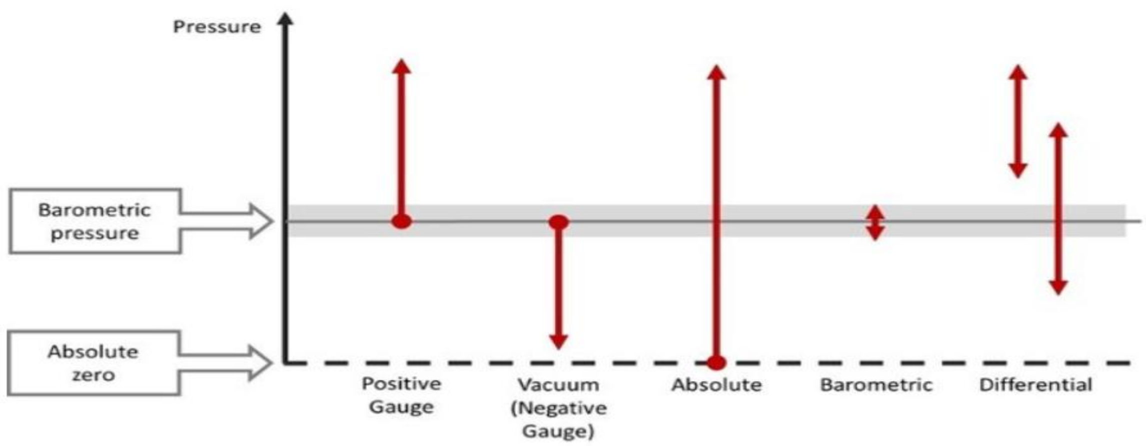

Figure (3.1): Different Types/Models of Pressures

- The two principal pressure types are **gauge** (or gage) and **absolute** pressure.
- **Vacuum** is sometimes considered as its own pressure type, although it is a negative gauge pressure.

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- **Barometric pressure** is also used in discussions, being the atmosphere's absolute pressure.
- **Differential pressure** is also considered a pressure type as being the difference of two separate pressures. In the end, all the pressure types are differential, with just a different point of comparison. They explained as follow:

3.3.1 Gauge Pressure

Gauge (gage) pressure is the **most commonly used pressure type**. With gauge pressure we always compare the pressure we are measuring **against the current atmospheric pressure.** So, it is the difference of the measured pressure and the current atmospheric pressure, meaning that are much above (or below) current atmospheric pressure. If our gauge pressure measurement device is open to atmospheric, it will always read zero, although the atmospheric pressure is different on any given day. Gauge pressure can be indicated as word "gauge" after the pressure unit (e.g. 150 kPa gauge). The abbreviation "g" is also used, although it is not fully legitimate and may cause confusion with the pressure unit.

One practical example of gauge pressure is a car's tire pressure; although we don't talk about "gauge" pressure, we measure and fill it up to certain gauge pressure, i.e. certain amount above atmospheric pressure, regardless if it is a low (rainy) or high (sunny) atmospheric pressure on that day.

3.3.2 Absolute Pressure

Absolute pressure is the pressure **compared to absolute vacuum**, so it is the difference of the measured pressure and the absolute vacuum. An absolute vacuum is a state where the vacuum is so deep that there are no air molecules left, so there is no pressure. In practice a perfect absolute vacuum is impossible to achieve, but we can get pretty close. Also, in outer space, the pressure is absolute vacuum. An **absolute pressure can never be negative**, or in practice not even zero. Absolute pressure should be indicated as word "absolute" after the pressure

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reading (e.g., 150 psi absolute). Sometimes you can see also abbreviations “a” or “abs” being used.

3.3.3 Vacuum Pressure

Vacuum pressure is a (gauge) pressure which is **below current atmospheric pressure**. Being a gauge pressure, it is compared against the current atmospheric pressure and is often indicated as negative gauge pressure. The term vacuum is sometimes also used as a generic term to refer to a pressure that is below atmospheric pressure, even if it could also be measured as absolute pressure. In that case it is of course not a negative number, it is just an absolute pressure being smaller than the current atmospheric absolute pressure. For example, if you pull a 40 kPa vacuum, that can be said to be -40 kPa gauge, but it can also be indicated in absolute pressure being for example 60 kPa absolute, if the barometric pressure is 100.000 kPa absolute at the moment.

3.3.4 Differential Pressure

As the name already hints, the differential pressure is a **difference of two separate pressures**. The value can be positive or negative (or zero) depending which of these two pressures is higher.

A common industrial application is the measurement of flow by comparing a differential pressure over a constriction in the tubing (usually zero-based), or a tank level measurement by measuring the differential pressure between tank top and bottom. Another common measurement is the very low differential pressure difference between a clean room and surrounding areas.

3.3.5 Barometric Pressure

The barometric pressure is the **absolute pressure of current atmospheric pressure** at a specific location. The nominal barometric pressure has been agreed

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to be 101.325 Pa absolute (101.325 kPa absolute, 1013.25 mbar absolute or 14.696 psi absolute). The barometric pressure is dependent on weather conditions, your location and your elevation, being the highest at sea level elevation and lowest at high mountains.

A weather forecast is one practical example of the use of absolute pressure to indicate high or low barometric pressure, roughly corresponding sunny or rainy weather. If a weather forecast would use gauge pressure, the air pressure would always be zero, so that would be pretty useless forecast (well, they often are useless anyhow).

The basic conversion rule between gauge and absolute pressure is the following:
Absolute pressure = atmospheric pressure + gauge pressure

3.4 Measuring Instruments of Pressure

A pressure sensor is a device for pressure measurement of gases or liquids. Pressure is an expression of the force required to stop a fluid from expanding, and is usually stated in terms of force per unit area. A pressure sensor usually acts as a transducer; it generates a signal as a function of the pressure imposed. For the purposes of this article, such a signal is electrical.

Pressure sensors are used for control and monitoring in thousands of everyday applications. Pressure sensors can also be used to indirectly measure other variables such as fluid/gas flow, speed, water level, and altitude. Pressure sensors can alternatively be called pressure transducers, pressure transmitters, pressure senders, pressure indicators, piezometers and manometers, among other names.

Pressure sensors can vary drastically in technology, design, performance, application suitability and cost. A conservative estimate would be that there may be over 50 technologies and at least 300 companies making pressure sensors worldwide.

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There is also a category of pressure sensors that are designed to measure in a dynamic mode for capturing very high-speed changes in pressure. Example applications for this type of sensor would be in the measuring of combustion pressure in an engine cylinder or in a gas turbine. These sensors are commonly manufactured out of piezoelectric materials such as quartz.

Some pressure sensors are pressure switches, which turn on or off at a particular pressure. For example, a water pump can be controlled by a pressure switch so that it starts when water is released from the system, reducing the pressure in a reservoir.

3.4.1 Types of Pressure Measurements

3.4.1.1 Absolute Pressure Sensor

This sensor measures the pressure relative to perfect vacuum. Absolute pressure sensors are used in applications where a constant reference is required, like for example, high-performance industrial applications such as monitoring vacuum pumps, liquid pressure measurement, industrial packaging, industrial process control and aviation inspection [2].

3.4.1.2 Gauge Pressure Sensor

This sensor measures the pressure relative to atmospheric pressure. A tire pressure gauge is an example of gauge pressure measurement; when it indicates zero, then the pressure it is measuring is the same as the ambient pressure. Most sensors for measuring up to 50 bar are manufactured in this way, since otherwise the atmospheric pressure fluctuation (weather) is reflected as an error in the measurement result.

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3.4.1.3 Vacuum Pressure Sensor

This term can cause confusion. It may be used to describe a sensor that measures pressures below atmospheric pressure, showing the difference between that low pressure and atmospheric pressure, but it may also be used to describe a sensor that measures absolute pressure relative to a vacuum.

3.4.1.4 Differential Pressure Sensor

This sensor measures the difference between two pressures, one connected to each side of the sensor. Differential pressure sensors are used to measure many properties, such as pressure drops across oil filters or air filters, fluid levels (by comparing the pressure above and below the liquid) or flow rates (by measuring the change in pressure across a restriction). Technically speaking, most pressure sensors are really differential pressure sensors; for example, a gauge pressure sensor is merely a differential pressure sensor in which one side is open to the ambient atmosphere.

Sealed Pressure Sensor

This sensor is similar to a gauge pressure sensor except that it measures pressure relative to some fixed pressure rather than the ambient atmospheric pressure (which varies according to the location and the weather).

3.4.2 Pressure-Sensing Technology:

There are two basic categories of analog pressure sensors,

3.4.2.1 Force Collector Types: These types of electronic pressure sensors generally use a force collector (such a diaphragm, piston, bourdon tube, or

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bellows) to measure strain (or deflection) due to applied force over an area (pressure).

3.4.2.1.1 Piezoresistive Strain Gauge

Uses the piezoresistive effect of bonded or formed strain gauges to detect strain due to applied pressure, resistance increasing as pressure deforms the material. Common technology types are Silicon (Monocrystalline), Polysilicon Thin Film, Bonded Metal Foil, Thick Film, Silicon-on-Sapphire and Sputtered Thin Film. Generally, the strain gauges are connected to form a Wheatstone bridge circuit to maximize the output of the sensor and to reduce sensitivity to errors. This is the most commonly employed sensing technology for general purpose pressure measurement.

3.4.2.1.2 Capacitive

Uses a diaphragm and pressure cavity to create a variable capacitor to detect strain due to applied pressure, capacitance decreasing as pressure deforms the diaphragm. Common technologies use metal, ceramic, and silicon diaphragms.

3.4.2.1.3 Electromagnetic

Measures the displacement of a diaphragm by means of changes in inductance (reluctance), LVDT, Hall Effect, or by eddy current principle.

3.4.2.1.4 Piezoelectric

Uses the piezoelectric effect in certain materials such as quartz to measure the strain upon the sensing mechanism due to pressure. This technology is commonly employed for the measurement of highly dynamic pressures. As the basic principle is dynamic no static pressures can be measured with piezoelectric sensors.

3.4.2.1.5 Strain-Gauge

Strain gauge-based pressure sensors also use a pressure sensitive element where metal strain gauges are glued on or thin film gauges are applied on by sputtering.

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This measuring element can either be a diaphragm or for metal foil gauges measuring bodies in can-type can also be used. The big advantages of this monolithic can-type design are an improved rigidity and the capability to measure highest pressures of up to 15,000 bar. The electrical connection is normally done via a Wheatstone bridge which allows for a good amplification of the signal and precise and constant measuring results [3].

3.4.2.1.6 Optical

Techniques include the use of the physical change of an optical fiber to detect strain due to applied pressure. A common example of this type utilizes Fiber Bragg Gratings. This technology is employed in challenging applications where the measurement may be highly remote, under high temperature, or may benefit from technologies inherently immune to electromagnetic interference. Another analogous technique utilizes an elastic film constructed in layers that can change reflected wavelengths according to the applied pressure (strain) [1].

3.4.2.1.7 Potentiometric

Uses the motion of a wiper along a resistive mechanism to detect the strain caused by applied pressure.

3.4.2.1.8 Force Balancing

Figure (3.2): A Force-Balanced Fused Quartz Bourdon Tube Pressure Sensor, the mirror that should be mounted to the armature is absent.

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Figure (3.2) shows the force-balanced fused quartz bourdon tubes use a spiral bourdon tube to exert force on a pivoting armature containing a mirror, the reflection of a beam of light from the mirror senses the angular displacement and current is applied to electromagnets on the armature to balance the force from the tube and bring the angular displacement to zero, the current that is applied to the coils is used as the measurement. Due to the extremely stable and repeatable mechanical and thermal properties of fused quartz and the force balancing which eliminates most non-linear effects these sensors can be accurate to around 1PPM of full scale [4]. Due to the extremely fine fused quartz structures which are made by hand and require expert skill to construct these sensors are generally limited to scientific and calibration purposes. Non force-balancing sensors have lower accuracy and reading the angular displacement cannot be done with the same precision as a force-balancing measurement, although easier to construct due to the larger size these are no longer used.

3.4.2.2 Other Types

These types of electronic pressure sensors use other properties (such as density) to infer pressure of a gas, or liquid.

3.4.2.2.1 Resonant

Uses the changes in resonant frequency in a sensing mechanism to measure stress, or changes in gas density, caused by applied pressure. This technology may be used in conjunction with a force collector, such as those in the category above. Alternatively, resonant technology may be employed by exposing the resonating element itself to the media, whereby the resonant frequency is dependent upon the density of the media. Sensors have been made out of vibrating wire, vibrating cylinders, quartz, and silicon MEMS. Generally, this technology is considered to provide very stable readings over time.

`

A pressure sensor, a resonant quartz crystal strain gauge with a bourdon tube force collector is the critical sensor of DART.[5] DART detects tsunami waves from the bottom of the open ocean. It has a pressure resolution of approximately 1mm of water when measuring pressure at a depth of several kilometres [6].

3.4.2.2.2 Thermal

Uses the changes in thermal conductivity of a gas due to density changes to measure pressure. A common example of this type is the Pirani gauge.

3.4.2.2.3 Ionization

Measures the flow of charged gas particles (ions) which varies due to density changes to measure pressure. Common examples are the Hot and Cold Cathode gauges.

3.5 Pressure Calibration

Pressure calibration is the comparison of the output of a device used to measure pressure with that of another pressure measurement device, or pressure measurement standard. This usually involves plumbing the device under test (DUT) to the standard device and generating a common pressure in the measurement circuit. The outputs of the devices are compared at one or more pressures, typically from the lowest to highest readings of the DUT's full scale range, or the range for which it is normally used. This comparison process is performed in a chain from the highest level of fundamental pressure realization, down to every day pressure measurement devices, to ensure pressure measurements are accurate and comply with accepted or mandated standards.

Pressure gauge can be calibrated using two ways:

`

3.5.1 Pressure Balance

In this method weights are added to a platform on a dead weight tester. The weights put a known force on to a piston. The piston has a known area, then the pressure can be calculated.

3.5.1.1 The principle of the Pressure Balance

1- A pressure balance consists of a vertical piston freely rotating within a cylinder. The two elements of well-machined quality define a surface called the 'effective area'. The pressure to be measured is applied to the base of the piston, creating an upward vertical force. This force is equilibrated by the gravitational downward force due to masses submitted to the local gravity and placed on the top of the piston. The piston is a part of the load.

2- Sometimes, for practical reasons, and essentially at low pressure, the cylinder rotates instead of the piston. The principle and the test methods are exactly the same in this case.

3- The pressure is transmitted to the movable element by a fluid which might be a gas (usually dry nitrogen) or a liquid (usually oil).

4- Sometimes the measuring element is not a piston-cylinder assembly, as in the case of the floating-ball balance which combines a ball to receive the load and a hemispheric base to support the ball. In this case a flow regulator controls the flow rate of gas in the clearance of the system. This type of pressure balance is used only for gas in gauge mode measurement.

5- When the masses are submitted to vacuum; the balance measures an absolute pressure. The residual pressure in the bell jar around the masses creates a force in opposition to the measured pressure. The residual pressure has to be measured and added to the pressure created by the masses.

`

6- When the overall masses are submitted to the atmosphere which also applies to the top of the piston, the balance measures a gauge pressure. In some cases, an adaptor allows the reversal of the piston-cylinder mounting: the balance then measures negative gauge pressure (below atmospheric pressure) and generates an upward force opposed to the gravitational one.

7- The general definition of the pressure measured by the balance is obtained by analysing the different components of the forces applied to the system. For the gas-operated balance in gauge mode, the pressure definition is as follows:

$$p_e = \frac{\sum_i m_i \cdot g \cdot (1 - \rho_a / \rho_{m_i})}{A_p \cdot [1 + (\alpha_p + \alpha_c) \cdot (t - t_r)]}$$

where:

p_e is the gauge pressure measured at the bottom of the piston,

mi is the individual mass value of each weight applied on the piston, including all floating elements,

g is the local gravity,

ρ_a is the density of air,

ρ_{mi} is the density of each weight,

A_p is the effective area of the piston-cylinder assembly at a reference temperature tr and at pressure pe. Depending on the type and range of the balance, A_p can be expressed:

(a) as a constant A_0 equal to the mean value of all the determinations

(b) from the effective area at null pressure A_0 and the first-order pressure distortion coefficient λ:

$$A_p = A_0 \cdot (1 + \lambda \cdot p),$$

where p is an approximate value of the measured pressure pe. It may be the nominal value.

(c) eventually, from a second-order polynomial, λ' being the second-order pressure distortion coefficient:

$$A_p = A_0 \cdot (1 + \lambda \cdot p + \lambda' \cdot p^2).$$

α_p is the linear thermal expansion coefficient of the piston,

α_c is the linear thermal expansion coefficient of the cylinder,

t is the measured temperature of the piston-cylinder assembly during its use,

t_r is the reference temperature of the piston-cylinder assembly (usually 20°C).

`

Alternatively, if the masses of the weights applied to the piston are conventional masses, the pressure is defined by the following equation:

$$p_e = \frac{\sum_i m_{ci} \cdot g \cdot \left(1 - \frac{\rho_{0a}}{\rho_0} + \frac{\rho_{0a} - \rho_a}{\rho_{m_i}}\right)}{A_p \cdot \left[1 + (\alpha_p + \alpha_c) \cdot (t - t_r)\right]},$$

where:

m_{ci} is the individual conventional mass value of each weight applied on the piston, including all floating elements,

ρ_{0a} is the conventional value of the air density, ρ_{0a}=1.2 kg/m3,

ρ_0 is the conventional value of the mass density, ρ_0=8000 kg/m3, and all other quantities as defined before.

If for all quantities SI units are used without prefixes, pe will emerge in pascals.

8- For the liquid-operated pressure balance, a similar expression could be considered, and the force due to the surface tension of the liquid has to be added to the gravitational force:

$$p_e = \frac{\sum_i m_i \cdot g \cdot (1 - \rho_a / \rho_{m_i}) + \sigma \cdot c}{A_p \cdot \left[1 + (\alpha_p + \alpha_c) \cdot (t - t_r)\right]}$$

where:

σ is the surface tension of the liquid,

c is the circumference of the piston or its extension at the level where it emerges from the oil.

Note: In some types of pressure balances, such as the dual-range ones, a correction has to be applied to take into account the fluid buoyancy on the piston. The value of this correction can often be higher than that due to the surface tension.

If the masses of the weights applied to the piston are conventional masses, the pressure is defined by this equation

$$p_e = \frac{\sum_i m_{ci} \cdot g \cdot \left(1 - \frac{\rho_{0a}}{\rho_0} + \frac{\rho_{0a} - \rho_a}{\rho_{m_i}}\right) + \sigma \cdot c}{A_p \cdot \left[1 + (\alpha_p + \alpha_c) \cdot (t - t_r)\right]}$$

`

9- The bottom of the piston when the balance is in equilibrium is usually considered to be the reference level of the balance. In some cases, for practical reasons, the initial weight is adjusted by the manufacturer to refer the reference level to the output connection of the balance. Special attention will be paid to the method used for the calibration of this type of instrument.

10- With the reference level being chosen at the bottom of the piston, equations (3.1, 3.1a, 3.2, 3.2a and 3.3) are only valid if the piston surface contacting with the pressure fluid has a simple cylindrical shape. If the piston surface deviates from the simple cylindrical shape, e.g., typically due to a free volume, a conical end or a step on the piston, additional volume V produced by this shape deviation must be taken into account for fluid buoyancy on the piston. The pressure corrected for the piston buoyancy is given by equations

in gauge mode: $$p_{e\_V} = p_e + \frac{(\rho_f - \rho_a) \cdot g \cdot V}{A_p \cdot [1 + (\alpha_p + \alpha_c) \cdot (t - t_r)]},$$

in absolute mode: $$p_{abs\_V} = p_{abs} + \frac{\rho_f \cdot g \cdot V}{A_p \cdot [1 + (\alpha_p + \alpha_c) \cdot (t - t_r)]},$$

where ρ_f is the density of the measuring fluid. The additional volume V can be positive (e.g., piston with free volume or conical end) or negative (e.g., stepped piston with an increase in radius). The additional volume is typically present in the following types of pressure balances: gas-operated low range, gas-operated oil-lubricated and dual-range ones.

11- When the pressure is expressed at a level different from the reference level, a corrective term (the head correction) has to be added to the pressure expressed above by equations (3.1-3.5)

in gauge mode: $$p_{e\_\Delta h} = p_{e\_\Delta V} + (\rho_f - \rho_a) \cdot g \cdot \Delta h,$$

in absolute mode: $$p_{abs\_\Delta h} = p_{abs\_\Delta V} + \rho_f \cdot g \cdot \Delta h,$$

with Δh being the difference between the altitude h1 of the balance reference level and the altitude h2 of the point where the pressure has to be measured, Δh = h1 - h2.

`

12- Equations (3.1-3.7) are valid for pressure balances of a floating -cylinder configuration as well. If the pressure reference level is chosen at the piston top located inside the cylinder cavity, the additional volume V in equations (3.4 and 3.5) is the volume of the cylinder cavity minus the volume of the piston part placed inside the cylinder cavity. This additional volume V is always positive.

Note: For a floating-piston as well as for a floating-cylinder configuration, the pressure reference level can always be chosen in such a way that the additional volume in equations (3.4 and 3.5) becomes equal to zero.

3.5.2 Direct Comparison Method

Here the pressure gauge that be calibrate disconnected to a master gauge. Pressure is applied to the pressure gauge at predetermined pressure increments over its full operating range. The value indicated by the pressure gauge is compared to the corresponding value indicated by the master gauge at each pressure increment. The percent error between the two values is calculated and the gauge is adjusted as necessary.

3.6 Observations

In this study four types of pressure gauges are calibrated using the both methods which are mentioned above, in the following the calibration observations are shown along with the item details and reference standards.

3.6.1 Pressure Balance Method Observations

3.6.1.1 Calibration Item no 1

Description:	Multifunction Calibrator
Manufacturer:	WIKA
Model:	Pascal-ET
Serial Number:	6211+6915
Range:	100 bar

`

Table (3.1): Reference Standards for Calibration Item no 1 in Pressure Balance Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
High Accuracy Pressure Indicator	Barptech	DPG3600	163053612	02/08/2021
Pneumatic Pressure Pump	Additel	Additel918	11819020019	-

Table (3.2): Calibration Results for Calibration Item no 1 in Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00			20.0	33	101.1	21.8
10	M_1	10.00			20.2	34	101.2	21.9
20	M_1, M_2	20.10			20.1	32	100.3	21.5
30	M_1, M_2, M_3,	30.10			21.3	31	100.6	21.3
40	M_1, M_2, M_3, M_4	40.05			21.1	34	101.0	21.1
50	M_1, M_2, M_3, M_4, M_5, M_9	50.06			21.5	33	99.8	21.8
60	C, M_7,	60.20			20.9	32	99.7	21.9
70	C, M_7, M_{10}	70.08			20.8	33	98.9	21.8
80	C, M_7, M_9	80.16			21.9	32	100.6	21.5
90	C, M_7, M_9, M_{10}	90.17			21.8	34	99.9	21.6
100	C, M_7, M_8	100.25			21.5	33	98.8	21.0

3.6.1.2 Calibration Item no 2

Description: Hydraulic Electronic Pressure Calibration System

Manufacturer: GENERALDH-BUDENBERG

Model: DH42

Serial Number: H542/468

Range: 0-1200 bar calibrated up to 800 bar

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Table (3.3): Reference Standards for Calibration Item no 2 in Pressure Balance Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
Electronic Pressure Gauge	Armaturenbau GmbH	DPG - 3600(+DPT-3220)	163053613/159785	02/08/2021

Table (3.4): Calibration Results for Calibration Item no 2 in Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00			20.7	33	101.2	21.7
100	C, M_7, M_8	100.44			20.6	32	100.3	21.5
200	C, M_6, M_7, M_8	200.56			21.5	33	100.6	21.6
300	C, M_1, M_7, M_8	298.89			21.7	34	101.0	21.8
400	C, M_1, M_6, M_7, M_8	399.66			21.5	33	99.8	21.4
500	C, M_1, M_2, M_7, M_8	500.02			20.9	32	99.7	21.5
600	C, M_1, M_2, M_6, M_7, M_8	600.18			20.8	34	98.9	21.7
700	C, M_1, M_2, M_3, M_7, M_8	700.26			21.6	32	100.6	21.5
800	C, M_1, M_2, M_3, M_6, M_7, M_8	800.33			21.8	34	99.9	21.6

3.6.1.3 Calibration Item no 3

Description Analogue Pressure gauge

Manufacturer Turkey

Model PAKKENS

Serial Number -

Range 40 bar

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Table (3.5): Reference Standards for Calibration Item no 3 in Pressure Balance Method

Description	Manufacturer	Model No.	Serial Number
High Accuracy Pressure Indicator	Barotech	DPG3600	163053613
Hydraulic Pressure Pump	Additel	Additel928	13318070008

Table (3.6): Calibration Results for Calibration Item no 3 in Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
10	M_1	10.09			21.2	29	101.2	20.9
20	$M_{1,}$ M_2	20.10			21.1	31	100.3	20.5
30	M_1, M_2, $M_{3,}$	30.17			21.3	30	100.6	20.3
40	$M_{1,}$ M_2, $M_{3,}$ M_4	40.05			21.1	32	101.0	20.1

3.6.1.4 Calibration Item no 4

Description: Digital Pressure gauge

Manufacturer: CalRef

Model: DGS700

Serial Number: 8070

Range: 700 bar

Table (3.7): Reference Standards for Calibration Item no 4 in Pressure Balance Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
Accuracy Pressure Indicator	Barptech	DPG3600	163053613	02/08/2021
ulic Pressure Pump	Additel	Additel928	13318070008	-

`

Table (3.8): Calibration Results for Calibration Item no 4 in Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00			20.2	31	99.9	21.3
50	C, M_9, M_{10}	49.09			20.1	30	100.1	21.5
100	C, M_7, M_8	99.95			21.3	32	100.2	21.4
200	C, M_6, M_7, M_8	199.80			21.1	31	101.0	21.3
300	C, M_1, M_7, M_8	299.95			21.5	32	99.8	21.5
400	C, , M_1, M_6, M_7, M_8	399.94			20.9	31	99.9	21.5
500	C, , M_1, M_2, M_7, M_8	500.05			20.9	31	99.9	21.5

3.6.2 Direct Comparison Method Observations

3.6.2.1 Calibration Item no 1

Description: Multifunction Calibrator

Manufacturer: WIKA

Model: Pascal-ET

Serial Number: 6211+6915

Range: 100 bar

Table (3.9): Reference Standards for Calibration Item no 1 in Direct Comparison Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
Accuracy Pressure Indicator	Barptech	DPG3600	163053612	02/08/2021
matic Pressure Pump	Additel	Additel918	11819020019	-

`

Table (3.10): Calibration Results for Calibration Item no 1 in Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)	Uncertainty of Measurement ± (bar)
0	0.00	0.00	0.238
10	10.00	0.00	0.238
20	20.10	0.10	0.238
30	30.10	0.10	0.238
40	40.15	0.15	0.238
50	50.20	0.20	0.238
60	60.25	0.25	0.238
70	70.30	0.30	0.238
80	80.45	0.45	0.238
90	90.45	0.45	0.238
100	100.55	0.55	0.238

3.6.2.2 Calibration Item no 2

Description: Hydraulic Electronic Pressure Calibration System

Manufacturer: GENERALDH-BUDENBERG

Model: DH42

Serial Number: H542/468

Range: 0-1200 bar calibrated up to 800 bar

Table (3.11): Reference Standards for Calibration Item no 2 in Direct Comparison Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
onic Pressure Gauge	Armaturenbau GmbH	DPG - 3600(+DPT-3220)	163053613/159785	02/08/2021

`

Table (3.12): Calibration Results for Calibration Item no 2 in Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)
0.00	0.01	-0.01
100.00	100.58	-0.58
200.00	198.97	1.03
300.00	298.59	1.41
400.00	400.82	-0.82
500.00	500.73	-0.73
600.00	599.74	0.26
700.00	699.49	0.51
800.00	800.99	-0.99

3.6.2.3 Calibration Item no 3

Description	Analogue Pressure gauge
Manufacturer	Turkey
Model	PAKKENS
Serial Number	-
Range	41 bar

Table (3.13): Reference Standards for Calibration Item no 3 in Direct Comparison Method

Description	Manufacturer	Model No.	Serial Number
Accuracy Pressure Indicator	Barotech	DPG3600	163053613
ulic Pressure Pump	Additel	Additel928	13318070008

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Table (3.14): Calibration Results for Calibration Item no 3 in Direct Comparison Method

Reference Reading (bar)	UUC Reading (bar)	Error (bar)	Uncertainty of Measurement ± (bar)
0.00	0.00	0.00	0.34
10.00	10.11	- 0.11	0.34
20.00	20.18	- 0.18	0.34
30.00	30.11	- 0.11	0.34
40.00	39.95	0.05	0.34

3.6.2.4 Calibration Item no 4

Description: Digital Pressure gauge

Manufacturer: CalRef

Model: DGS700

Serial Number: 8070

Range: 700 bar

Table (3.15): Reference Standards for Calibration Item no 4 in Direct Comparison Method

Description	Manufacturer	Model No.	Serial Number	Calibration due date
Accuracy Pressure Indicator	Barptech	DPG3600	163053613	02/08/2021
ulic Pressure Pump	Additel	Additel928	1331807000 8	-

`

Table (3.16): Calibration Results for Calibration Item no 4 in Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)	Uncertainty of Measurement ± (bar)
0	0.00	0.00	0.751
50	49.93	- 0.07	0.751
100	99.92	- 0.08	0.751
200	199.70	- 0.30	0.751
300	299.93	- 0.07	0.751
400	399.96	- 0.04	0.751
500	500.08	0.08	0.751

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Chapter Four

Experimental Work

In this chapter the calibration procedure of the both method of calibrations is shown where the steps are explained and illustrated in vivid way. Along with that the data evaluation is carried out also from which the further comparison of the study is accomplished.

4.1 Pressure Balance Method Calibration Procedure (Cross-Floating)

4.1.1 Preparing for Calibration

The calibration should only be carried out when the pressure balance is in good working order. The operation of the pressure balance and the gauge pressure should be carried out according to the laboratory's calibration procedure and the manufacturer's technical manual.

4.1.1.1 Calibration Room

The following parameters shall be controlled according to the uncertainty regime. Typically:

- Ambient temperature within 15 °C and 25 °C, stabilised within ±2 °C. For lower uncertainty, typically 0.01 %, the temperature of the piston-cylinder assembly should preferably be measured.
- Control the opening of doors and the movement of operators to keep a stable atmosphere, and control ventilation in order to prevent intense air flow above or below the piston balances.

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4.1.1.2 Device Installation

- Install the devices away from the air disturbances such as ventilation and air-conditioning.
- Use a rigid, stable table supporting the full load, with its horizontal plane checked with a spirit level.
- Respect the verticality of the piston as recommended by the manufacturer: use the built-in spirit level, or a laboratory spirit level on the top of the piston to minimise the tilt. This should be checked also at full mass load.
- Use short, wide-bore pipework. This is more critical at low pressure.
- Ensure the cleanliness and the tightness of the tubing.
- Install an appropriate drainage system to control the nature of the fluid in the tubing.
- Attach a suitable temperature measurement system.

4.1.1.3 Pressure Generation

4.1.1.3.1 For Gas Gauge Pressure

(a) Use a clean and dry gas (nitrogen for example), at a temperature near ambient.

(b) Adjust the pressure input to the range of the intercompared instruments.
(c) Clean the tubing of any liquid (for the oil-lubricated type).

4.1.1.3.2 For Gas Absolute Pressure

(a) Use a clean pump, or, when using mechanical rotational pumps, use an appropriate trap.

(b) Use an appropriate vacuum pump to ensure that the residual pressure over the mass-piston set is less than typically 10 Pa or 10-5 of the measured pressure, whichever is the higher, unless otherwise recommended by the manufacturer. (c) Measure the residual pressure with a vacuum gauge calibrated and connected directly to the bell jar.

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4.1.1.3.3 For Liquid Pressure

(a) Use the liquid recommended by the manufacturer.
(b) If the liquid in the balance under calibration is not the same as the liquid in the standard, use an appropriate interface/separator to avoid any mixture of the two liquids.
(c) Clean the tubing of any other liquid.
(d) Clean the fluid in the tubing of any possible internal gas.

4.1.1.4 Preparation of the Pressure Balance

The pressure balance shall be placed in the laboratory at least 12 hours before the calibration is started, to reach thermal equilibrium.
(a) Check that the oil is free of impurities. If not, drain all the tubing and replace the oil in the tank.
(b) With the pressure circuit closed and half the set of weights placed on the piston, the piston shall be moved upwards and downwards by means of the spindle pump. Thus, the mobility of the piston is examined over the total range of displacement.
(c) If necessary, and using the technical manual, remove the piston-cylinder assembly, and clean the surfaces of the two pieces with a suitable solvent or pure soap, and with a soft dry cloth according to the manufacturer's recommendations. Inspect the piston and the cylinder for surface scratches and corrosion. Relubricate the piston with clean liquid if the piston-cylinder operates in liquid, or if the balance operates in gas, but with an oil-lubricated piston-cylinder assembly.
(d) Examine the free rotation time (for the hand-rotating pressure balances only). Weights corresponding to 2/10 of maximum pressure are placed upon the piston.

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The initial rotation rate should be approximately 30 rpm. Measure the elapsed time until the piston is stationary. This time should be at least 3 min.

(e) Examine the descent rate of the piston. The piston descent rate is observed at maximum pressure when the piston is rotating. Measure the time interval in which the piston drops from top to bottom position. This time should be at least 3 minutes. Note, for the last two parameters, the stated values should be related to the technical instructions of the manufacturer.

(f) Connect the pressure balance to the gauge pressure under calibration. (g) Identify the reference level for pressure balance. The reference level is normally defined by the manufacturer at the bottom surface of the piston when it is in the working position. In the absence of reference level information, and when the bottom surface of the piston is not accessible, the reference level is generally defined at the outlet pipe connection level.

(h) For absolute pressure, pump for 30 min. at the beginning of the calibration to eliminate the water vapour in the bell jar. Use dry nitrogen as the working gas.

(j) Rotate the piston or the cylinder while keeping to the manufacturer's recommendation.

(k) For hand-rotating balances, check the clockwise and anticlockwise direction influence (if any), or indicate the rotation direction in the certificate.

4.1.2 Calibration Procedure

(a) Place the weights on the pressure balance, so that the masses correspond to the fixed pressure point.

(b) Adjust the pressure to equilibrate the balance.

(c) Perform an adjustment with small weights on the reference pressure balance, until the equilibrium condition has been found. The equilibrium should be

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considered as reached when the proper falling rate is found (i.e., no flow of fluid in the tubing).

(d) Note the reference number of each of the weights applied on the balance.

(e) Note the temperature of the piston-cylinder assembly of the balance. If the balance is not equipped with a temperature probe, note the surrounding air temperature using an electronic thermometer attached to some suitable point of the balance. This information shall be included in the certificate.

(f) Note the measured value of the gauge pressure under calibration, then calculate the reference pressure according to the equation and found the error.

4.1.3 Data Evaluation

- Calculation of the reference pressure:

The pressure measured by the pressure balance is calculated using the equations presented in chapter 3. In our study the equation that’s used is the following one:

$$p_e = \frac{\sum_i m_i \cdot g \cdot (1 - \rho_a / \rho_{m_i}) + \sigma \cdot c}{A_p \cdot \left[1 + (\alpha_p + \alpha_c) \cdot (t - t_r)\right]}$$

- The results are presented in the form of the tables below and including:

(i) The reference pressure calculated from the above equation by pressure balance.

(ii) The corresponding pressure measured by pressure gauge.

(iii) The difference between the measured pressure and the reference pressure for each pressure equilibrium, as residuals of the effective area modelling.

(iv) The other data (Mass of the Reference Reading, room temperature, humidity, Atm Pressure, and piston temperature).

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Table (4.1): Data Evaluation of Calibration Item no 1 for Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00	0.00000	0.0000	20.0	33	101.1	21.8
10	M_1	10.00	10.02719	-0.02719	20.2	34	101.2	21.9
20	$M_{1,}$ M_2	20.10	20.05431	0.04569	20.1	32	100.3	21.5
30	$M_{1,}$ M_2, $M_{3,}$	30.10	30.08166	0.01834	21.3	31	100.6	21.3
40	$M_{1,}$ M_2, $M_{3,}$ M_4	40.05	40.10901	-0.05901	21.1	34	101.0	21.1
50	$M_{1,}$ M_2, $M_{3,}$ $M_{4,}$ $M_{5,}$ M_9	50.06	50.13643	-0.07643	21.5	33	99.8	21.8
60	C, $M_{7,}$	60.20	57.60885	2.59115	20.9	32	99.7	21.9
70	C, $M_{7,}$ M_{10}	70.08	67.61195	2.46805	20.8	33	98.9	21.8
80	C, $M_{7,}$ M_9	80.16	77.61516	2.54484	21.9	32	100.6	21.5
90	C, $M_{7,}$ M_9, M_{10}	90.17	87.61876	2.55124	21.8	34	99.9	21.6
100	C, $M_{7,}$ M_8	100.25	97.62194	2.62806	21.5	33	98.8	21.0

Table (4.2): Data Evaluation of Calibration Item no 2 for Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00	0.00000	0.0000	20.7	33	101.2	21.7
100	C, $M_{7,}$ M_8	100.44	97.62194	2.8180	20.6	32	100.3	21.5
200	C, $M_{6,}$ $M_{7,}$ M_8	200.56	197.6532	2.9068	21.5	33	100.6	21.6
300	C, $M_{1,}$ $M_{7,}$ M_8	298.89	297.6867	1.2033	21.7	34	101.0	21.8
400	C, $M_{1,}$ $M_{6,}$ $M_{7,}$ M_8	399.66	397.7164	1.9436	21.5	33	99.8	21.4
500	C, $M_{1,}$ $M_{2,}$ $M_{7,}$ M_8	500.02	497.7522	2.2678	20.9	32	99.7	21.5
600	C, $M_{1,}$ $M_{2,}$ M_6, M_7, M_8	600.18	597.7825	2.3975	20.8	34	98.9	21.7
700	C, $M_{1,}$ $M_{2,}$ M_3, M_7, M_8	700.26	697.8141	2.4459	21.6	32	100.6	21.5
800	C, $M_{1,}$ $M_{2,}$ M_3, M_6, $M_{7,}$ M_8	800.33	797.8473	2.4827	21.8	34	99.9	21.6

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Table (4.3): Data Evaluation of Calibration Item no 3 for Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
10	M_1	10.09	10.02719	0.06281	21.2	29	101.2	20.9
20	M_1, M_2	20.10	20.05461	0.04539	21.1	31	100.3	20.5
30	$M_1, M_2, M_3,$	30.17	30.08211	0.08789	21.3	30	100.6	20.3
40	M_1, M_2, M_3, M_4	40.05	40.10961	-0.05961	21.1	32	101.0	20.1

Table (4.4): Data Evaluation of Calibration Item no 4 for Pressure Balance Method

Nominal Value	Mass of the Reference Reading (bar)	UUT Reading (bar)	Reference Pressure Calculated	Error (bar)	T	RH %	Atm Pressure KPa	Piston Temp
0	-	0.00	0.0000	0.0000	20.2	31	99.9	21.3
50	C, M_9, M_{10}	49.09	50.13613	-1.04613	20.1	30	100.1	21.5
100	C, M_7, M_8	99.95	97.62194	2.32806	21.3	32	100.2	21.4
200	C, M_6, M_7, M_8	199.80	197.6535	2.1465	21.1	31	101.0	21.3
300	C, M_1, M_7, M_8	299.95	297.688	2.262	21.5	32	99.8	21.5
400	C, M_1, M_6, M_7, M_8	399.94	397.7182	2.2218	20.9	31	99.9	21.5
500	C, M_1, M_2, M_7, M_8	500.05	497.7514	2.2986	20.9	31	99.9	21.5

4.2 Direct Comparison Method Calibration Procedure

4.2.1 Calibration Requirements

• Ensure that the reference instrument must be at least 3 times more accurate than the UUC or the maximum permissible error of the reference instrument must be 1/3 of the maximum permissible error of the UUC by conducting the TUR role.

• For gauges with a pointer step, the accuracy class will cover 10% to 100% of range

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• For gauges with a free zero, the accuracy class will cover 0% to 100% of range and zero shall be used as an accuracy check point.

• The total error of indication at reference temperature 20 ºC of the gauge shall not exceed the values given in the Table (4.5).

Table (4.5): Maximum Permissible Errors and Number of Calibration Points (according to BS EN 837-1:1998)

Accuracy classes	Limits of permissible (percentage of span)	Number of Calibration point
0.10	±0.10 %	10
0.25	±0.25 %	10
0.60	±0.60 %	10
10.0	±1.00 %	5
1.6	±1.6 %	5
2.5	±2.5 %	5
4	±4 %	4

• The oil seal shall be used in calibration of gauges that have to be kept clean and oil free (e.g., oxygen gauges, medical gauges, etc.).

4.2.2 Environmental Condition

According to the technical procedure "Facilities and Environmental Condition" The performance tests shall be carried out in a laboratory at ambient temperature within 23 °C ± 5°C with a temperature stability during the testing period of ± 1°C and relative humidity range less than 70%.

4.2.3 Procedures

4.2.3.1 Inspecting and Cleaning the Gauge

• Visually inspect the gauge to be calibrated for cleanliness and freedom from apparent mechanical defects.

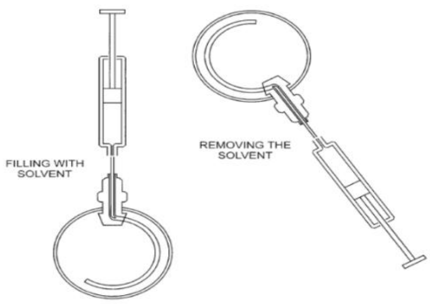

Figure (4.1): Cleaning gauge

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• Cleaning gauge Figure (4.1):

(a) Fill syringe with solvent (Proprietary cold degreasing liquid).

(b) With gauge connection pointing upwards put needle into connection and insert by feel the point into

(c) The hole leading to the tube.

(d) Inject the solvent. Ideally the tube should be half full.

(e) Shake gauge in various attitudes to agitate solvent.

(f) Suck solvent back into syringe, holding gauge at an angle.

(g) Check that solvent removed is clean. To be sure that all oil has been removed, repeat cleaning

(h) Process until solvent removed from gauge is as clean as that put in.

(i) Shake out solvent remaining in gauge.

4.2.3.2 Calibration Method

(a) The pressure gauge is to be calibrated as a whole (measuring chain), if possible.

(b) The specified mounting position is to be taken into consideration

(c) The calibration is to be carried out in measurement points uniformly distributed over the calibration range.

(d) Depending on the measurement uncertainty aimed at, one or several measurement series are necessary.

(e) The comparison between the measurement values for calibration item and reference or working standard can be performed by two different methods:

- Adjustment of the pressure according to the indication of the calibration item,
- Adjustment of the pressure according to the indication of the standard.

(f) The time for preloading at the highest value and the time between two preloadings should be at least 30 seconds.

(g) After preloading and after steady-state conditions have been reached and the calibration item permitting, the indication of the calibration item is set to zero. The zero reading is carried out immediately afterwards.

(h) For the pressure step variation in a measurement series, the time between two successive load steps should be the same and not be shorter than 120 seconds and the reading should be made 30 seconds after the start of the pressure change at the earliest.

Table (4.6): Calibration Sequences

Calibration sequence	Measurement uncertainty aimed at, in % of the measurement span (*)	Number of measurement points with zero up/down	Number of preloadings	Load change + waiting time (**) seconds	Waiting time at upper limit of measurement range (***) minutes	Number of measurement series	
						up	down
A	< 0,1	9	3	> 30	2	2	2
B	0,1 ... 0,6	9	2	> 30	2	2	1
C	> 0,6	5	1	> 30	2	1	1

(i) The pressure gauges have to be slightly tapped to minimize any frictional effect of the pointer system, and the measurement value for the upper limit of the calibration range is to be recorded prior to and after the waiting time. The zero reading at the end of a measurement series is made 30 seconds after complete relief at the earliest.

4.2.3.3 Calibration Sequences

The calibration sequence will be as described in Table (4.6)

(a) Reference to the span was used to allow the sequence (necessary calibration effort) to be selected from Table 4.6, as the accuracy specifications of the manufacturers are usually related to the measurement span.

(b) One has in any case to wait until steady-state conditions (sufficiently stable indication of standard and calibration item) are reached.

(c) For Bourdon tube pressure gauges, a waiting time of five minutes is to be observed. For quasi-static calibrations (piezoelectric sensor principle), the waiting times can be reduced.

- The hysteresis is calculated form the difference in applied pressure for the same indication point or the difference in pressure indication for the same applied pressure on falling and rising pressure.

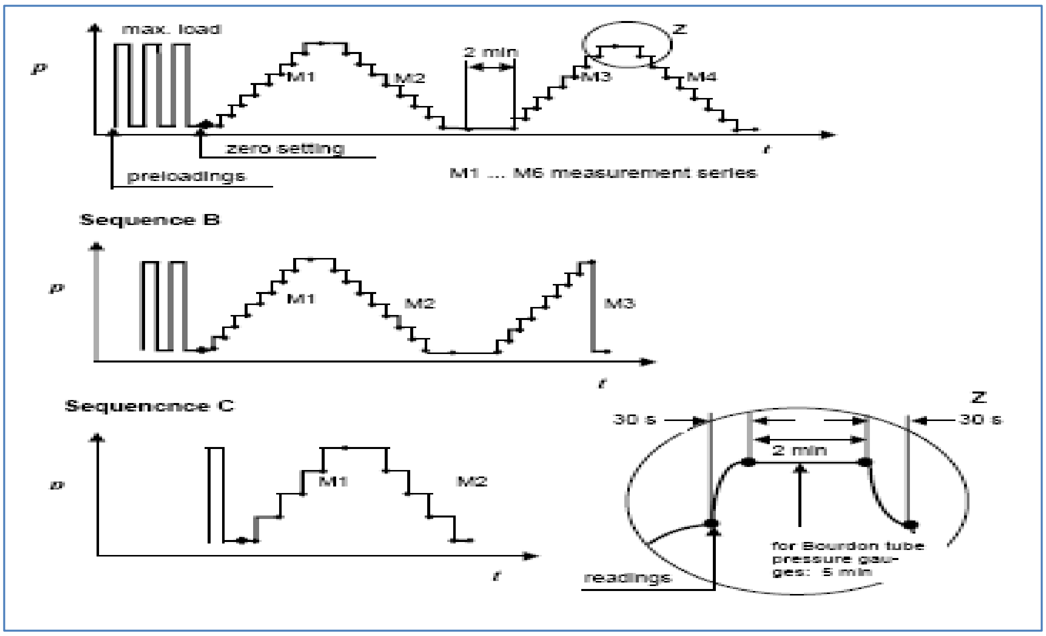

Figure (4.2): Visualization of the Calibration Sequences

- The values of measured error and hysteresis shall not exceed the values given in Table (4.5).
- The number of test point for different classes are shown in Table (4.6).
- The maximum scale value is a test point.
- Zero is a test point Visually inspect the gauge to be calibrated for cleanliness and freedom from apparent mechanical defects.

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4.2.4 Data Evaluation

The readings of the reference standards and unit under calibration are measured directly from respective pressure gauges and resulted errors are evaluated from that; in the below tables all of the data are presented:

Table (4.7): Data Evaluation of Calibration Item no 1 for Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)
0	**0.00**	**0.00**
10	**10.00**	**0.00**
20	**20.10**	**0.10**
30	**30.10**	**0.10**
40	**40.15**	**0.15**
50	**50.20**	**0.20**
60	**60.25**	**0.25**
70	**70.30**	**0.30**
80	**80.45**	**0.45**
90	**90.45**	**0.45**
100	**100.55**	**0.55**

Table (4.8): Data Evaluation of Calibration Item no 2 for Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)
0.00	0.01	-0.01
100.00	100.58	-0.58
200.00	198.97	1.03
300.00	298.59	1.41
400.00	400.82	-0.82
500.00	500.73	-0.73
600.00	599.74	0.26
700.00	699.49	0.51
800.00	800.99	-0.99

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Table (4.9): Data Evaluation of Calibration Item no 3 for Direct Comparison Method

Reference Reading (bar)	UUC Reading (bar)	Error (bar)
0.00	0.00	0.00
10.00	10.11	- 0.11
20.00	20.18	- 0.18
30.00	30.11	- 0.11
40.00	39.95	0.05

Table (4.10): Data Evaluation of Calibration Item no 4 for Direct Comparison Method

Reference Reading (bar)	UUT Reading (bar)	Error (bar)	Uncertainty of Measurement ± (bar)
0	**0.00**	**0.00**	**0.751**
50	**49.93**	**- 0.07**	**0.751**
100	**99.92**	**- 0.08**	**0.751**
200	**199.70**	**- 0.30**	**0.751**
300	**299.93**	**- 0.07**	**0.751**
400	**399.96**	**- 0.04**	**0.751**
500	**500.08**	**0.08**	**0.751**

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Chapter Five

Results and Discussion

In this chapter the results which obtained from the two methods of calibration are discussed; then further of the discussion is reached. Subsequently, the recommendation regarding the study is appointed out so that it can be referred to for better results.

5.1 Discussion of Results

5.1.1 Pressure Balance Method

In calibration the term traceability introduced so that to offer a series of comparisons till reach the SI unit. Primary pressure reference standards are used to measure and generate pressures to a high level of accuracy and repeatability for calibration purposes. These instruments are used to ensure that the measurement uncertainty of all pressure instrumentation which are referred to the standard are kept within performance requirements. The primary reference pressure standard that's used is deadweight testers or pressure balances, These instruments provide a pressure reference to compare the reading of a device under test during a calibration, also since these primary reference pressure standards use mass in a gravitational field and a dimensionally stable piston and cylinder system to measure and produce pressure, it's inherent in their operation that they are consistent and repeatable, when all environmental conditions are accounted for in which repeatability is another essential aspect in calibration. Primary standards provide uniformity to calibration that ensures repeatability and contributes to the desired level of quality and accuracy to meet each requirement. There are number of factors that influence the pressure measurement and these factors are handled in the pressure balance method so that the measurements are more accurate and repeatable. Some of these factors are mentioned below:

(a) Altitude: with an increase in the altitude, the length of the column of the overlying air on the surface of the earth decreases and hence the weight or the pressure exerted by the atmosphere also decreases.

(b) Temperature: when the atmospheric temperature increases, the air expands and loses density and similarly when the temperature decreases the air becomes denser and naturally a.p increases.

(c) Water Vapour: water vapour is lighter than the dry air so, if the content of water vapor in the air is higher, the a.p would be lower and vice-versa.

(d) Atmospheric Pressure and air currents: when temperature increases in an area, the air becomes lighter and rises up, as a result, a low pressure develops there and to fill up the void and neutralize that low pressure, Cooler air descends in that area.

5.1.2 Direct Comparison Method

The calibration facilities provided within the instrumentation department of a company or some calibration laboratories provide the first link in the calibration chain- Figure (5.1). Instruments used for calibration at this level are known as working standards. In our case the direct comparison method which employed to calibrate the pressure gauge with another precise and accurate pressure gauge is categorised under this calibration level. As such, working standard instruments are kept solely for calibration duties, and for no other purpose; then it can be assumed that they will maintain their accuracy over a reasonable period of time because use-related deterioration in accuracy is largely eliminated. However, over the longer term, the characteristics of even such standard instruments will drift, mainly due to aging effects in components within them. Therefore, over this longer term, a program must be instituted for calibrating working standard

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instruments at appropriate intervals of time against instruments of yet higher accuracy. The instrument used for calibrating working standard instruments is known as a secondary reference standard. This must obviously be a very well-engineered instrument that gives high accuracy and is stabilized against drift in its performance with time. This implies that it will be an expensive instrument to buy. It also requires that the environmental conditions in which it is used be controlled carefully in respect of ambient temperature, humidity, and so on.

Furthermore, the secondary standard is calibrated by standards laboratories are closely monitored by national standards organizations which provide the primary standard level where it relies the SI unit and; in our case, this primary standard is the pressure balance.

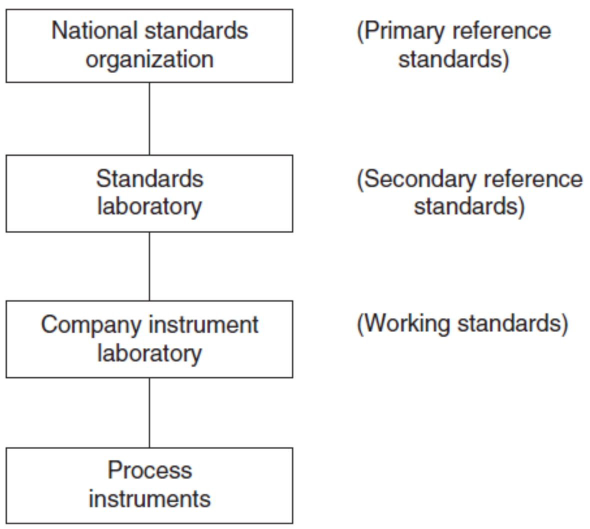

Figure (5.1): Calibration Chain.

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5.2 Conclusion

Owing to the above discussion of both methods of calibration where each method is addressed in brief with the regard of different aspects, and from the results that's obtained from the both methods, and eventually with the referring to the concept of traceability that's also mentioned above it is concluded that calibration of pressure gauge using pressure balance which is the primary standard is more accurate, precise, reliable and gives more repeatable measurement.

5.3 Recommendations:

Deciding the method of calibration depends on the level of accuracy that's the measuring device is having, therefore knowing the right accuracy level of the gauge pressure is the key point to determine the appropriate method of calibration. Also, the simple rule in regard to the frequency of calibrating pressure gauges is to follow the manufacturer's recommendation. However, there are some special cases where you could extend the interval a bit. A good reason for doing this would be if you have a proven track record with calibrating a specific device. For example, you might chart the drift of an instrument over a period of time, and based on that data you are confident that you no longer have to calibrate the instrument annually, but can extend it to two or three years and still be safe.

Another instance where you might be able to extend the calibration cycle of an instrument is for a gauge that has one special application and is used very rarely. You might only calibrate it right before you use it. The advantage of extending calibration intervals is that it saves time and money, but only if you are confident that you are not risking the safety or accuracy of your equipment.

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Appendices

Appendice 1: High Accuracy Pressure Indicator

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Appendice 2: Pressure Gauge

Appendice 3: Pressure Pump

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Appendice 4: Dead Weight Tester