Laboratory Report

Pressure

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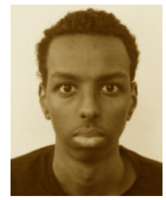
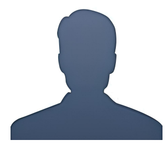
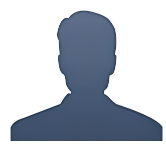
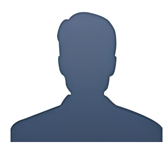
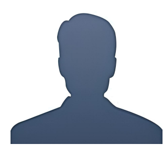
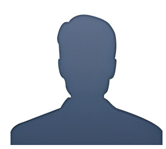
Contribution Table

Student	Course	Contribution	Picture
Sakariye Abiikar	Mechanical Engineering		
Alireza Alishahi	Mechanical Engineering		
Naim Alrifai	Mechanical Engineering		
Munachi J Atuegbu	Mechanical Engineering		
Ehsan Haque	Mechanical Engineering		
Abdul Mueed	Mechanical Engineering		
Abdelrahman Shehata	Mechanical Engineering		
Varley, Freddie	Mechanical Engineering		

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1 Abstract

In this experiment, we calibrated and compared the performance of multiple pressure-measuring devices, including two Bourdon gauges, a Budenberg pressure gauge and a Hg glass manometer, in tandem with a reference pressure calibrator (DPI-603 Portable Pressure Calibrator), which served as the baseline for pressure measurements and as the source of the applied pressure. The devices were connected to the DPI-603 Portable Pressure Calibrator, enabling us to apply both positive and negative pressures in increments of approximately ±5 kPa. Through this process, we were able to get an exhaustive dataset that demonstrated notable differences in the pressure-measuring devices' performance. [Placeholder breif results findings]. These results highlighted the importance of selecting appropriate devices based on precision requirements and operating conditions, as well as the potential impact of human error in reading analog instruments like the Bourdon gauges and Hg manometer.

2 Introduction

In engineering and scientific applications, pressure measurement is essential, playing a critical role in fields such as fluid dynamics, meteorology, and industrial control. Over time, pressure-measuring instruments have evolved, from early liquid column manometers to modern mechanical and digital gauges, each designed to provide accurate measurements under varying conditions.

A key distinction in pressure measurement is between **absolute** and **gauge** pressure.
Absolute pressure is measured relative to a vacuum, while gauge pressure is measured relative to atmospheric pressure. This distinction influences the design and function of pressure-measuring devices.

Historically, the invention of the Bourdon gauge by Eugène Bourdon in 1849 marked a significant advancement in pressure measurement. It provided a robust and reliable means of monitoring pressure in industrial settings, where durability and consistency were paramount. On the other hand, liquid column manometers, particularly those using mercury, have been essential in laboratory settings due to their precision in measuring small pressure differences.

Despite the advantages of different pressure-measuring devices, each has limitations, such as calibration errors and environmental influences.

Previous studies have highlighted various challenges and findings related to pressure measurement devices. For example, a study by Hodgkinson et al. (2020) found that the accuracy of home blood pressure monitors varied significantly, with validated monitors showing a higher pass rate in static pressure tests compared to unvalidated ones. This emphasizes the importance of validation and calibration in ensuring the accuracy of pressure-measuring devices.

In this experiment, we aimed to evaluate the performance and accuracy of various pressure-measuring devices under controlled conditions, comparing their responses to varying pressure levels.

3 Theory

When we talk about pressure, the first thing that comes to mind is its physical definition. It refers to the effect or various types of deflection when a force is applied to a surface.

$$P = \frac{F}{A} \qquad \text{Eq. 1}$$

- P = Pressure (Pa, Pascal)
- F = Force applied (N, Newton)
- A = Surface area (m^2)

Local pressure P_{local} varies spatially. It peaks under concentrated loads (red zone) and vanishes at free edges (blue zone).

$$P_{\text{local}} = \frac{dF}{dA} \qquad \text{Eq. 2}$$

Critical for analyzing stress concentrations in engineering designs.

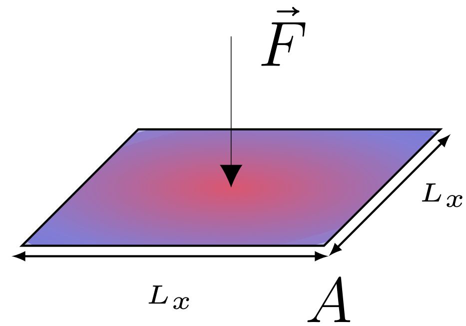


Figure 1: Illustration of pressure application

Average pressure (P) assumes uniform distribution. Local pressure (P_{local}) reveals real-world stress hotspots.

Pressure measurement fundamentally relies on observing its physical effects on measurable systems. The accompanying figures demonstrate three classical approaches:

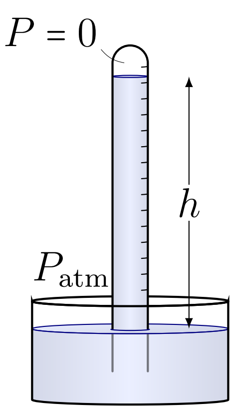


Figure 2: Torricelli's method

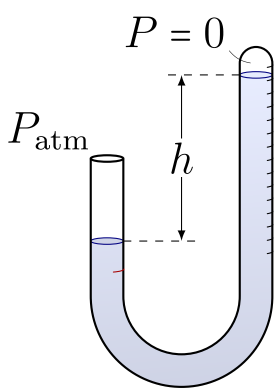


Figure 3: Open manometers

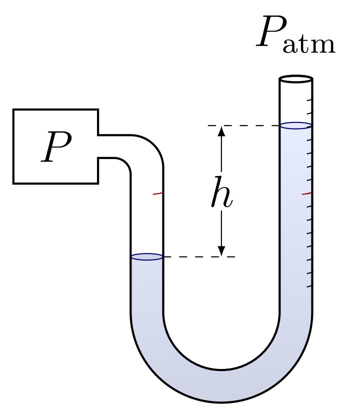


Figure 4: Sealed manometers

Each technique quantifies pressure by correlating it with dimensional changes - either in liquid column elevation or elastic element deformation. The choice between methods depends on required precision, pressure range, and whether absolute or differential measurements are needed. Pressure is categorized into two main groups:

3.1 Absolute Pressure

Absolute pressure, or absolute zero pressure, is the lowest possible pressure measurable. Consequently, all measured pressures are positive in comparison to this reference point. Achieving absolute zero pressure is practically impossible unless calculated or represented through an extremely accurate curve.

3.2 Gauge Pressure

Gauge pressure, also known as relative pressure, is measured relative to local atmospheric pressure. Since we live under constant atmospheric pressure, it is often convenient to measure the difference between actual pressure and atmospheric pressure, which is referred to as gauge pressure. This measurement is commonly used in industrial applications.

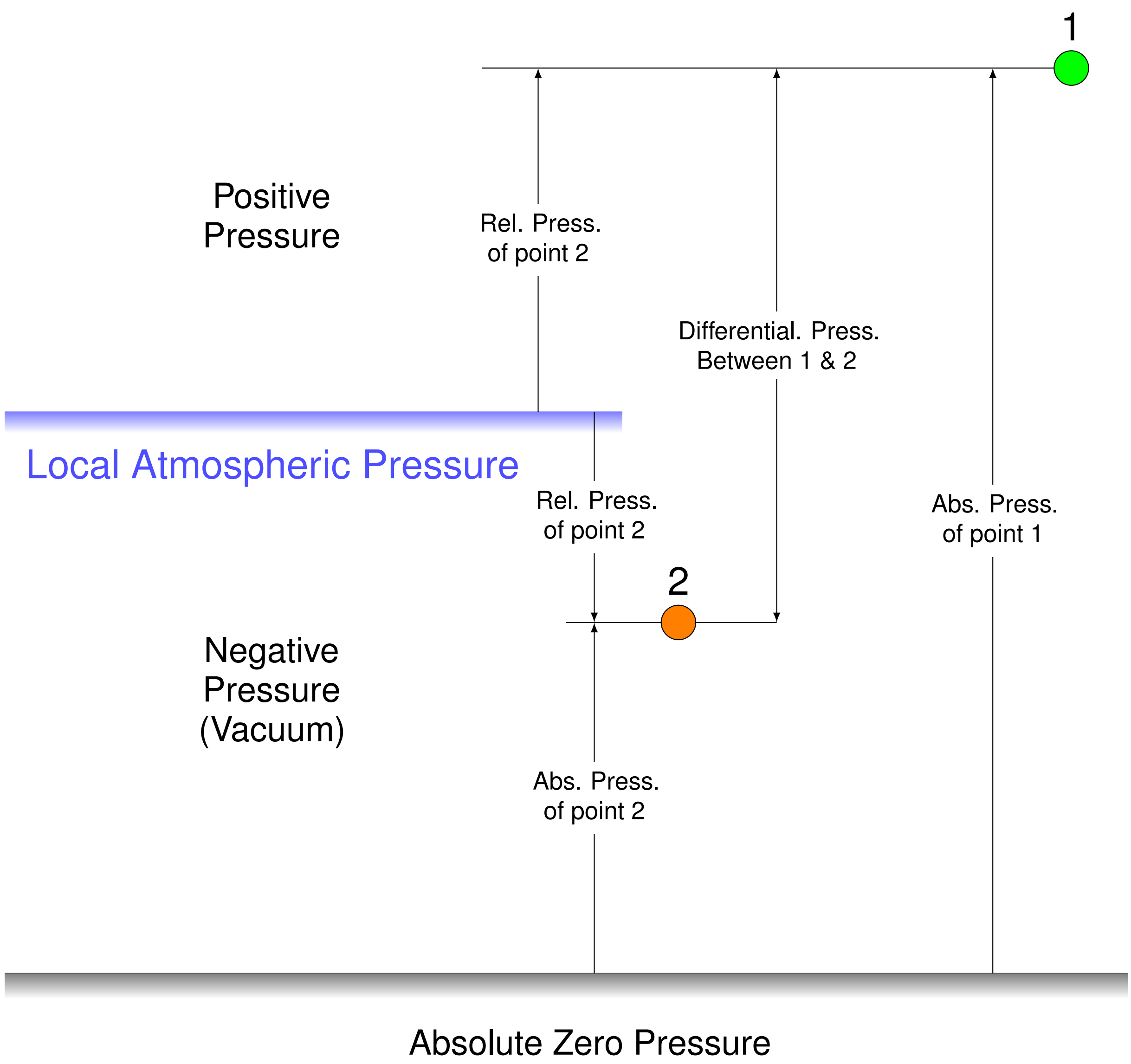
It is important to note that:

- Any pressure between local atmospheric pressure and absolute zero pressure is called **vacuum pressure**.
- Any pressure higher than local atmospheric pressure is considered **positive pressure**.

The relationship between absolute and gauge pressure is given by:

$$P_{\text{absolute}} = P_{\text{atmosphere}} + P_{\text{gauge}} \qquad \text{Eq. 3}$$

The following diagram illustrates the definitions of pressure more clearly.



3.3 Devices and Mechanisms

3.3.1 Bourdon Gauges

A Bourdon gauge consists of a curled up tube, with one end closed and the other open to the system.

As the pressure increases, the tube uncurls which can then be used to give a reading of pressure. The tube has been flattened, which causes the pressure exerted outwards to act on two opposing flat planes, making the tube straighten in a more predictable fashion.

The tip of the tube is connected to a linkage and a pivot, which is then connected to a movement (gearing system).

This mechanism measures the mechanical movement of the tube resulting from the force created by the pressure. As shown in Equation 1, if the area remains constant, force and pressure are directly proportional. This means that with knowledge of the mechanical properties of the tube material and the force required to move it, you can accurately determine the fluid pressure in the tube.

However, this requires the pressure to remain within certain boundaries. Excessive pressure could exceed the material's yield point, causing plastic deformation that would permanently damage the gauge and render it inaccurate.

Types of Bourdon Gauges

There are three main types of Bourdon gauges, each with different sensitivities and pressure ratings:

- **C-Type:**

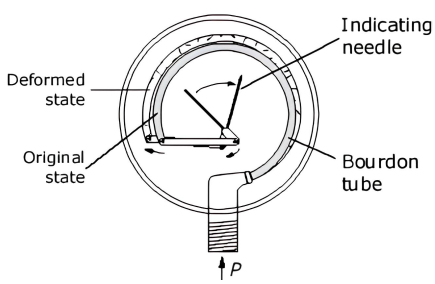


Figure 5: C-Type Bourdon gauge (Efunda, 2024)

The C-Type Bourdon gauge features a flattened metal tube formed into a C-shape, with approximately 6mm of tip movement. This simple design makes it the **least accurate** Bourdon type, as the small movement requires mechanical amplification through gears and linkages.

These additional components can introduce inefficiencies and potential accuracy issues from loose or sticking parts.

Consequently, C-Type gauges are best suited for general-purpose applications where high precision isn't critical.

- **Spiral:**

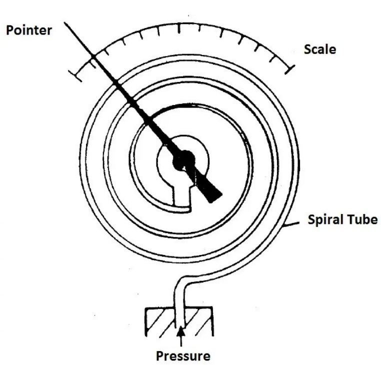


Figure 6: Spiral Bourdon gauge (InstTools, 2017)

This is similar to the C type bourdon gauge it follows the same principles of as pressure increases, it causes the coil to deform which can be measured and converted to a pressure reading.

Spiral gauges employ a coiled tube that provides 15-20mm of movement, three times more than C-types. This greater displacement eliminates the need for error-prone gear mechanisms.

The enhanced sensitivity (±0.5% accuracy) comes at higher cost, but proves essential for laboratory instruments and precision process control where small pressure changes matter.

- **Helical:**

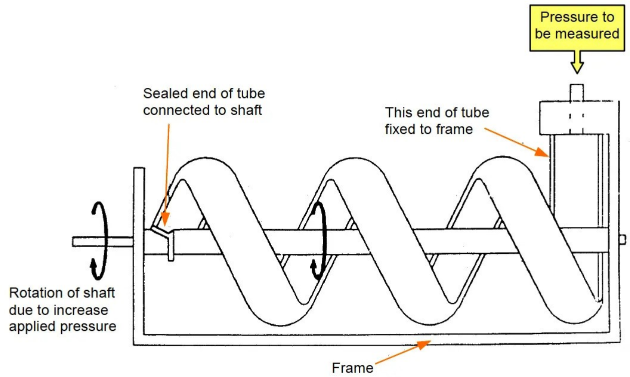


Figure 7: Helical-type Bourdon gauge (InstTools, 2017)

The helical structure offers variable sensitivity across different pressure ranges. More coils enable operation at higher pressures while maintaining accuracy. The tip motion decreases as pressure increases, allowing customization of the optimal working range by adjusting the number of coils. Like spiral gauges, helical types maintain good efficiency due to minimal moving parts.

(Brannan, n.d.)(InstTools, 2017)(ScienceDirect,n.d.),

3.4 Pressure Units

Unit	Pa	bar	psi	atm	cm Hg
Pa	1	1×10^{-5}	1.450×10^{-4}	9.869×10^{-6}	0.00750062
bar	1×10^{5}	1	14.5038	0.986923	75.0062
psi	6894.76	0.0689476	1	0.068046	51.7149
atm	101325	1.01325	14.6959	1	76.0032
cm Hg	1333.22	0.013332	0.19337	0.013158	1

Table 1: Standard Pressure Unit Conversions

Definiton 1: Pascal

The Pascal (Pa) is the SI unit of pressure, named after the French mathematician and physicist Blaise Pascal. It is defined as one Newton per square meter ($\mathrm{N\,m^{-2}}$).

$$1\,\text{Pa} = 1\,\text{kN m}^{-2}$$

As a relatively small unit, the Pascal is commonly used in scientific fields such as laboratory research or atmospheric studies.

Definiton 2: Atmosphere

The atmosphere (atm) is a unit of pressure defined as the average atmospheric pressure at sea level on Earth. Were

$$1\,\text{atm} \approx 101\,325\,\text{Pa}$$

The atmosphere is commonly used in chemistry and physics to describe gas pressures, especially in contexts like gas laws (e.g., Boyle's Law and Charles's Law), as well as in scuba diving to describe underwater pressures. It is used for convenience, providing a standardized unit for atmospheric pressure in various scientific and engineering applications.

Definiton 3: Bar

The bar is a metric unit of pressure, though it is not part of the International System of Units (SI). It is defined as

$$1\,\text{bar} = 100\,000\,\text{Pa}$$

This exact by definition. However, the relationship between bar and atm involves a small fractional difference due to the empirical value of standard atmospheric pressure, it is very close, specifically

$$1\,\text{bar} \approx 0.986923\,\text{atm}$$

Which is just 1.013% off. The bar is commonly used in meteorology, engineering, and industrial applications, as it provides a convenient scale for measuring pressures near atmospheric pressure.

Definiton 4: Pound per square inch

The pound per square inch (psi) is a unit of pressure primarily used in the United States and other countries that follow the Imperial system. It is defined as the pressure exerted by one pound-force applied to an area of one square inch. PSI is widely used in automotive, mechanical engineering, and hydraulic systems, such as measuring tire pressure.

The conversion factor between psi and Pascal is given as:

$$1\,\text{psi} = 6894.76\,\text{Pa}.$$

This conversion is derived from the definition of the pound-force (lbf) and the inch.
One **pound-force (lbf)** is defined as the force required to accelerate a mass of one pound under the influence of gravity. In the metric system, 1 pound-force is approximately equivalent to 4.44822 Newtons (N). This is based on the following formulation:

$$1\,\text{lbf} = 1\,\text{lb} \times g$$

$$1\,\text{lbf} = 0.453592\,\text{kg} \times 9.80665\,\text{m/s}^2 = 4.44822\,\text{N}.$$

The force of one pound-force is applied over an area of one square inch. One square inch is defined as:

$$1\,\text{inch}^2 = 0.00064516\,\text{m}^2.$$

Thus, the conversion from psi to Pascal is calculated by dividing the force in Newtons by the area in square meters:

$$1\,\text{psi} = \frac{4.44822\,\text{N}}{0.00064516\,\text{m}^2} \approx 6894.76\,\text{Pa}.$$

This precise conversion reflects the accurate definitions of the pound-force and the inch, with the result ensuring consistent and reliable unit conversion between the Imperial and SI systems.

Definiton 5: Millimeter of Mercury

The millimeter of mercury (mmHg) is a unit of pressure historically based on the height of a mercury column that exerts a given pressure. It is commonly used in medical and scientific applications, particularly in measuring blood pressure and vacuum pressures.

It is defined as:

$$1\,\text{mmHg} = 133.322\,\text{Pa}$$

This conversion is derived from the hydrostatic pressure equation:

$$P = \rho g h$$

- ρ : Density of mercury $(13.5951\,\text{g/cm}^3)$
- g : Gravitational acceleration $(9.80665\,\text{m/s}^2)$
- h : Height $(\text{mm, interchangeable})$.

$$\frac{g}{cm^3} \times \frac{m}{s^2} \times mm$$

$$g\frac{m}{s^2} \times \frac{mm}{cm^3}$$

$$10^{-3}N \times 10^3 m^{-2}$$

$$Nm^{-2} = \text{Pa}$$

Although mmHg is not an SI unit, it remains widely used in medicine (e.g., blood pressure readings of 120/80 mmHg) and laboratory sciences for its convenience in low-pressure measurements.

4 Method & Experimental Procedures

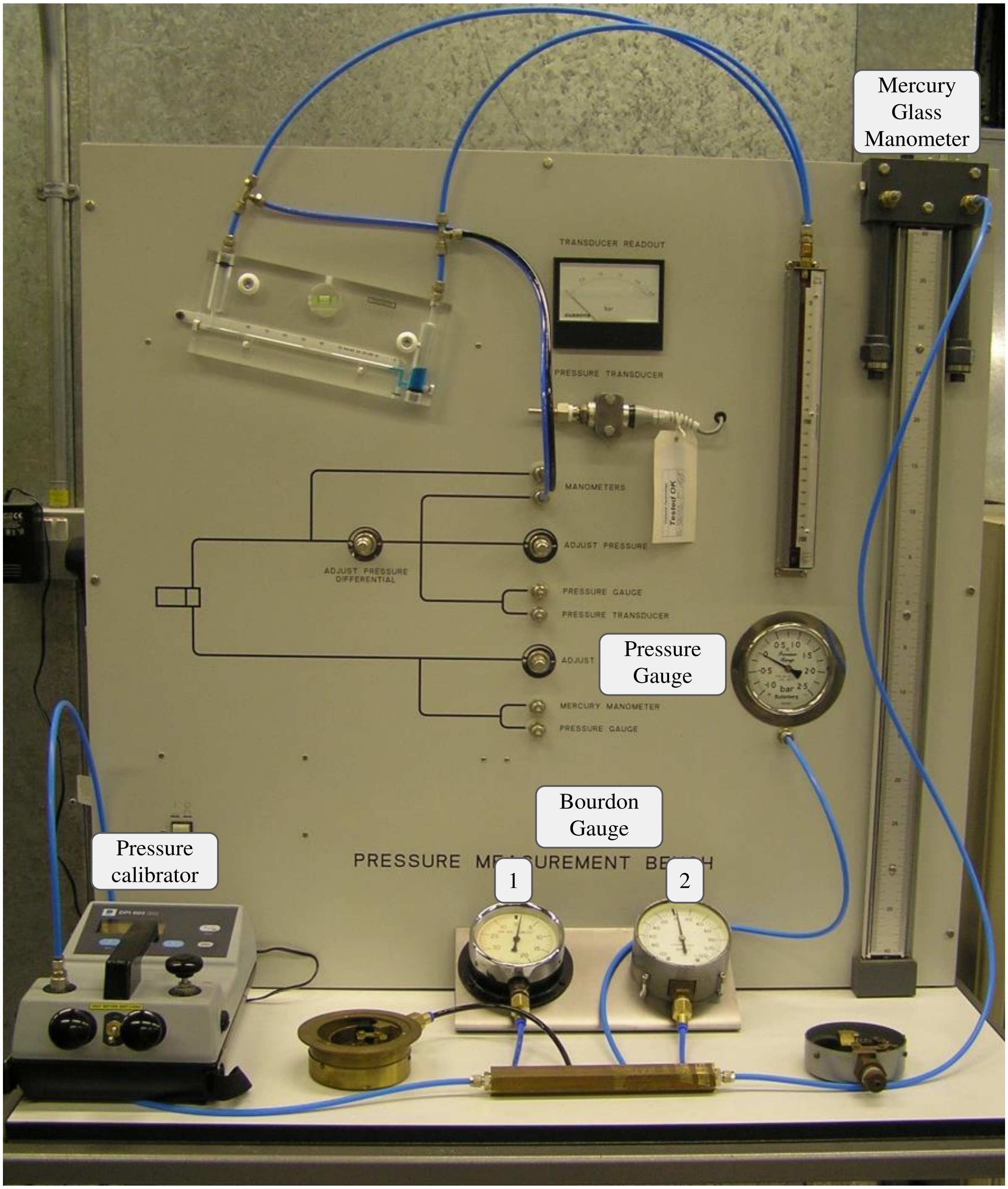


Figure 8: Pressure Measurement Bench

POSITIVE															
#	Reference Value	Pressure Calibrator MAX 75 kPa			Bourdon Gauge 1			Bourdon Gauge 2			Bundenberg Pressure Gauge		Hg Glass Manometer (+) MAX 32 cm Hg		
		kPa	bar	bar P_{abs}	**psi**	bar	bar P_{abs}	**kN/m^2**	bar	bar P_{abs}	**bar**	bar P_{abs}	**cm Hg**	bar	bar P_{abs}
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

NEGATIVE															
#	Reference Value	Pressure Calibrator MAX 75 kPa			Bourdon Gauge 1			Bourdon Gauge 2			Bundenberg Pressure Gauge		Hg Glass Manometer (+) MAX 32 cm Hg		
		kPa	bar	bar P_{abs}	**psi**	bar	bar P_{abs}	**kN/m^2**	bar	bar P_{abs}	**bar**	bar P_{abs}	**cm Hg**	bar	bar P_{abs}
1															
2															
3															
4															
5															
6															
7															
8															
9															
10															

Mercury manometer Pressure = Density × Gravity × Height in metres = $13600 \times 9.81 \times$ Hg height in metres

Atmospheric Pressure (Patm) from the Digital Manometer This is a fill-in line with a specific length: __________.mbar (1000 mbar = 1 bar)

Bordon Gauge 1, Bourden Gauge 2, and Bundenberg Gauge offsets

Figure 9: Form for recording pressure measurements

The experiment **summary** is as follows:

The instructor provided us with a comprehensive demonstration on how to operate the pressure calibrator, guiding us through the process of setting up the equipment and interpreting the corresponding gauge readings.

Prior to starting the experiment, we were given essential safety instructions, including precautions to prevent compromising our data and ensuring the safety of everyone involved.

As the experiment progressed, we worked as a team to carefully apply the required pressures, analyzing the gauge readings and reaching a consensus on the correct values, which were then recorded in the designated pressure measurement table (Figure 9).

A detailed breakdown of the **exact steps** we followed is as follows:

4.1 Operating Procedure

1. The instructor inspected the test rig's pneumatic connections to ensure they were secure.
2. The instrument's vent valve was opened as part of the setup process.
3. Given the choice between vacuum (-) and excess (+) pressure, we initially set the selector on the front of the DPI-603 (±VE in Figure 10) to positive pressure. This setting allowed us to apply the necessary excess pressure for the procedure.
4. The unit was powered on by pressing the power button.
5. Using the pressure units button, we cycled through the available options (in Hg, bar, etc.) and selected kPa.

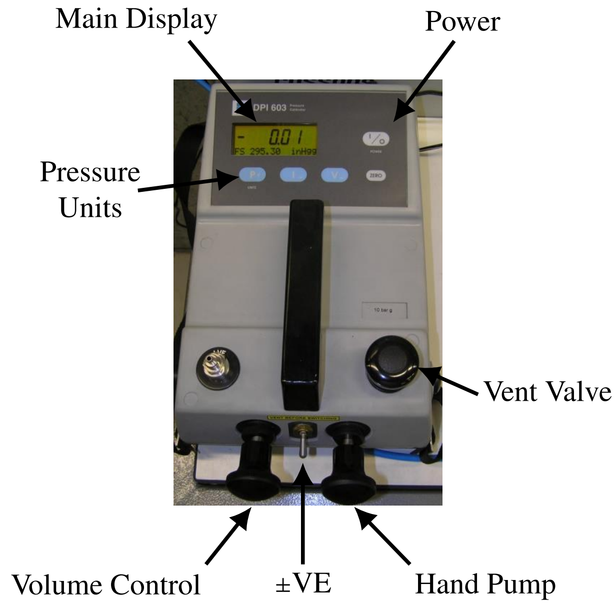


Figure 10: DPI-603 Portable Pressure Calibrator

6. The vent valve was closed and used to zero the instrument. It was concluded that this procedure should be carried out by the instructor due to the vent valve's sensitivity.

Here Steps 1–6 primarily cover the setup phase and were mainly carried out by the instructor. It was now our role to conduct the rest of the experiment, which proceeded as follows:

7. We used the hand pump to pressurize the system to the required value. To achieve precise control, we vented air using the vent valve and adjusted the pressure by pumping air as needed.
8. Once the required incremental was observed on the pressure calibrator, we then observe and recorded the readings seen on the following gauges:

Figure 11: Gauges & Manometer
Refer to Figure 8 for illustrations labels.

9. By reaching on a agreement as a team over what is being read on the instruments for this related pressure value on the calibrator, we recorded them in the designated pressure measurement table (Figure 9).
10. This procedure (Steps 7-9) is repeated, beginning with an **initial reading of 0 kPa** and continuing until the tenth increment, with each increment approximately +5 kPa.
11. Once we're done, we go back and repeat steps 6–10, except this time we do for the vacuum (−5kPa).

This concludes everything that was done in the lab so that we may draw conclusions from the information in the tables.

5 Data, Calculations and Results

Original Data-Set

Pressure Calibrator

kPa

+	-
0	0
5.7	-5.6
10.4	-12.1
16.0	-18.0
21.1	-21.8
27.7	-25.4
34.2	-29.3
40.0	-33.6
46.1	-37.6
52.2	-41.7

Table 2: Pressure Calibrator

Pressure measuring instruments

psi

+	-
1.0	1.2
2.0	0.4
2.6	-0.5
3.4	-2.0
4.1	-2.8
5.0	-4.0
6.0	-6.0
6.8	-7.1
7.6	-8.3
8.5	-9.5

Table 3: Bourdon Gauge 1

kN/m^2

+	-
1.0	2.5
8.0	-1.0
14.0	-9.0
20.0	-15.0
25.0	-20.0
30.0	-23.0
39.0	-27.0
45.0	-32.0
50.0	-36.0
57.0	-40.0

Table 4: Bourdon Gauge 2

bar

+	-
-0.05	-0.05
0.00	-0.10
0.04	-0.16
0.10	-0.24
0.15	-0.27
0.22	-0.30
0.29	-0.35
0.35	-0.40
0.40	-0.44
0.47	-0.49

Table 5: Budenberg Pressure Gauge

cm Hg

+	-
0.4	0.4
3.5	-0.7
5.3	-3.7
7.4	-5.4
9.4	-6.8
11.6	-8.2
14.2	-9.6
16.4	-11.3
18.7	-12.8
21.0	-14.4

Table 6: Hg Glass Manometer

Zeroed out Data-Set

Pressure Calibrator

kPa

+	-
0	0
5.7	-5.6
10.4	-12.1
16.0	-18.0
21.1	-21.8
27.7	-25.4
34.2	-29.3
40.0	-33.6
46.1	-37.6
52.2	-41.7

Table 7: Pressure Calibrator (Zeroed)

Pressure measuring instruments

psi

+	-
0	0
1.0	-0.8
1.6	-1.7
2.4	-3.2
3.1	-4.0
4.0	-5.2
5.0	-7.2
5.8	-8.3
6.6	-9.5
7.5	-10.7

Table 8: Bourdon Gauge 1 (Zeroed)

kN/m^2

+	-
0	0
7.0	-3.5
13.0	-11.5
19.0	-17.5
24.0	-22.5
29.0	-25.5
38.0	-29.5
44.0	-34.5
49.0	-38.5
56.0	-42.5

Table 9: Bourdon Gauge 2 (Zeroed)

bar

+	-
0	0
0.05	-0.05
0.09	-0.11
0.15	-0.19
0.20	-0.22
0.27	-0.25
0.34	-0.30
0.40	-0.35
0.45	-0.39
0.52	-0.44

Table 10: Budenberg (Zeroed)

cm Hg

+	-
0	0
3.1	-1.1
4.9	-4.1
7.0	-5.8
9.0	-7.2
11.2	-8.6
13.8	-10.0
16.0	-11.7
18.3	-13.2
20.6	-14.8

Table 11: Hg Glass (Zeroed)

Now, we need to perform some unit conversions to ensure consistency across all measurements.

In the context of this study, as seen in the table in Figure 9, we are provided with a row for calculating bar and bar P_{abs}, which directly suggests that all the pressures should be expressed in bar for all comparisons. The selection of unit does not substantially influence the outcomes of the conclusions we seek to get. I will later demonstrate that the results remain consistent across multiple pressure unit conversions.

That aside, here i covert them all to **bar**, using the relevant calculations outlined in Table 1.

$\text{kPa} \xrightarrow{\times 0.01} \text{Bar}$

kPa +	kPa -	Bar +	Bar -
0	0	0	0
5.7	-5.6	0.06	-0.06
10.4	-12.1	0.10	-0.12
16.0	-18.0	0.16	-0.18
21.1	-21.8	0.21	-0.22
27.7	-25.4	0.28	-0.25
34.2	-29.3	0.34	-0.29
40.0	-33.6	0.40	-0.34
46.1	-37.6	0.46	-0.38
52.2	-41.7	0.52	-0.42

$\text{psi} \xrightarrow{\times 0.0689} \text{Bar}$

psi +	psi -	Bar +	Bar -
0	0	0	0
1.0	-0.8	0.07	-0.06
1.6	-1.7	0.11	-0.12
2.4	-3.2	0.17	-0.22
3.1	-4.0	0.21	-0.28
4.0	-5.2	0.28	-0.36
5.0	-7.2	0.34	-0.5
5.8	-8.3	0.4	-0.57
6.6	-9.5	0.46	-0.66
7.5	-10.7	0.52	-0.74

$\text{kN/m}^2 \xrightarrow{\times 0.01} \text{Bar}$

kN/m² +	kN/m² -	Bar +	Bar -
0.0	0.0	0	0
7.0	-3.5	0.07	-0.04
13.0	-11.5	0.13	-0.12
19.0	-17.5	0.19	-0.18
24.0	-22.5	0.24	-0.23
29.0	-25.5	0.29	-0.26
38.0	-29.5	0.38	-0.30
44.0	-34.5	0.44	-0.35
49.0	-38.5	0.49	-0.39
56.0	-42.5	0.56	-0.43

$\text{cm Hg} \xrightarrow{\times 0.01333} \text{Bar}$

cm Hg +	cm Hg -	Bar +	Bar -
0	0	0	0
3.1	-1.1	0.04	-0.01
4.9	-4.1	0.07	-0.05
7.0	-5.8	0.09	-0.08
9.0	-7.2	0.12	-0.10
11.2	-8.6	0.15	-0.11
13.8	-10.0	0.18	-0.13
16.0	-11.7	0.21	-0.16
18.3	-13.2	0.24	-0.18
20.6	-14.8	0.27	-0.20

Final Data-Set

Pressure Calibrator

Bar	
+	-
0	0
0.06	-0.06
0.10	-0.12
0.16	-0.18
0.21	-0.22
0.28	-0.25
0.34	-0.29
0.40	-0.34
0.46	-0.38
0.52	-0.42

Table 12: Pressure Calibrator as bar

Pressure measuring instruments

Bar	
+	-
0	0
0.07	-0.06
0.11	-0.12
0.17	-0.22
0.21	-0.28
0.28	-0.36
0.34	-0.50
0.4	-0.57
0.46	-0.66
0.52	-0.74

Table 13: Bourdon Gauge 1 as bar

Bar	
+	-
0	0
0.07	-0.04
0.13	-0.12
0.19	-0.18
0.24	-0.23
0.29	-0.26
0.38	-0.30
0.44	-0.35
0.49	-0.39
0.56	-0.43

Table 14: Bourdon Gauge 2 as bar

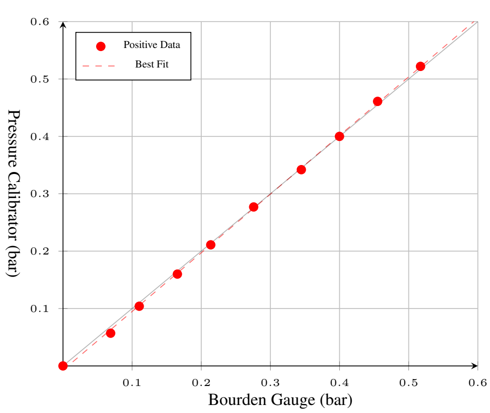
Bar	
+	-
0	0
0.05	-0.05
0.09	-0.11
0.15	-0.19
0.20	-0.22
0.27	-0.25
0.34	-0.30
0.40	-0.35
0.45	-0.39
0.52	-0.44

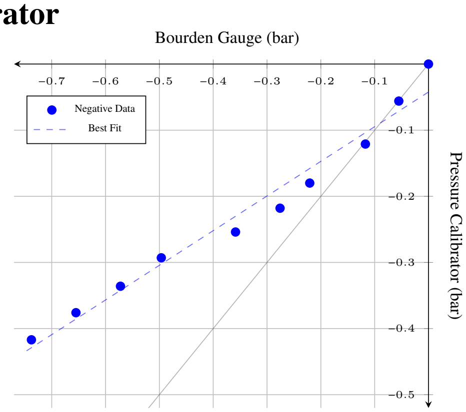
Table 15: Budenberg

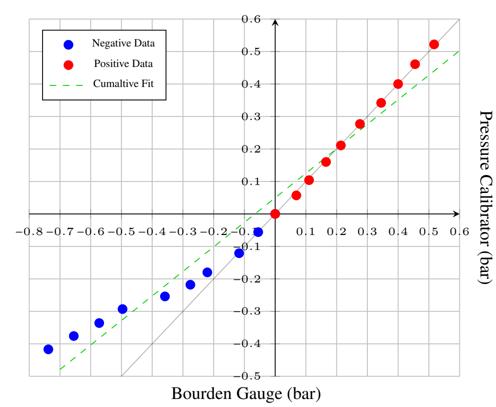
Bar	
+	-
0	0
0.04	-0.01
0.07	-0.05
0.09	-0.08
0.12	-0.10
0.15	-0.11
0.18	-0.13
0.21	-0.16
0.24	-0.18
0.27	-0.20

Table 16: Hg Glass as bar

5.1 Borden Gauge 1 vs Calibrator







Positive, best-fit equation:

$$y = 1.0224x - 0.0074$$

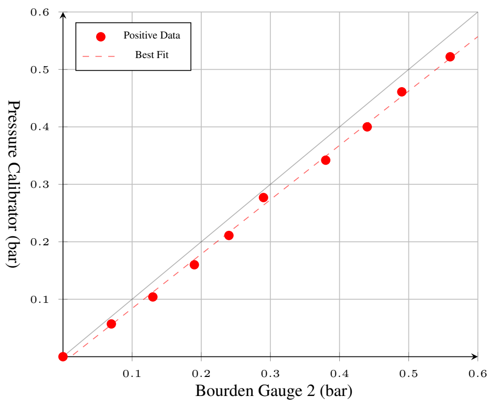
Negative, best-fit equation:

$$y = 0.5241x - 0.0423$$

Cumulative, best-fit equation:

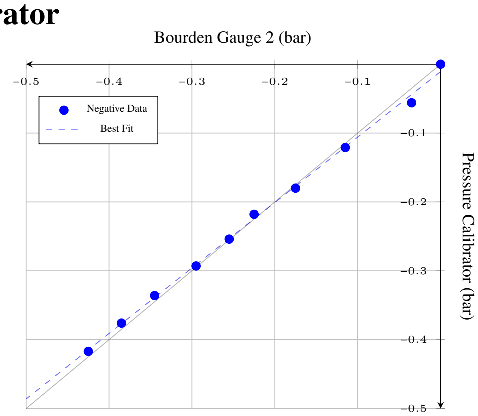
$$y = 0.7554x + 0.0496$$

5.2 Borden Gauge 2 vs Calibrator



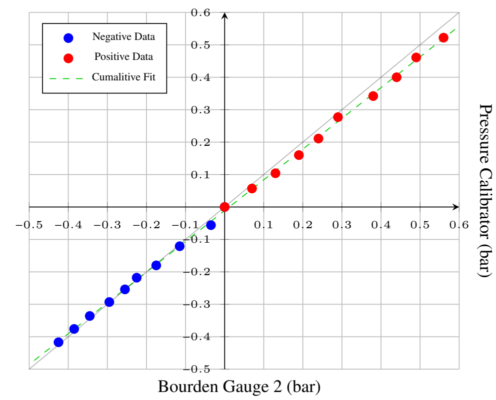
Positive, best-fit equation:

$$y = 0.9462x - 0.0106$$



Negative, best-fit equation:

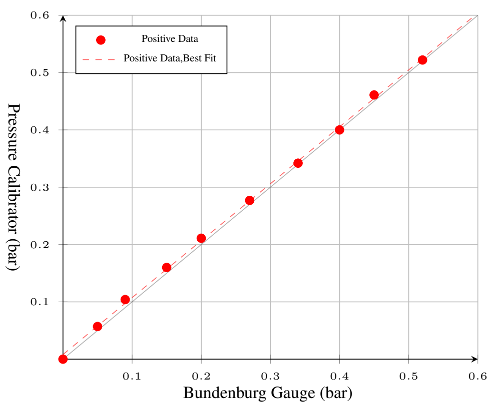
$$y = 0.9509x - 0.0107$$



Cumulative, best-fit equation:

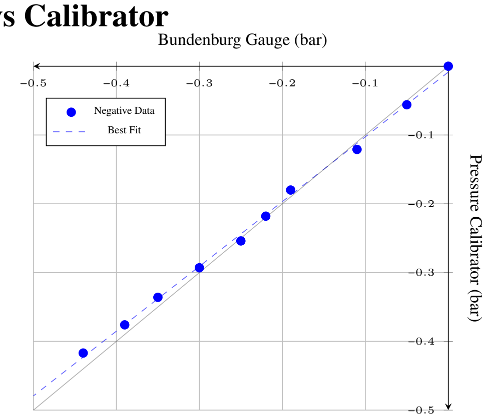
$$y = 0.9483x - 0.0112$$

5.3 Bundenburg Gauge bar vs Calibrator



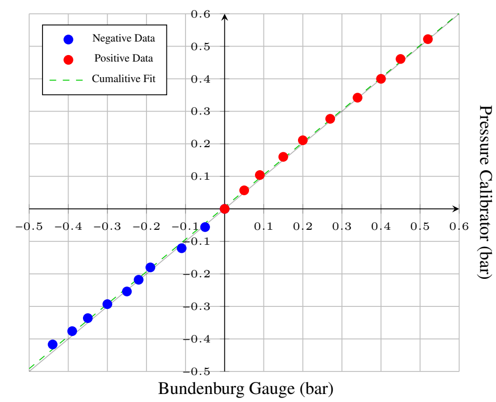
Positive, best-fit equation:

$$y = 0.9932x + 0.0081$$



Negative, best-fit equation:

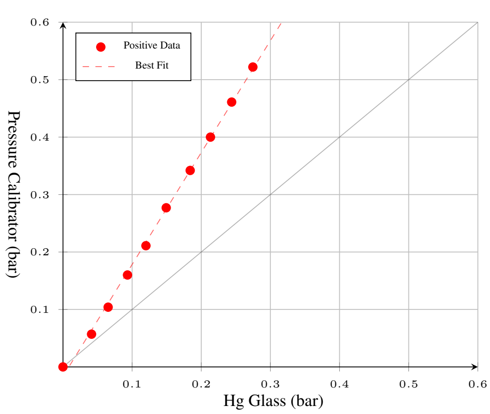
$$y = 0.9416x - 0.0085$$



Cumulative, best-fit equation:

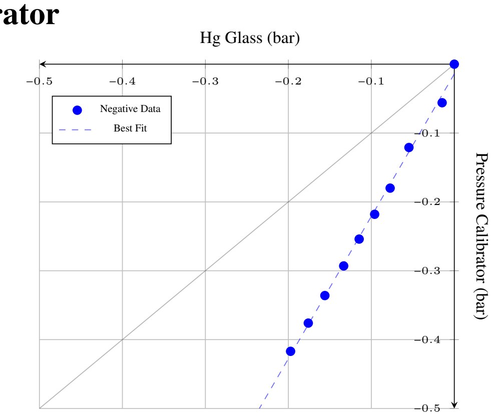
$$y = 0.9941x + 0.0057$$

5.4 Hg Manometer vs Calibrator



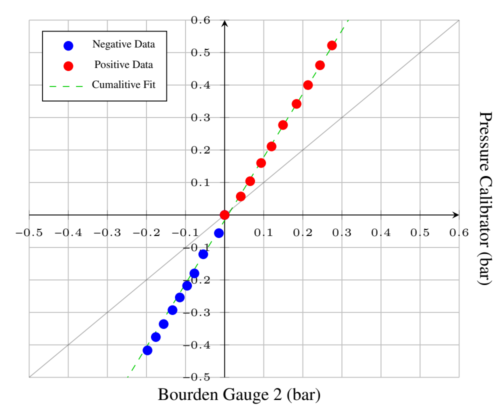
Positive, best-fit equation:

$$y = 1.9488x - 0.0166$$



Negative, best-fit equation:

$$y = 2.0679x - 0.0142$$



Cumulative, best-fit equation:

$$y = 1.9488x - 0.0166$$

5.5 Percentage errors

Since the desired ideal value for the gradient is 1, we can calculate the percentage error using the following formula:

$$\%\text{Error} = \frac{\text{Value} - \text{Ideal}}{\text{Ideal}} \times 100 \qquad \text{Eq. 4}$$

Gauge	Pressurized		Vacuum		Cumulative	
Borden Gauge 1	1.0224	2.24%	0.5241	-47.59%	0.7554	-24.46%
Borden Gauge 2	0.9462	-5.38%	0.9509	-4.91%	0.9483	-5.17%
Bundenburg Gauge	0.9932	-0.68%	0.9416	-5.84%	0.9941	-0.59%
Hg Manometer	1.9488	94.88%	2.0679	106.79%	1.9488	94.88%

Table 17: Gradients of Best-Fit Equations for Different Gauges

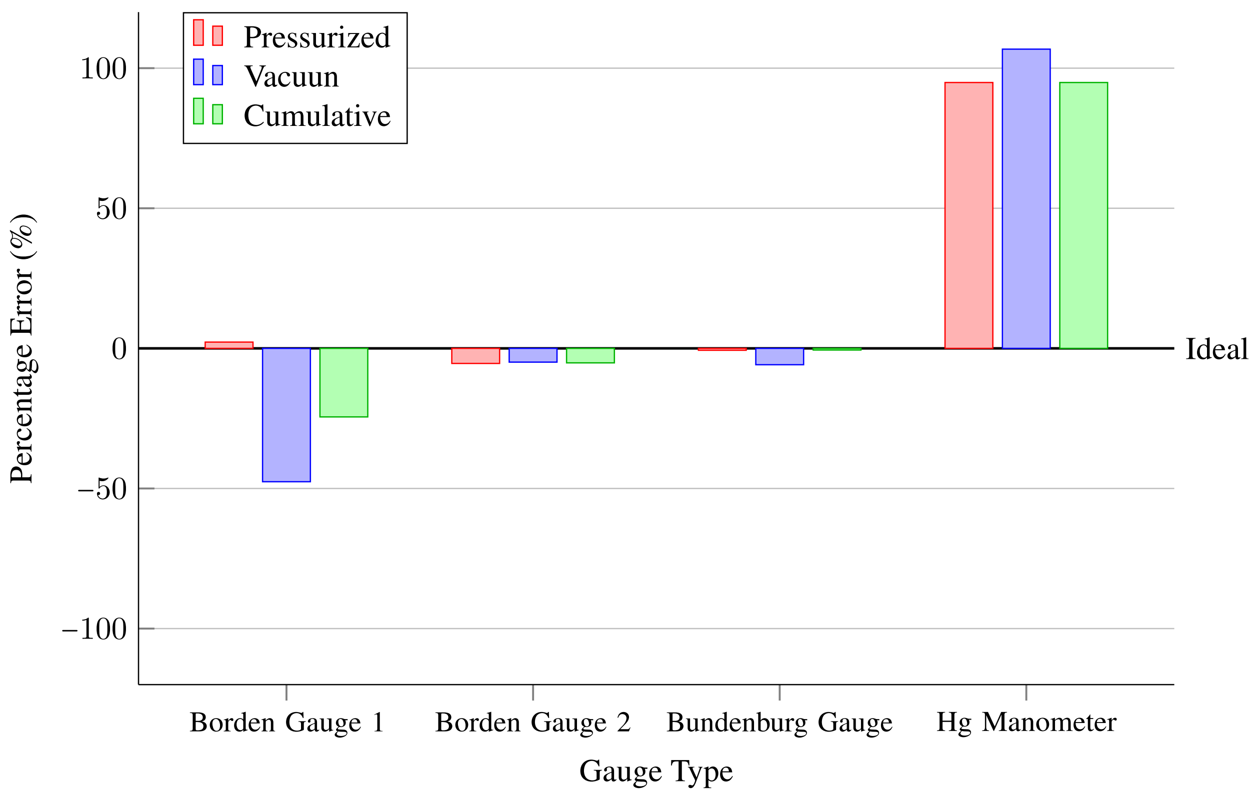


Figure 12: Percentage errors bar chart for gauge measurements

6 Discussion of Results

7 Conclusions

8 Recommendations

9 References

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10 Appendix