# Pressure Measurement

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## Introduction

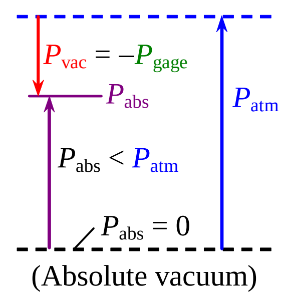
- ***Pressure*** is defined as *the normal force exerted by a fluid per unit area*.
- In this learning module, we discuss various ways to measure pressure.

## Dimensions, units, and conversion factors for pressure

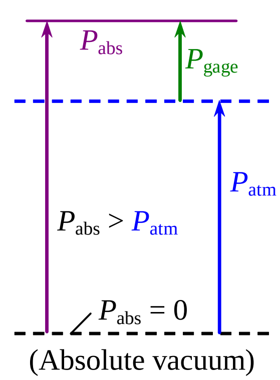
- The dimensions of pressure are $\{P\} = \{\text{pressure}\} = \left\{\dfrac{\text{force}}{\text{area}}\right\} = \left\{\dfrac{\text{mL/t}^2}{\text{L}^2}\right\}$, or $\boxed{\{P\} = \left\{\dfrac{\text{m}}{\text{Lt}^2}\right\}}$.
- In the metric (SI) system, the pressure unit is the ***pascal*** (Pa), where $\boxed{1\ \text{Pa} = 1\ \text{N/m}^2}$. But since a pascal is a very small unit, the ***kilopascal*** (kPa) is more popular. $\boxed{1\ \text{kPa} = 1000\ \text{Pa}}$.
- In the English system, the pressure unit is ***pound-force per square inch*** (psi), where $\boxed{1\ \text{psi} = 1\ \text{lbf/in}^2}$.
- In either unit system, another popular unit of pressure is ***standard atmosphere*** (atm), defined as the pressure at standard temperature and pressure at sea level, $\boxed{1\ \text{atm} = 101{,}325\ \text{Pa} = 14.696\ \text{psi}}$.
- Pressure is often expressed as a ***head***, which is *pressure expressed as an equivalent column height of a liquid*, as discussed below. For example, it is common to hear someone say something like "The pressure is 3.2 inches of water." What this means is that the pressure is high enough to push a column of water up 3.2 in.
- Here are some ***unity conversion factors*** for pressure: $\boxed{\left(\dfrac{1\ \text{psi}}{6.89476\ \text{kPa}}\right) = 1}$, $\boxed{\left(\dfrac{1\ \text{atm}}{760\ \text{mm Hg at }0^\circ\text{C}}\right) = 1}$,
$\boxed{\left(\dfrac{1\ \text{psi}}{144\ \text{lbf/ft}^2}\right) = 1}$, $\boxed{\left(\dfrac{0.1333\ \text{kPa}}{1\ \text{mm Hg at }0^\circ\text{C}}\right) = 1}$, $\boxed{\left(\dfrac{1\ \text{atm}}{29.92\ \text{in Hg at }30^\circ\text{F}}\right) = 1}$, and $\boxed{\left(\dfrac{0.2490\ \text{kPa}}{1\ \text{in H}_2\text{O at }20^\circ\text{C}}\right) = 1}$.

## Absolute, gage, and vacuum pressure

- The pressure you are used to using in thermodynamics is the ***absolute pressure*** ($P$ or $P_{abs}$), defined as *pressure measured relative to absolute vacuum* (absolute zero pressure). Some pressure measuring devices measure absolute pressure.



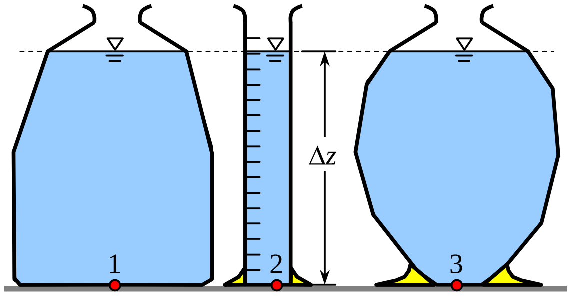

- Many pressure measuring devices, however, measure instead the ***gage pressure*** ($P_{gage}$), defined as *pressure measured relative to the local atmospheric pressure* ($P_{atm}$). An alternative definition of gage pressure is *the difference between absolute pressure* ($P_{abs}$) *and local atmospheric pressure* ($P_{atm}$).
- In equation form, the relationship between absolute and gage pressure is $\boxed{P_{gage} = P_{abs} - P_{atm}}$.
- Gage pressure can be positive or negative, depending on whether the absolute pressure is, respectively, greater than or less than the local atmospheric pressure.



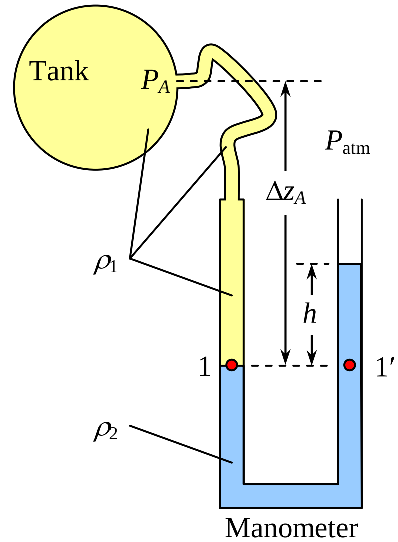

- When the absolute pressure is below atmospheric pressure, some engineers use ***vacuum pressure*** ($P_{vac}$), defined as *the difference between local atmospheric pressure* ($P_{atm}$) *and absolute pressure* ($P_{abs}$).
- In equation form, $\boxed{P_{vac} = P_{atm} - P_{abs}}$. Thus, comparing $P_{gage}$ and $P_{vac}$, $\boxed{P_{vac} = -P_{gage}}$.
- Absolute, gage, and vacuum pressures are illustrated in the sketches to the right for two cases: The top case is for $P_{abs} < P_{atm}$, and the bottom case is for $P_{abs} > P_{atm}$.
  - For the top case ($P_{abs} < P_{atm}$), $P_{gage}$ is negative and $P_{vac}$ is positive.
  - For the bottom case ($P_{abs} > P_{atm}$), $P_{gage}$ is positive and $P_{vac}$ is generally not defined since it would be negative.
- Some engineers like to indicate whether the pressure is absolute, gage, or vacuum by the *units* rather than by using a subscript on $P$. For example, in the English system, $P_{gage}$ = 12.0 psi may be expressed as $P$ = 12.0 psi gage or $P$ = 12.0 psig, and $P_{abs}$ = 26.7 psi may be expressed as $P$ = 26.7 psi absolute or $P$ = 26.7 psia.
- Similarly, in SI units, $P_{vac}$ = 99.8 kPa may be expressed instead as $P$ = 99.8 kPa vacuum. In this case, if local atmospheric pressure $P_{atm}$ = 100.2 kPa, the gage pressure is $P_{gage}$ = –0.4 kPa or $P$ = –0.4 kPa gage.

## Pressure measurement with liquid columns – manometers

- When a liquid is *at rest*, a condition known as ***hydrostatics***, the pressure *does not* change in the *horizontal* direction (*x* or *y*), but it *does* change in the *vertical* direction (*z*).
- In hydrostatics, a simple relationship between two pressures at different elevations *in the same fluid* is $P_{\text{below}} = P_{\text{above}} + \rho g\left|\Delta z\right|$.




- The shape of the container does not matter, as sketched to the right. In this case, our simple equation shows that $P_1 = P_2 = P_3 = P_{\text{atm}} + \rho g \Delta z$ . The pressure at the bottom is the same for all three containers.
- Note that the upside-down triangle at the water surface indicates that the surface is exposed to atmospheric pressure.
- The above relationship enables us to design a simple device to measure pressure – by using a column height of liquid. Devices that measure pressure this way are called ***manometers***.

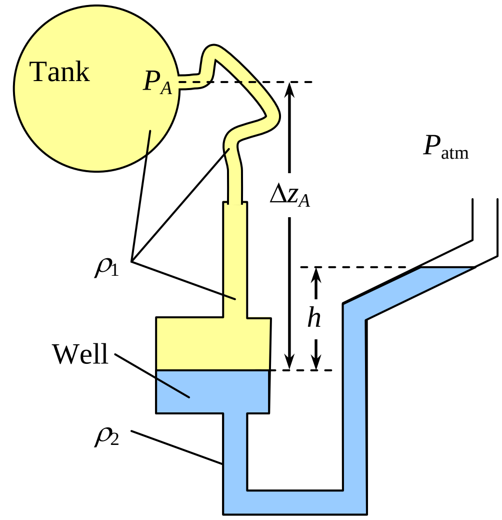



- The simplest manometer is a ***U-tube manometer***, as sketched to the right. It consists of a U-shaped tube (usually made out of glass or clear plastic) that is partially filled with a liquid of density $\rho_2$ (blue liquid in the diagram).
- When the two sides of the U-tube manometer are exposed to different pressures, the liquid moves as a plug from one side to the other.
- In the sketch, for example, the left side of the manometer is exposed to a pressurized tank ($P = P_A$), and the right side is exposed to local atmospheric pressure ($P = P_{\text{atm}}$).
- The fluid in the tank and in the left side of the manometer (colored yellow in the diagram) may be a gas or a liquid, with density $\rho_1 < \rho_2$. *Note*: If two liquids are used, they must not be miscible.
- We apply our simple hydrostatics formula to this case to calculate $P_A$:
  - On the left side, between point *A* and point 1, $P_1 = P_A + \rho_1 g \Delta z_A$ .
  - Similarly, on the right side, between the manometer fluid surface (which is at atmospheric pressure) and point 1′, $P_{1'} = P_{\text{atm}} + \rho_2 g h$ .
  - However, because points 1 and 1′ are at the *same* elevation through the *same* fluid in *hydrostatics*, $P_{1'} = P_1$. Thus, $P_A = P_1 - \rho_1 g \Delta z_A$ or $P_A = P_{\text{atm}} + \rho_2 g h - \rho_1 g \Delta z_A$.


- In many cases, fluid 1 is very light compared to fluid 2 (e.g., air and water or air and mercury). In such cases we may neglect the hydrostatic pressure change in fluid 1. In this example, the above equation simplifies to $P_A \approx P_{\text{atm}} + \rho_2 g h$ or, in terms of gage pressure, $P_{A,\text{gage}} \approx \rho_2 g h$.
- With pressure expressed as a column height of liquid, as above, elevation *h* is called the ***head***.
- Since manometer head is easily visible, a U-tube manometer is often used to monitor flow rates. For example, in the photo to the right (from Tom Lenker), a U-tube manometer is used to check that air is flowing though a pipe used to remove radon gas from the basement of a house. [The air is obviously flowing.]

- For measurement of large pressures, the U-tube manometer must be tall, and this was a serious issue in the days before mechanical pressure measurement instruments were developed. The cupula on the building shown here, for example (at Alden Labs in Holden, MA, courtesy of David Schowalter) was built to accommodate a very tall manometer.

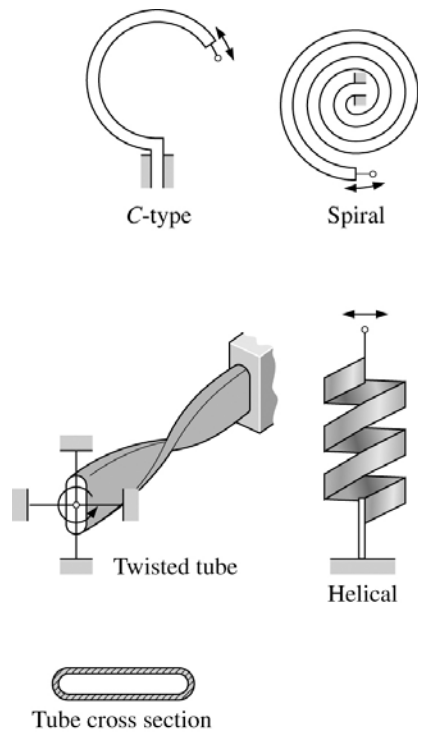
- To get more resolution from a U-tube manometer, one of the legs is often inclined at some shallow angle, as sketched to the right. This device is called an ***inclined U-tube manometer***.
- Compared to the previous manometer, we see that all the elevations are the same. So what is the advantage? *We can measure a finer vertical resolution on an inclined tube compared to a vertical tube*, since the ruler is placed at an angle.
- Oftentimes, a ***well*** is placed on one side of the manometer for convenience, as sketched here on the left side. Such a manometer is called a ***well-type manometer***. The cross-sectional area of the well is much greater than that of the tube on the right side, so that the liquid level in the well stays nearly constant as pressure $P_A$ is varied. This enables the user to read $h$ from a known zero reference point (which is adjustable).



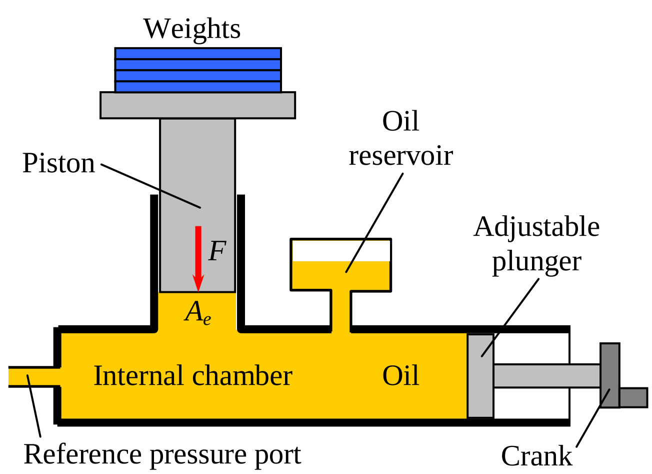

Well-type inclined manometer

**Mechanical pressure gages**

- Many types of mechanical pressure gages have been invented. *Mechanical pressure gages do not require electricity* – they work by purely mechanical means.
- Among mechanical pressure gages, the most common is the ***Bourdon tube***, several varieties of which are sketched to the right.
  - The Bourdon tube itself is a flattened hollow metal tube that is coiled, bent, or twisted.
  - In all cases, one end of the Bourdon tube is open, fixed in position, and exposed to the pressure being measured.
  - The other end is sealed, but connected (sometimes through complex linkages) to the dial of a pressure gage.
  - When the open end is exposed to a reference pressure (typically atmospheric pressure), the scale is set (calibrated) to read zero.
  - When the pressure rises inside the Bourdon tube, it uncoils, unbends, or untwists, and the dial on the pressure gage moves.
  - The pressure gage is calibrated to display pressure in any desired units. The sensitivity of the gage depends on the size, thickness, and stiffness of the Bourdon tube.
  - The reference pressure can be any desired pressure, but usually it is either *atmospheric* (the gage measures *gage pressure*) or a *vacuum* (the gage measures *absolute pressure*).

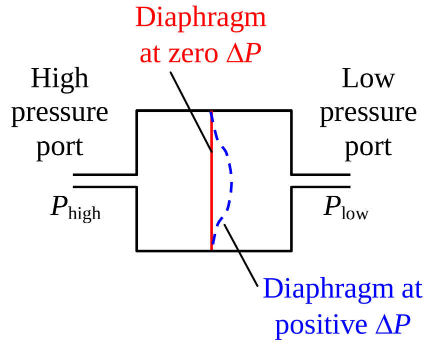



- Another type of mechanical pressure gage is called a ***deadweight tester***.
- Deadweight testers are used primarily for *calibration*, and can measure extremely high pressures (up to 10,000 psi in some applications!).
- As its name implies, a deadweight tester measures pressure *directly* through application of a weight that provides a force per unit area – the fundamental definition of pressure.
- It is constructed with an internal chamber filled with a fluid (usually oil), along with a tight-fitting piston and cylinder, and plunger, as sketched to the right.
  - Weights are applied to the top of the piston, which exerts a force on the oil in the chamber.
  - The total force $F$ acting on the oil at the piston-oil interface is the weight of the piston plus the total weight of the calibration weights.
  - Since the piston cross-sectional area $A_e$ is known, the pressure is calculated as $\boxed{P = F / A_e}$.



- The only significant source of error is that due to static friction along the interface between the piston and cylinder, but even this error is usually negligibly small.
- A reference pressure port (on the left side in the above sketch) is connected to either an unknown pressure that is to be measured, or to a pressure sensor that is to be calibrated.

**Electronic pressure transducers**




- The general term used for pressure sensors that employ some kind of electronics is ***pressure transducer***.
- Many varieties of electronic pressure transducers are available, but the most common is the ***diaphragm transducer***, in which *the difference in pressure from one side of the diaphragm to the other causes the diaphragm to deform*, as sketched to the right.
- The diaphragm itself is usually a thin, metal, circular plate that is held firmly about its circumference.
- When pressure is applied on one side, it deforms as sketched, much like a trampoline with a weight on it.
- Obviously, various ranges of pressure can be measured, depending on the thickness and elastic properties of the diaphragm (thick diaphragms for large pressures and thin diaphragms for small pressures).
- To obtain pressure, the amount of deformation of the diaphragm must be measured, and calibrated to give an electrical output (voltage or current) that is proportional to the applied pressure.
- The low pressure port determines the type of pressure measurement:
  - If the low port is connected to some pressure $P_{low}$ in the system, the device is called a ***differential pressure transducer***. It measures the pressure difference between $P_{high}$ and $P_{low}$.
  - If the low port is connected to a known reference pressure ($P_{low} = P_{ref}$), the device measures pressure relative to the reference pressure.
    - A common reference pressure is zero ($P_{low} = 0$) – the right chamber in the above sketch is sealed off after a vacuum is drawn in the chamber. This is an ***absolute pressure transducer***.
    - Another common reference pressure is atmospheric ($P_{low} = P_{atm}$) – the right chamber in the above sketch is open to the atmosphere. This is a ***gage pressure transducer***.
- There are various ways to measure the deflection or deformation of the diaphragm. In all cases, the electrical signal must be calibrated to yield a pressure reading. In addition, a zeroing mechanism is usually provided.
  - Strain gage – a strain gage is mounted on the diaphragm, sensing strain in the deforming diaphragm.
  - Capacitance – the diaphragm is mounted close to a fixed parallel plate, across which the capacitance is measured. As the diaphragm deforms, the capacitance changes.
  - LVDT – a small rod is mounted on the diaphragm, and it is attached to the core of a linear variable displacement transducer.
  - Optical – various optical techniques can also be used to measure the degree of diaphragm deformation.

**Piezoelectric pressure transducers**

- Piezoelectric transducers work on the principle that a ***piezoelectric crystal*** develops an *electric charge that is proportional to an applied compression or tension force*. In simple language, when you press on it, it produces an electrical current that can be measured and calibrated to read applied pressure.
- Nowadays, ***piezoelectric pressure transducers*** have become very common because they are rugged, small, and inexpensive. They also have good dynamic response, and can be used for dynamic (fluctuating) pressure measurements.

- Piezoelectric transducers are used for more than measuring pressure:
- They are used as pickups on string instruments such as violins, cellos, and acoustic guitars (see pictures to the right).
- They are used in pulse-echo ultrasonic transducers. In this case, the piezo element both creates and senses the vibrations of the ultrasonic waves.
- There are some applications in which piezoelectric materials are actually used to generate power – e.g., on dance floors!