

Understanding Pressure and Pressure Measurement

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Introduction

Fluid systems, pressure and pressure measurements are extremely complex. The typical college curriculum for Mechanical Engineers includes at least two semesters in fluid mechanics. This paper will define and explain the basic concepts of fluid mechanics in terms that are easily understood while maintaining the necessary technical accuracy and level of detail.

Pressure and Pressure Measurement

What is fluid pressure? Fluid pressure can be defined as the measure of force per-unit-area exerted by a fluid, acting perpendicularly to any surface it contacts (a fluid can be either a gas or a liquid, fluid and liquid are not synonymous). The standard SI unit for pressure measurement is the Pascal (Pa) which is equivalent to one Newton per square meter (N/m^2) or the KiloPascal (kPa) where $1\text{ kPa} = 1000\text{ Pa}$. In the English system, pressure is usually expressed in pounds per square inch (psi). Pressure can be expressed in many different units including in terms of a height of a column of liquid. The table below lists commonly used units of pressure measurement and the conversion between the units.

	kPa	mm Hg	millibar	in H2O	PSI
1 atm	101.325	760.000	1013.25	406.795	14.6960
1 kPa	1.000	7.50062	10.000	4.01475	0.145038
1 mm Hg	0.133322	1.000	1.33322	0.535257	0.0193368
1 millibar	0.1000	0.750062	1.000	0.401475	0.0145038
1 in H2O	0.249081	1.86826	2.49081	1.000	0.0361
1 PSI	6.89473	51.7148	68.9473	27.6807	1.000
1 mm H2O	0.009806	0.07355	9.8×10^{-8}	0.03937	0.0014223

Figure 1. Conversion Table for Common Units of Pressure

Pressure measurements can be divided into three different categories: *absolute pressure*, *gage pressure* and *differential pressure*. *Absolute pressure* refers to the absolute value of the force per-unit-area exerted on a surface by a fluid. Therefore the absolute pressure is the difference between the pressure at a given point in a fluid and the absolute zero of pressure or a perfect vacuum. *Gage pressure* is the measurement of the difference between the absolute pressure and the local atmospheric pressure. Local atmospheric pressure can vary depending on ambient temperature, altitude and local weather conditions. The U.S. standard atmospheric pressure at sea level and 59°F (20°C) is 14.696 pounds per square inch absolute (psia) or 101.325 kPa absolute (abs). When referring to pressure measurement, it is critical to specify what reference the pressure is related to. In the English system of units, measurement relating the pressure to a reference is accomplished by specifying pressure in terms of pounds per square inch absolute (psia) or pounds per square inch gage (psig). For other units of measure it is important to specify gage or absolute. The abbreviation 'abs' refers to an absolute measurement. A gage pressure by convention is always positive. A 'negative' gage pressure is defined as vacuum. Vacuum is the measurement of the amount by which the local atmospheric pressure exceeds the absolute pressure. A perfect vacuum is zero absolute pressure. Figure 2 shows the relationship between absolute, gage pressure and vacuum. *Differential pressure* is simply the measurement of one unknown pressure with reference to another unknown pressure. The pressure measured is the difference between the two unknown pressures. This type of pressure measurement is commonly used to measure the pressure drop in a fluid system. Since a differential pressure is a measure of one pressure referenced to another, it is not necessary to specify a pressure reference. For the English system of units this could simply be psi and for the SI system it could be kPa.

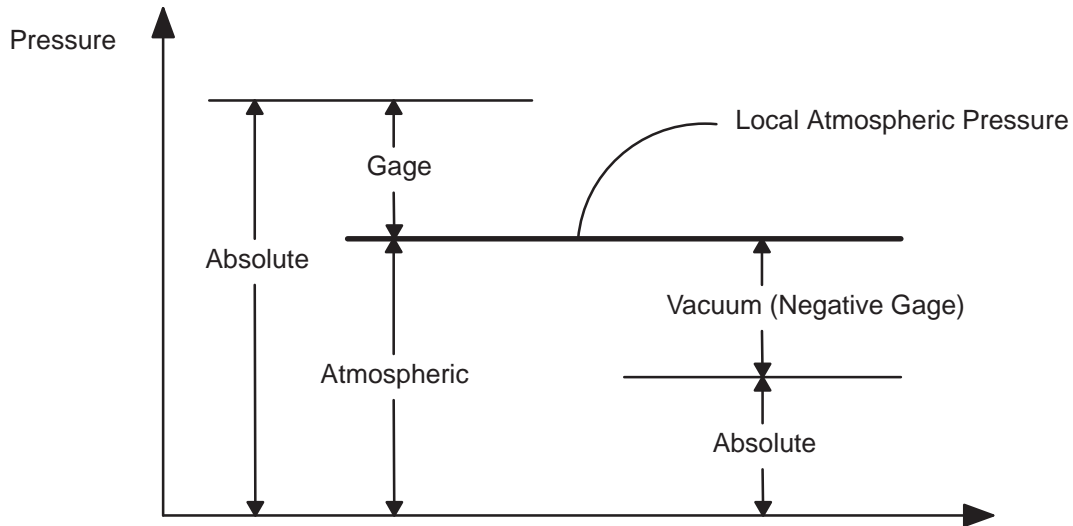


Figure 2. Pressure Term Relationships

In addition to the three types of pressure measurement, there are different types of fluid systems and fluid pressures. There are two types of fluid systems; *static systems* and *dynamic systems*. As the names imply, a static system is one in which the fluid is at rest and a dynamic system is one in which the fluid is moving.

Static Pressure Systems

The pressure measured in a static system is *static pressure*. In the pressure system shown in Figure 3, a uniform static fluid is continuously distributed with the pressure varying only with vertical distance. The pressure is the same at all points along the same horizontal plane in the fluid and is independent of the shape of the container. The pressure increases with depth in the fluid and acts equally in all directions. The increase in pressure at a deeper depth is essentially the effect of the weight of the fluid above that depth. Figure 4 shows two containers with the same fluid exposed to the same external pressure – P . At any equal depth within either tank the pressure will be the same. Note that the sides of the large tank are not vertical. The pressure is dependent only on depth and has nothing to do with the shape of the container. If the working fluid is a gas, the pressure increase in the fluid due to the height of the fluid is in most cases negligible since the density and therefore the weight of the fluid is much smaller than the pressure being applied to the system. However, this may not remain true if the system is large enough or the pressures low enough. One example considers how atmospheric pressure changes with altitude. At sea level the standard U.S. atmospheric pressure is 14.696 psia (101.325 kPa). At an altitude of 10,000 ft (3048 m) above sea level the standard U.S. atmospheric pressure is 10.106 psia (69.698 kPa) and at 30,000 ft (9144 m), the standard U.S. atmospheric pressure is 4.365 psia (30.101 kPa).

The pressure in a static liquid can be easily calculated if the density of the liquid is known. The absolute pressure at a depth H in a liquid is defined as:

$$P_{abs} = P + (\rho \times g \times H)$$

Where :

P_{abs} is the absolute pressure at depth H .

P is the external pressure at the top of the liquid. For most open systems this will be atmospheric pressure.

ρ is the density of the fluid.

g is the acceleration due to gravity ($g = 32.174 \text{ ft/sec}^2$ (9.81 m/sec^2)).

H is the depth at which the pressure is desired.

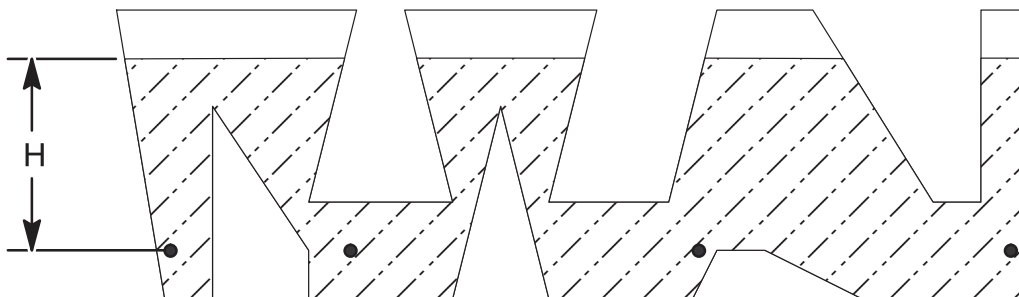


Figure 3. Continuous Fluid System

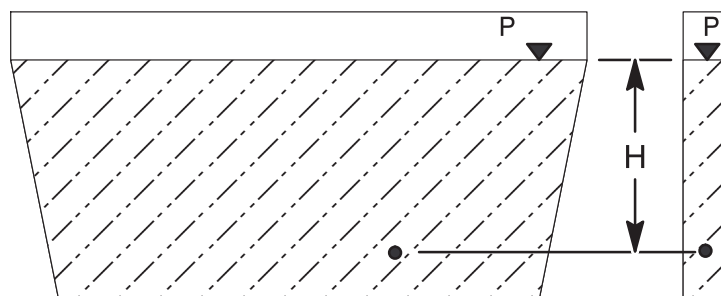


Figure 4. Pressure Measurement at a Depth in a Liquid

Dynamic Pressure Systems

Dynamic pressure systems are more complex than static systems and can be more difficult to measure. In a dynamic system, pressure typically is defined using three different terms. The first pressure we can measure is *static pressure*. This pressure is the same as the static pressure that is measured in a static system. Static pressure is independent of the fluid movement or flow. As with a static system the static pressure acts equally in all directions. The second type of pressure is what is referred to as the *dynamic pressure*. This pressure term is associated with the velocity or the flow of the fluid. The third pressure is *total pressure* and is simply the static pressure plus the dynamic pressure.

Steady-State Dynamic Systems

Care must be taken when measuring dynamic system pressures. For a dynamic system, under steady-state conditions, accurate static pressures may be measured by tapping into the fluid stream perpendicular to the fluid flow. For a dynamic system, steady-state conditions are defined as no change in the system flow conditions: pressure, flow rate, etc. Figure 5 illustrates a dynamic system with a fluid flowing through a pipe or duct. In this example a static pressure tap is located in the duct wall at point A. The tube inserted into the flow is called a Pitot tube. The Pitot tube measures the total pressure at point B in the system. The total pressure measured at this point is referred to as the *stagnation pressure*. The stagnation pressure is the value obtained when a flowing fluid is decelerated to zero velocity in an isentropic (frictionless) process. This process converts all of the energy from the flowing fluid into a pressure that can be measured. The stagnation or total pressure is the static pressure plus the dynamic pressure. It is very difficult to accurately measure dynamic pressures. When dynamic pressure measurement is desired, the total and static pressures are measured and then subtracted to obtain the dynamic pressure. Dynamic pressures can be used to determine the fluid velocities and flow rates in dynamic systems.

When measuring dynamic system pressures, care must be taken to ensure accuracy. For static pressure measurements, the pressure tap location should be chosen so that the measurement is not influenced by the fluid flow. Typically, taps are located perpendicular to the flow field. In Figure 5, the static pressure tap at point A is in the wall of the duct and perpendicular to the flow field. In Figures 6a and 6c the static taps (point A) in the pressure probes are also perpendicular to the flow field. These examples show the most common type of static pressure taps, however there are many different static pressure tap options. For total or stagnation pressure measurements, it is important that the Pitot or impact tube be aligned parallel to the flow field with the tip of the tube pointing directly into the flow. In Figures 6b and 6c, the Pitot tube is aligned parallel with the flow, with the tube opening pointing directly into the flow. Although the static pressure is independent of direction, the dynamic pressure is a vector quantity which depends on both magnitude and direction for the total measured value. If the Pitot tube is misaligned with the flow, accuracy of the total pressure measurement may suffer. In addition, for accurate pressure measurements the pressure tap holes and probes must be smooth and free from any burrs or obstructions that could cause disturbances in the flow. The location of the pressure

AN1573

taps and probes, static and total, must also be selected carefully. Any location in the system where the flow field may be disturbed should be avoided, both upstream and downstream. These locations include any obstruction or change such as valves, elbows, flow splits, pumps, fans, etc. To increase the accuracy of pressure measurement in a dynamic system, allow at least 10 pipe / duct diameters downstream of any change or obstruction and at least 2 pipe / duct diameters upstream. In addition the pipe / duct diameter should be much larger than the diameter of the Pitot tube. The pipe / duct diameter should be at least 30 times the Pitot tube diameter. Flow straighteners can also be used to minimize any variations in the direction of the flow. Also, when using a Pitot tube, it is recommended that the static pressure tap be aligned in the same plane as the total pressure tap. On the Pitot–static tube, the difference in location is assumed to be negligible.

Flow-through pipes and ducts will result in a velocity field and dynamic pressure field that are non-uniform. At the wall of any duct or pipe there exists a no-slip boundary due to friction. This means that at the wall itself the velocity of the fluid is zero. Figure 5 shows an imaginary velocity distribution in a duct. The shape of the distribution will depend on the fluid conditions, system flow and pressure. In order to accurately determine the average dynamic pressure across a duct section, a series of total pressure readings must be taken across the duct. These pressure measurements should be taken at different radii and clock positions across the cross section of a round duct or at various width and height locations for a rectangular duct. Once this characterization has been performed for the duct, a correlation can be easily made between the total pressure measurement at the center of the duct relative to the average duct total pressure. This technique is also used to determine the velocity profile within the duct.

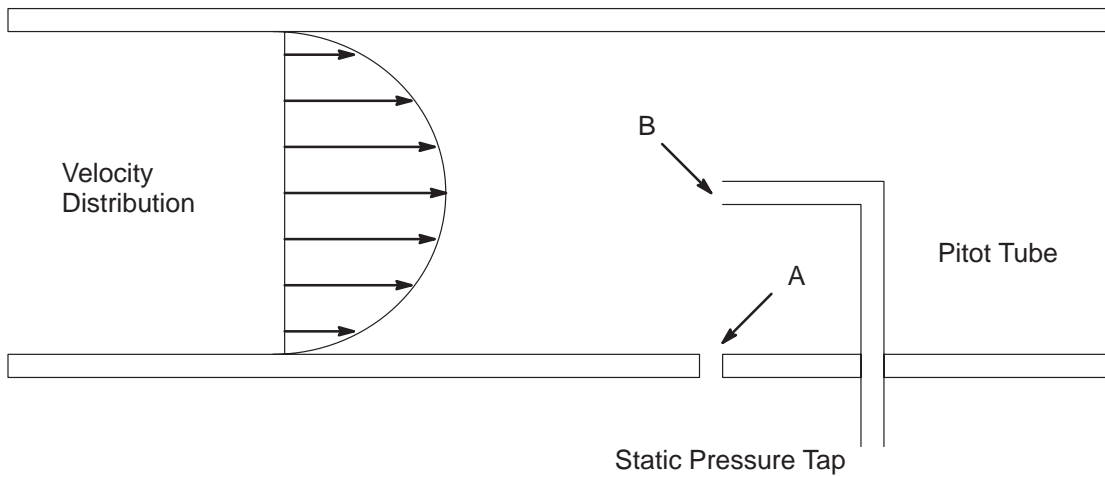


Figure 5. Static and Total Pressure Measurements Within a Dynamic Fluid System.

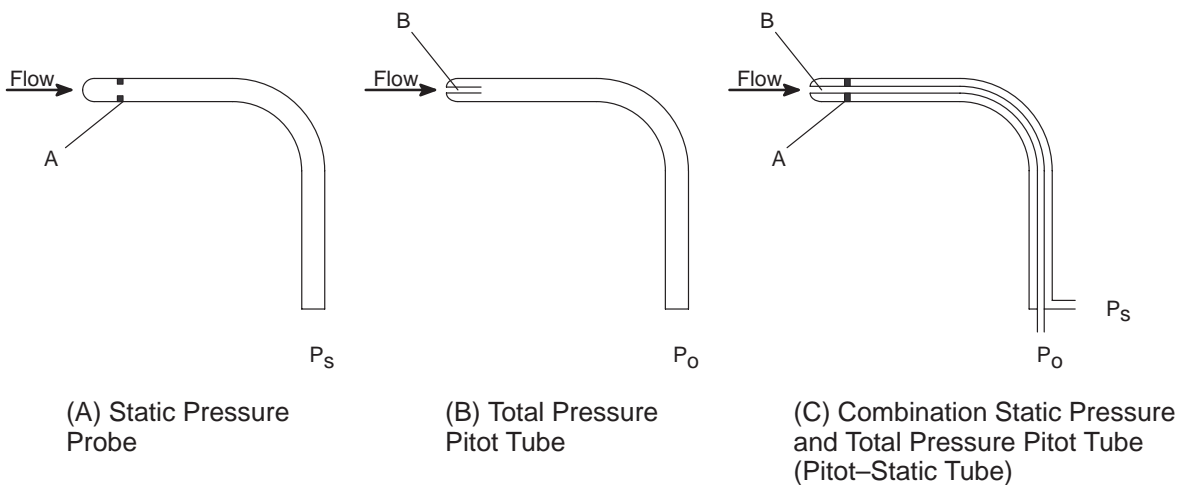


Figure 6. Types of Pressure Probes

Transient Systems

Transient systems are systems with changing conditions such as pressures, flow rates, etc. Measurements in transient systems are the most difficult to accurately obtain. If the measurement system being used to measure the pressure has a faster response time than the rate of change in the system, then the system can be treated as quasi-steady-state. That is, the measurements will be about as accurate as those taken in the steady-state system. If the measurement of the system is assumed to be a snap shot of what is happening in the system, then you want to be able to take the picture faster than the rate of change in the system or the picture will be blurred. In other words, the measurement results will not be accurate. In a pressure measurement system, there are two factors that determine the overall measurement response: (1) the response of the transducer element that senses the pressure, and (2) the response of the interface between the transducer and the pressure system such as the pressure transmitting fluid and the connecting tube, etc. For Motorola pressure sensors, the second factor usually determines the overall frequency response of the pressure measurement system. The vast majority of pressure systems that require measurements today are quasi-steady-state systems where system conditions are changing relatively slowly compared to the response rate of the measurement system or the change happens instantaneously and then stabilizes.

Two transient system examples include washing machines and ventilation ducts in buildings. In a washing machine, the height of the water in the tub is measured indirectly by measuring the pressure at the bottom of the tub. As the tub fills the pressure changes. The rate at which the tub fills and the pressure changes is much slower than the response rate of the measurement system. In a ventilation duct, the pressure changes as the duct registers are opened and closed, adjusting the air movement within the building. As more registers are opened and closed, the system pressure changes. The pressure changes are virtually instantaneous. In this case, pressure changes are essentially incremental and therefore easy to measure accurately except at the instant of the change. For most industrial and building control applications, the lag in the pressure measurement system is negligible. As the control or measurement system becomes more precise, the frequency response of the measurement system must be considered.

Motorola Pressure Sensors


This application note has covered various types of pressures that are measured and how to tap into a system to measure the desired pressures. How are the actual pressure measurements made? There are many types of pressure measurement systems ranging from simple liquid tube manometers to bourdon-tube type gages to piezo-electric silicon based transducers. Today, as electronic control and measurement systems are replacing mechanical systems, silicon-based pressure transducers and sensors are becoming the sensors of choice. Silicon micromachined sensors offer very high accuracies at very low cost and provide an interface between the mechanical world and the electrical system. Motorola carries a complete line of silicon based pressure sensors which feature a wide range of pressures with various levels of integration on a single chip. These levels of integration start with the basic uncompensated, uncalibrated pressure sensor all the way to the fully integrated, temperature compensated, calibrated and signal conditioned pressure sensors. The response time of Motorola's MPX series silicon pressure sensors is typically 1 millisecond or less. For static or dynamic systems, Motorola's pressure sensors are an excellent solution for pressure measurement systems.

Conclusion

Pressures and pressure measurements can be extremely complex and complicated. However, for most systems it is relatively easy to obtain accurate pressure measurements if the proper techniques are used.

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