Tech Brief

Fundamentals of Hydraulics: Pressure

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Summary

Hydraulics is the branch of engineering that focuses on the practical problems of collecting, storing, measuring, transporting, controlling, and using water and other liquids. This *Tech Brief* is the first of two that will discuss some fundamental hydraulic problems and will focus primarily on pressure. The second will discuss flow.

Why is understanding hydraulics important?

The science of hydraulics is as old as civilization itself. For centuries, engineers have succeeded in making water flow from one place to another with as few hitches as possible. When problems do occur, they are usually related to the hydraulics involved in pipe flow.

Liquids in motion produce forces and pressure whenever the velocity, flow direction, or elevation changes. Knowing pipe pressure and flow at certain points along the pipe's path can help determine pipe size and capacity. It also can help in determining what pipe material would work best in given situations. Further, having an understanding of hydraulics can help system managers decide if pressure reducers or pumps are necessary to transport water in an efficient manner. Most small water and wastewater systems do not have an engineer on staff, or even one they can consult, who might be able to answer simple or basic questions about hydraulics. And the cost of engineering advice can quickly add up. Because many small systems are on tight budgets, understanding hydraulics can save money.

Units and Variables

First of all, understanding that water has a unit weight is important. System designers need this information to calculate other variables. The physical and hydraulic behavior of wastewater is so similar to that of clean water that there is generally no difference in the design or analysis of systems involving these two liquids. For practical purposes, water and wastewater are considered to be incompressible liquids because their volume does not change significantly with changing pressure. Water or wastewater has a unit weight of 62.4 pounds per cubic foot (62.4 lb/

ft^3); so, one cubic foot (1ft x 1ft x 1ft) of water weighs 62.4 lbs. There are 7.48 gallons in a cubic foot, with each gallon weighing approximately 8.34 pounds, so 7.48 gal x 8.34 lbs/gal = 62.4 pounds.

In the metric system, the term for weight (force due to gravity) is called a Newton (N), and the unit weight of water is 9,800 Newtons per cubic meter (9,800 N/m^3). More appropriately, this is expressed as 9.8 kilonewtons per cubic meter (9.8 kN/m^3), where the prefix kilo stands for 1,000.

Other important design information:

One pound per square inch (lbs/in^2 or psi) is approximately equal to 2.31 feet of water height (column of water) no matter how big around or square the column is. One foot of water height is approximately equal to 0.434 psi.

Pressure

Water or wastewater exerts force and pressure against the walls of its container, whether it is stored in a tank or flowing in a pipe. But there is a difference between force and pressure, although they are closely related. Specifically, pressure is defined as force per unit area. In U.S. units, pressure is usually expressed in pounds per square inch (lb/in^2 or psi). In SI metric units, pressure is expressed in Newtons per square meter (N/m^2). For convenience, the unit N/m^2 is called a Pascal (Pa). Since a pressure of 1 Pa is a relatively small pressure (1 Pa = 0.000145 psi), the term kilopascal (kPa) will be used in most practical hydraulics applications. 1 kPa = 1000 Pa = 0.145 psi.
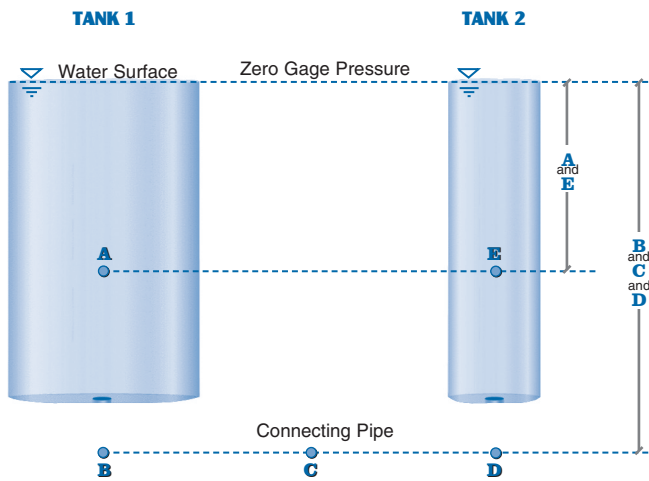
In this equation, pressure can be expressed as:

$$P = F/A$$

Where P = pressure
  F = force
  A = area over which the force is distributed

TANK 1

Water Surface   Zero Gage Pressure

TANK 2

A and E

A

E

B and C and D

Connecting Pipe

B   C   D

Figure 1

The pressure at point A equals the pressure at point E, since these points are at the same depth in the water. Likewise, the hydrostatic pressure at points B, C, D are equivalent.

Hydrostatic Pressure

The pressure water exerts is called *hydrostatic pressure*. These principles always apply to hydrostatic pressure:

1. Pressure depends only on the depth of water above the point in question (not on the water surface area).
2. Pressure increases in direct proportion to the depth of water.
3. Pressure in a continuous volume of water is the same at all points that are at the same depth or elevation.
4. Pressure at any point in the water acts in all directions at the same magnitude.

Consider the two tanks connected by a horizontal pipe shown in Figure 1. The water surfaces in both tanks are at the same elevation. Pressure at the water's surface equals zero.

Pressure also exists at the free surface because of the weight of air above. This pressure is called atmospheric or barometric pressure. Atmospheric pressure at sea level is approximately 14.7 psi or 101 kPa. In practical applications, however, atmospheric pressure is not used for hydraulic calculations and is considered to be a zero reference or starting point. This application is referred to as gauge pressure as opposed to absolute pressure.

Figure 1 shows two storage tanks side by side that have different volumes but are the same height. Many water systems may have encountered this circumstance when they need to upgrade and find that the older tank may be larger than the newer one. This figure expresses that pressure at the same elevations—from a larger diameter (more water storage) to a smaller

diameter storage tank—is still the same. The pressure at point B near the bottom of the tank is greater than the pressure at point A. In application, if point B were exactly twice as deep as point A, the gauge pressure at point B would be exactly twice the pressure at point A because pressure varies in direct proportion to the depth. Again, in Figure 1, consider point E in Tank 2. Since point E is at the same depth below the water surface as point A, the pressure at point E is the same as the pressure at point A. Note that it makes no difference that Tank 2 is narrower than Tank 1. Hydrostatic pressure depends only on the height of water above the points and not on the volume or surface area of the water. Even though point C in the connecting pipe does not have water directly above it, it still has the same pressure as points B and D.

Calculating Pressure

In customary U. S. units, 1 ft^3 of water weighs 62.4 lbs. So a 1-ft depth of water on an area of 1 ft^2, or 144 in^2, the pressure at the bottom would be P = 62.4 lbs/144 in^2 = 0.43 psi per foot of water (lbs/in^2)/ft. This is usually written as:

P = 0.43 x h

Where P = hydrostatic pressure in psi (lbs/in^2)
    h = water depth from surface in ft
    0.43 psi/ft or (lbs/in^2)/ft

In SI-metric units, 1 m^3 of water weighs 9.8 kN. So a 1 meter (m) depth of water on an area of 1 m^2 would have a pressure of 9.8 kN/m^2 or usually written as 9.8 kPa. This can be written as:

P = 9.8 x h

Where P = hydrostatic pressure in kPa or kN/m^2
    h = water depth from surface in meters (m)
    9.8 kPa or (kN/m^2)/m

Example 1

A small water system has an elevated water storage tank and connecting ductile iron pipeline as shown in Figure 2. A typical situation for a small water system operator might be a recurrent leak at point D, the lowest elevation. Patching the pipe with band clamps may no longer be an option and replacing an entire joint or two of the pipe with something other than ductile iron is now necessary. Knowing the pressure at this point in the distribution system will aid in selecting pipe material, such as PVC, that is correctly classified and save money in the long run.

Calculate the hydrostatic pressures at points A, B, C, and D.

Solution

For the above example, the diameter is known because the operator has worked on this pipe in the past. Usually the elevations can be obtained from as-built drawings or maybe topographic maps with some measurements of the tank overflow for maximum water height.

Point A: The depth of water above point A in the tank is

equal to the difference in elevation between the maximum water surface and the tank bottom, or 2000 ft – 1,950 ft = 50 ft. using the above U. S. equation for calculating pressure we get:

$P = 0.43 \times h$
$P = 0.43 \text{ psi/ft} \times 50 \text{ ft}$
$P = 21.5 \text{ psi or lbs/in}^2$

Point B: the total depth of water above point B is 2,000 ft – 1,900 ft = 100 ft. The pressure at point B is:

$P = 0.43 \times h$
$P = 0.43 \text{ psi/ft} \times 100 \text{ ft}$
$P = 43 \text{ psi or lbs/in}^2$

Point C: The pressure at point C is equal to the pressure at point B because these points are at the same elevation.

Pressure at C = Pressure at B = 43 psi

Point D: The total depth of water above point D is 2,000 ft – 1,600 ft = 400 ft. The pressure is:

$P = 0.43 \times h$
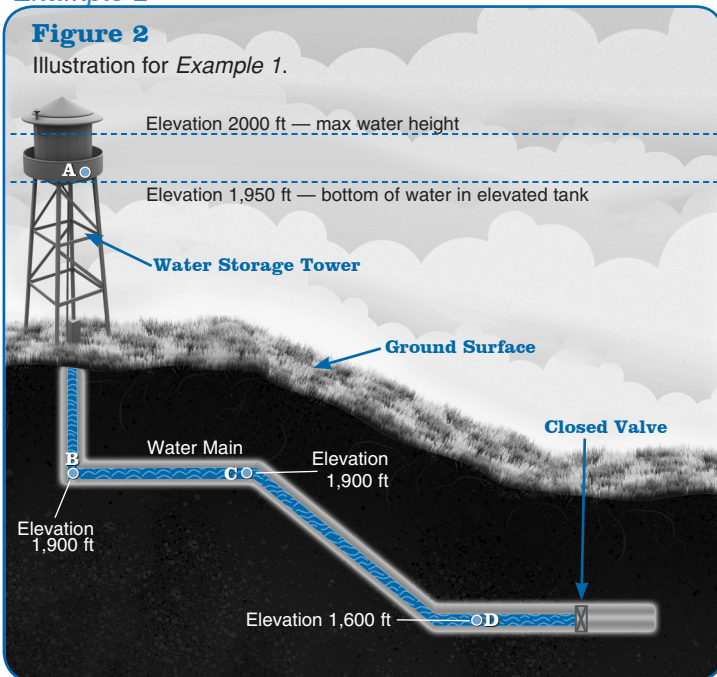$P = 0.43 \text{ psi/ft} \times 400 \text{ ft}$
$P = 172 \text{ psi or lbs/in}^2$

The pressure is 172 psi (this would be the maximum working pressure at Point D) so the pipe class or pressure rating would have to be able to handle a pressure of 172 psi.

Example 2

Figure 2
Illustration for *Example 1*.

Elevation 2000 ft — max water height

A

Elevation 1,950 ft — bottom of water in elevated tank

Water Storage Tower

Ground Surface

Closed Valve

Water Main
B
C
Elevation 1,900 ft
Elevation 1,900 ft

Elevation 1,600 ft — D

Another example an operator might encounter is providing a water-tap for a customer with a house at the top of a hill. The tap and meter are at the bottom of the hill. Most state regulatory agencies or public service commissions require a minimum pressure of approximately 30 psi at the meter at the property line.

In this example, a 6-inch main provides the service line.

The pressure at the water meter well or pit is 48 psi. The house sets on a hill, and, according to the topographic maps, the meter is at elevation 350 feet, and the house is set at elevation of 430 feet. The elevation difference is the problem—not the service line that winds back and forth up the hill, despite the pressure losses due to friction in small diameter service lines (minimal for our concerns in this case).

Calculate the pressure drop from the meter to the house location:

Meter elevation is 350 feet and house elevation is 430 feet

350 ft – 430 ft = h
–80 ft = h

Using the pressure equation:

$P = 0.43 \times h$
$P = 0.43 \times -80 \text{ ft}$
$P = -34.4 \text{ psi of pressure drop}$

In this problem, the house has a bathroom on the second floor. Estimate another 10 feet of elevation to the second floor of the house 430 ft (elevation at first floor) – 440 ft (elevation at second floor) = –10 ft.

So there is an added pressure drop to the second floor of:

$P = 0.43 \times -10 \text{ ft}$
$P = -4.3 \text{ psi additional pressure drop}$

Total pressure drop of –34.4 psi + –4.3 psi = –38.7 psi.

So the pressure at the second floor of the house is:

48 psi at the meter – 38.7 psi pressure drop = 9.3 psi

Whether required or not, it may be good customer relations to tell customers that they will have low-water pressure on the second floor. A low-pressure waiver agreement or a long-service line agreement is an option. Also explain to customers that they can install small booster pumps that they own and maintain—not the water system—to increase pressure.

Example 3

An inverse of the situation in example 2 might be a customer with a house in the valley with an elevation below 139 feet from the connecting point at the main at the property line. The pressure reading at the meter reads 106 psi.

What would the pressure be at the house? Neglect the friction losses in the service line.

Using the pressure equation:

$$P = 0.43 \times h$$
$$P = 0.43 \times 139 \text{ ft}$$
$$P = 59.77 \text{ psi increase in pressure}$$

Giving a total pressure of 106 psi + 59.77 psi = 165.77 psi

This is too much pressure for the house plumbing and even the service line into the house. A pressure regulator needs to be installed at/with the meter (water systems responsibility) as well as at the house (customers responsibility). A high-pressure waiver agreement may be necessary.

Pressure Head

It is often convenient to express pressure in terms of the height of a column of water, in meters or feet, instead of terms of psi or kPa. This is called pressure head, and is the actual or equivalent height of water above the point in question.

For example, in the first example (example 1) the pressure head at point D would be 400 ft of water instead of 172 psi.

In some instances, the pressure in terms of psi or kPa may be known but the system would prefer to use units of pressure head instead. This is done, for example, when evaluating water distribution systems to determine how high the pressure will push the water up a hill in elevation. Rearranging the terms in the pressure equation, we get:

For U.S. units

$$h = P / 0.43$$

where h = height of water in feet
P = hydrostatic pressure in psi (lbs/in^2)

Or the equation can be simplified to:

$$h = 2.3 \times P$$
the 2.3 comes from dividing 1 by 0.43

For the SI units

$$h = P / 9.8$$

where h = the height of water in meters
P = hydrostatic pressure in kPa or kN/m^2
9.8 kPa or (kN/m^2)/m

Or the equation can be simplified to:

$$h = 0.1 \times P$$
The 0.1 comes from 1 divided by 9.8

A common misconception is that pressure increases when the pipe size decreases.

Pressure does not increase with changing pipe diameter. Pascal's Principle states that a pressure applied to a fluid system at rest is felt throughout the entire system. This means that, regardless of pipe diameter, water system pressure is felt everywhere. Decreasing pipe diameter will increase the velocity, but will reduce the flow rate of the water—meaning that as the pipe size decreases the water or fluid merely goes faster. If anything, when the water is flowing (in motion) from a larger diameter pipe to a smaller diameter pipe the pressure drops due to friction losses in the smaller diameter pipe.

Closing

Hydraulics can be complex when designing or analyzing entire collection or distribution systems. Knowing the correct formulas to calculate forces or pressure is the first step in having a properly functioning system. Pipe size, tank storage, and location are all key in getting water to system customers.

Several software and spreadsheet programs are available to assist in the hydraulics of system design. However, the data they generate is only as good as the information that is input. Knowing the fundamentals of hydraulics can help users get the most out of these programs.

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