

Liquid level measurement using hydrostatic pressure and buoyancy

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Questions

Question 1

A vessel containing a weak acid/water mixture has a calibrated level range of 0 to 10 feet, measured by a pressure transmitter at the bottom. Suppose that the specific gravity of the normal mixture is 1.12 (112% heavier than pure water, giving 1.12 inches of water column pressure for every inch of vertical height), and that the liquid level happens to be at 6 feet.

Now, suppose some pure acid is added to the vessel, increasing the actual liquid level *and* increasing the liquid density at the same time. The new liquid level is 7 feet high and the specific gravity has increased to 1.35. Assuming the transmitter has been calibrated for the original specific gravity of 1.12, what will its output signal correspond to in feet of liquid level? In other words, if this transmitter's output signal were driving a level indicator device for an operator to read, how many feet of level would the indicator device register?

Identify an alternative method for liquid level measurement that would not be affected by changes in liquid density.

[file i00245](#)

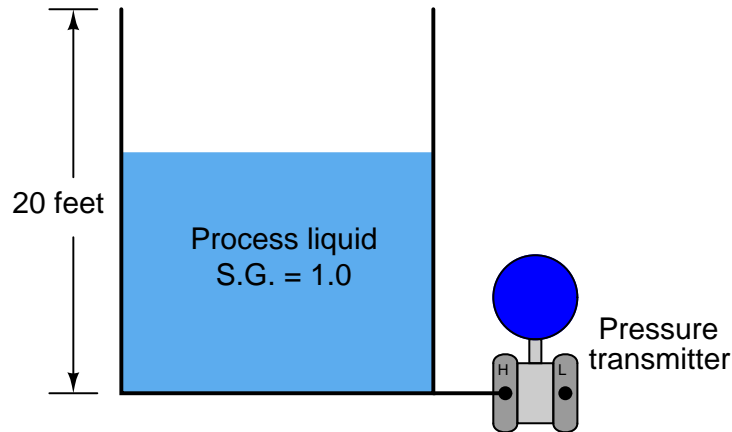
Question 2

An open vessel contains water at 60° F. A pressure transmitter located at the bottom of the vessel measures the hydrostatic pressure ("head") generated by the water and outputs a signal corresponding to level. Suppose that the temperature of this vessel were to increase over time to 110° F due to exposure to very hot outside air (the vessel is located in Death Valley, California during the summer). Knowing that an increase in water temperature will result in a decrease in density, what will happen to the level transmitter's output as the vessel heats up? Will the transmitter output increase, decrease, or stay the same? Why?? Assume that no water enters or exits the vessel during the period of heating from 60° F to 110° F.

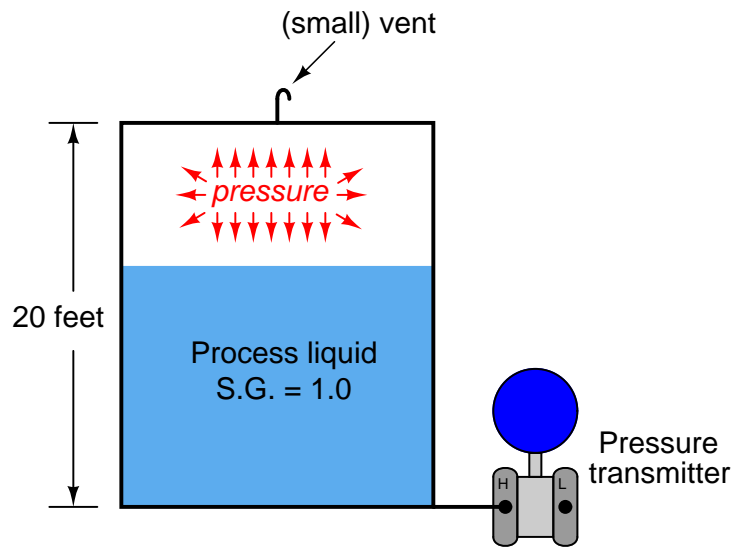
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Question 3

A vessel holding some process liquid needs to have its level monitored. The range of level in this vessel is 0 to 20 feet, and the process liquid has a specific gravity of 1.0 (like water). Someone decides to attach a pressure transmitter to the bottom of the vessel to infer level from hydrostatic pressure like this:



Later, a top is added to this vessel to keep rain from entering in. Unfortunately, though, this process liquid tends to emit vapor which will be trapped by the closed vessel and create a pressure inside of it. A small vent is added to the top of the vessel to permit the vapor to escape, but it is a *small* vent, not big enough to ensure a total absence of vapor pressure buildup at all times:

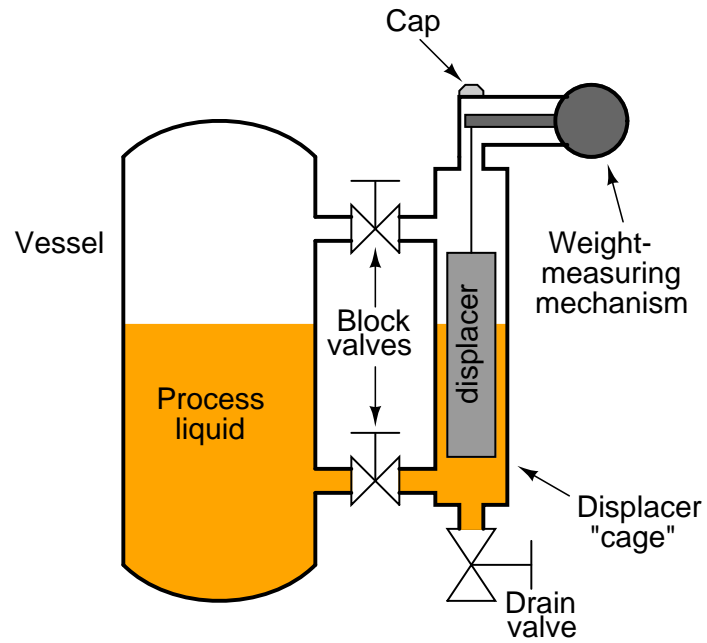


What problem in level measurement will result from there being an occasional vapor pressure buildup inside this vessel? How may this problem be corrected so that the liquid level will be accurately measured at all times?

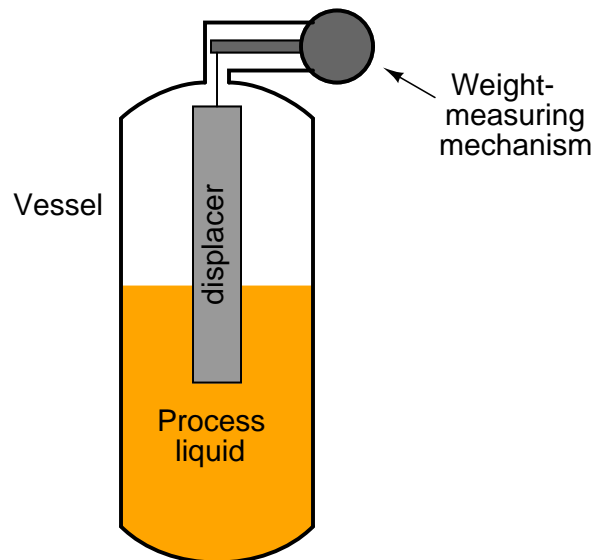
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Question 4

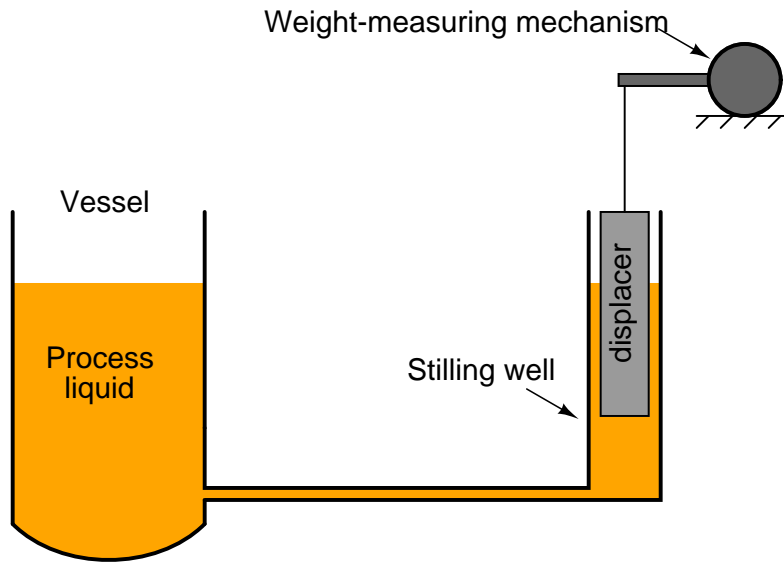
The principle of buoyancy may be used to create a level transmitter instrument, generating an output signal proportional to the change in weight of a “displacer” rod suspended in a liquid:



Often, the displacer is housed inside its own “cage” for easy removal from the process, as shown above, or it may be inserted directly into the process vessel like this:



If the vessel is open and the liquid inside is turbulent due to mixing or other agitation, a *stilling well* serves the same purpose as a cage:



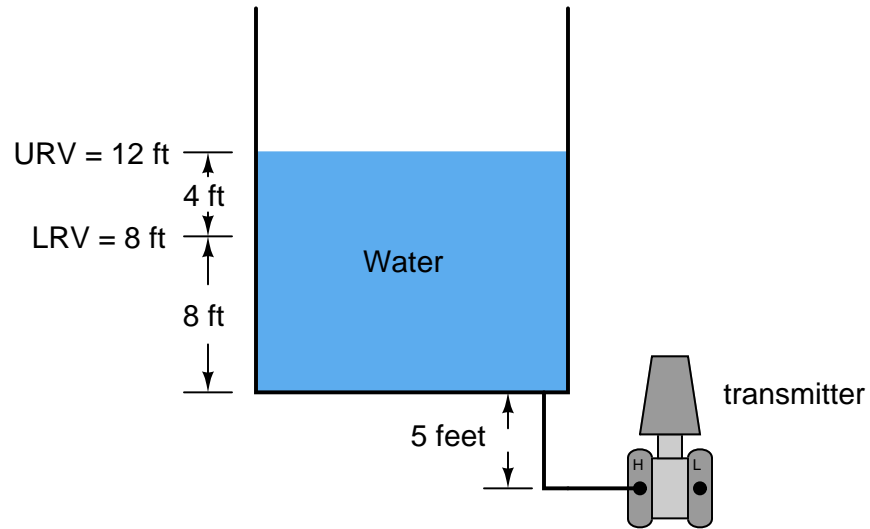
To calibrate such an instrument, it must be isolated from the process liquid. Sometimes this means simply closing block valves and draining the cage. Other times it means removing the displacer mechanism from the vessel entirely. But once the displacer is hanging dry, there is the problem of simulating a 100% condition for calibration purposes.

Describe a way to make the displacer “think” it is fully submerged in process liquid when it in fact is hanging freely in the air. Explain how you would be able to *precisely* and *accurately* simulate this condition, as well as any given condition of partial displacer submersion for that matter.

[file i00276](#)

Question 5

The following storage vessel holds water. The hydrostatic-pressure level transmitter is located 5 feet below the bottom of the vessel, and the desired level measurement range is 8 feet to 12 feet:



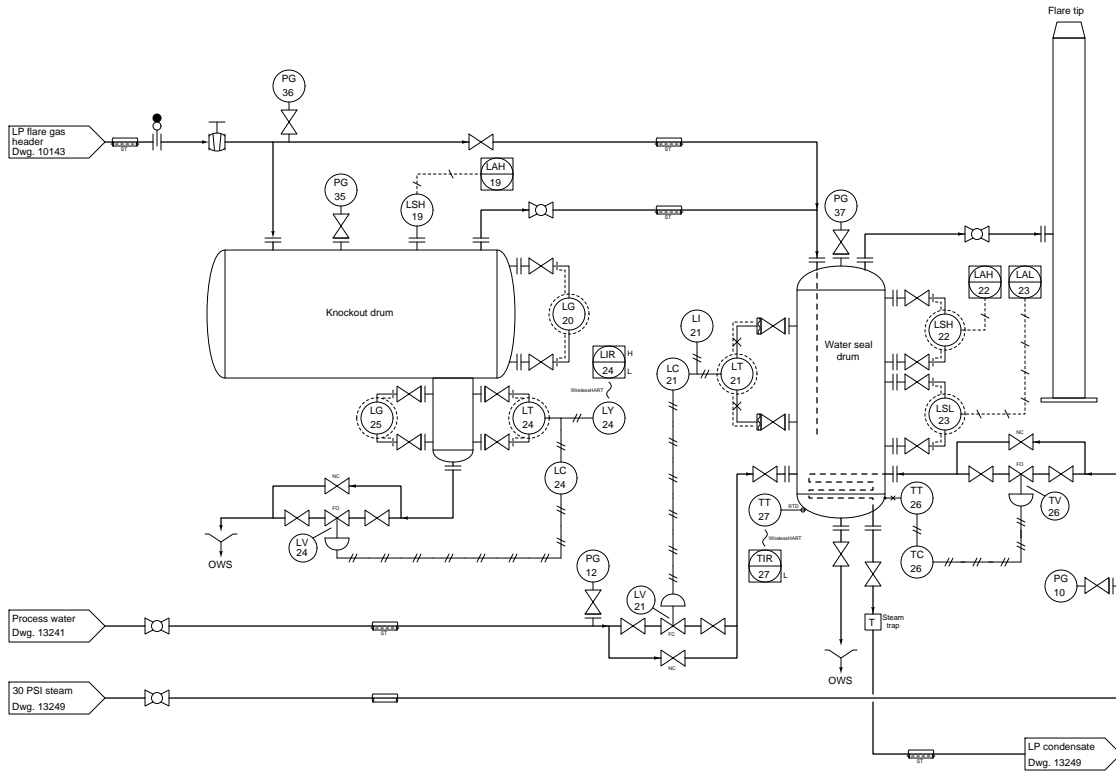
Assuming a pneumatic transmitter with an output range of 3 PSI to 15 PSI, and a calibration accuracy of +/- 1% of span, complete the following calibration table for the transmitter:

Process level (ft)	Percent of span (%)	Δ pressure sensed ("W.C)	Output signal ideal (PSI)	Output signal min. (PSI)	Output signal max. (PSI)
	0				
	10				
	25				
	50				
	75				
	90				
	100				

file i00257

Question 6

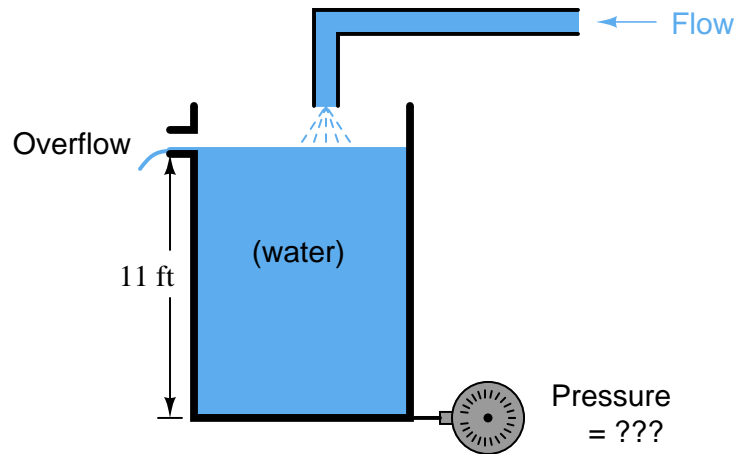
Determine the LRV and URV settings for the water seal drum lever transmitter (LT-21), assuming the LRV point is at the lower nozzle and the URV point is at the upper nozzle (the two nozzles being 3 feet 8 inches apart from each other), and that the remote seal fill fluid has a specific gravity of 0.934:



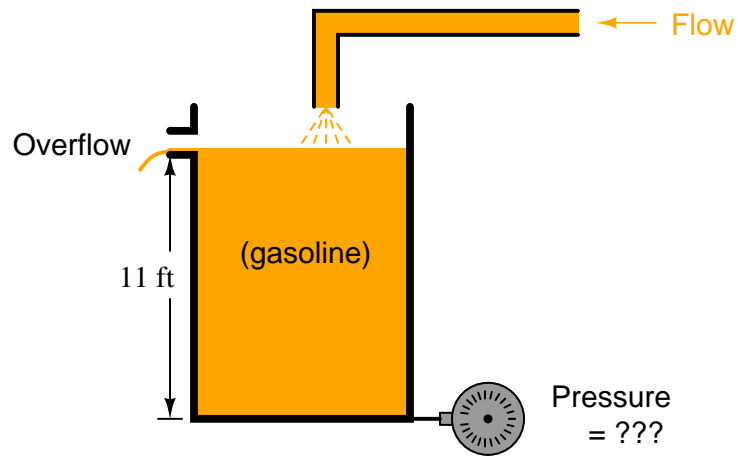
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Question 7

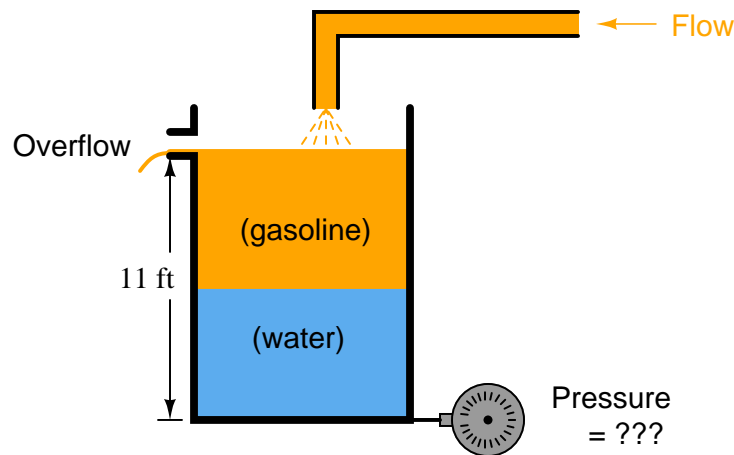
Calculate the hydrostatic pressure generated at the bottom of this vessel (in units of PSI) when it is completely filled with water:



Now calculate the hydrostatic pressure at the bottom of this vessel (in units of PSI) when it is completely filled with gasoline (density = 42 lb/ft^3):



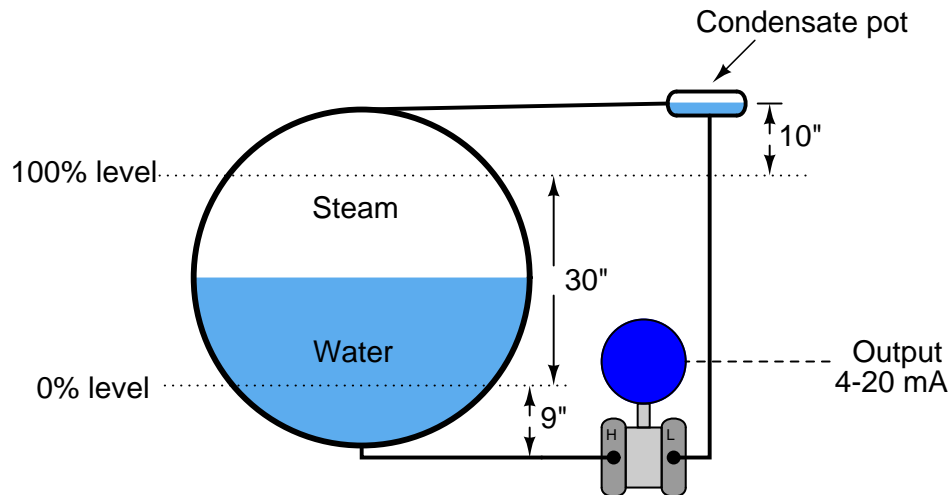
What do you think the pressure will be at the bottom of the vessel if it is exactly half-full of gasoline and half-full of water, with a gasoline-water *interface* at the 5.5 foot mark? Explain your reasoning.



[file i00308](#)

Question 8

Calculate the differential pressure sensed by the level transmitter at three different water levels in this boiler steam-drum level measurement system: 0%, 50%, and 100%.



Assume a density for (hot) boiler drum water of 36 lb/ft^3 , a density for steam in the drum of 7 lb/ft^3 , and a density for (warm) water in the “wet leg” of 61.8 lb/ft^3 . If the pressure at the “low” (L) side of the transmitter is greater than the pressure at the “high” (H) side, be sure to express the differential pressure quantity as a negative number.

Credit will be given for correctly calculating each of the differential pressures:

- (6 points) Transmitter ΔP at 0% water level = _____ ”W.C.
- (6 points) Transmitter ΔP at 50% water level = _____ ”W.C.
- (6 points) Transmitter ΔP at 100% water level = _____ ”W.C.

[file i00516](#)

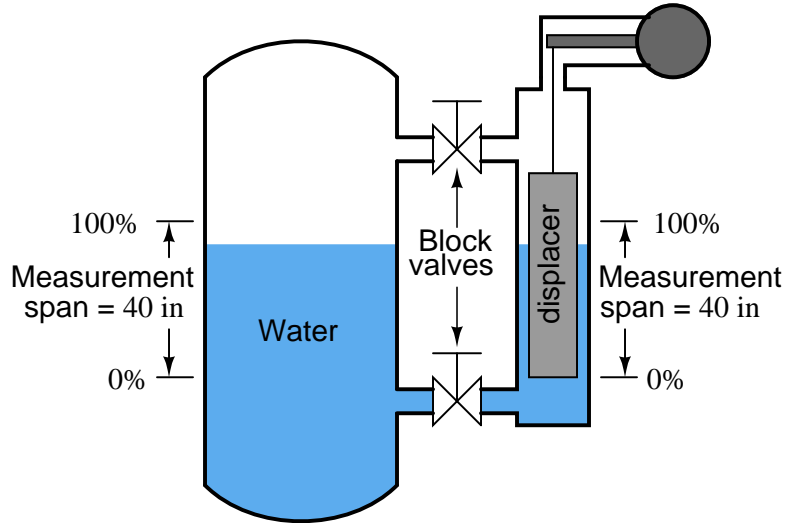
Question 9

A displacer-type density transmitter registers a displacer weight of 6.3 pounds with the cage completely full of sample liquid. The displacer has a dry weight of 14 pounds, a density of 120 lb/ft³, and is cylindrical in shape. Calculate the density of the liquid in units of pounds per cubic foot.

[file i00283](#)

Question 10

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:



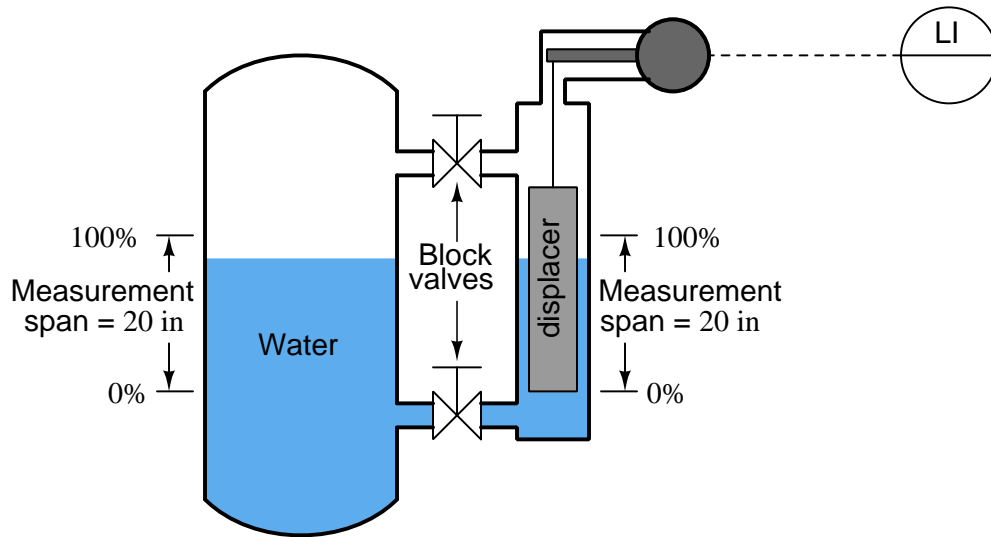
The cylindrical displacer weighs 15 pounds (dry) and has a diameter of 2 inches. The process liquid is water. The 0% process liquid level (LRV) is even with the bottom of the displacer. Assume an electronic transmitter mechanism with an output range of 4 to 20 mA.

Process level (in)	Percent of span (%)	Buoyant force (lb)	Output signal ideal (mA)
	0		
	25		
	50		
	75		
	100		

[file i00508](#)

Question 11

Determine a basic 5-point (0%, 25%, 50%, 75%, and 100%) calibration table for the displacer level transmitter in this scenario:



The cylindrical displacer weighs 9 pounds (dry) and has a diameter of 2 inches. The process liquid is water. The 0% process liquid level (LRV) is even with the bottom of the displacer. Assume an electronic transmitter mechanism with an output range of 4 to 20 mA.

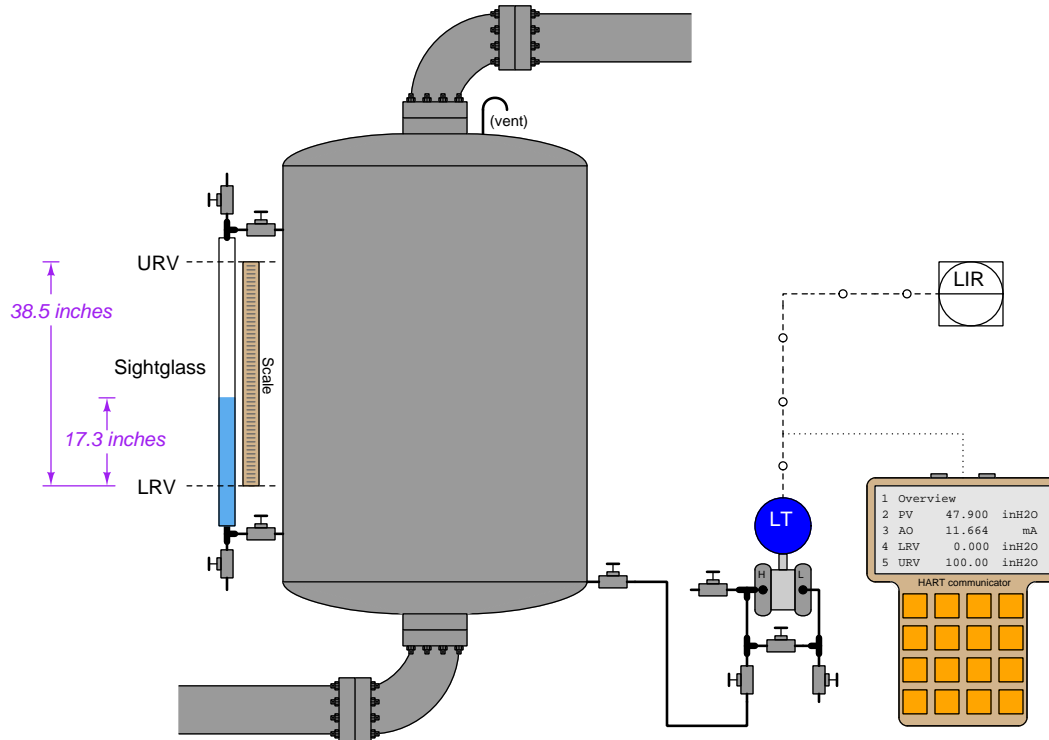
Process level (in)	Percent of span (%)	Buoyant force (lb)	Output signal ideal (mA)
	0		
	25		
	50		
	75		
	100		

Suppose the level indicator (LI) registers a liquid height of 16.5 inches when operators tell you the actual liquid level inside the vessel is 16 inches above the LRV point (as registered by a sightglass). Using a multimeter, you measure 17.2 mA output by the level transmitter. Based on this information, where is the problem in this system?

file i00509

Question 12

When installing a hydrostatic level transmitter on a working process, one must determine the proper lower- and upper-range values (LRV and URV) for the transmitter in order to properly register 0% at the LRV liquid level and 100% at the URV liquid level. If all fluid densities and physical dimensions are known in advance, this is a simple matter of a few mathematical calculations. However, sometimes it is difficult to know all the physical dimensions in advance, especially the elevation or suppression. Consider this example, assuming clean water as the process liquid and a static pressure of 0 PSIG inside the (vented) process vessel:



This “smart” transmitter has already been *calibrated* (i.e. *trimmed*) at the instrument shop to accurately register applied pressure and to accurately output its 4-20 mA signal, but its range values have not been customized to the installation. Reading off the sightglass’s scale, we find a vertical distance of 38.5 inches between the LRV and URV points marked on the sightglass, and we also see the current liquid level is 17.3 inches above the marked LRV point. Using a HART communicator to interrogate this “smart” transmitter, we see that the registered pressure at this process condition is 47.9 inches of water column (“WC”), which is greater than 17.3 inches registered by the sightglass due to the transmitter’s *suppression*.

Based on this information alone, calculate the appropriate LRV and URV settings to program into the smart transmitter, so that it will output 4 mA when the process water level is at the LRV height and 20 mA when the water level is at the URV height:

LRV = _____ ”WC (@ 4 mA)

URV = _____ ”WC (@ 20 mA)

Also, determine the appropriate LRV and URV settings for the indicating recorder (LIR) so that it will register the same as the scale (in inches) alongside the sightglass:

LRV = _____ inches (@ 4 mA)

URV = _____ inches (@ 20 mA)

file i02870

Answer 1

If the liquid level in the vessel rises to 7 feet, the transmitter should (ideally) output a final signal corresponding to 7 feet of level. However, since the transmitter in question is a hydrostatic pressure type, and the liquid density has increased as well, it will not register accurately anymore.

The old specific gravity was 1.12, and the new specific gravity is 1.35. The error in span will be the ratio of the new specific gravity to the old, or $1.35/1.12 = 1.2054$. In other words, the new acid/water mixture is 1.2054 times denser than it is supposed to be, according to how the transmitter was calibrated. Thus, the transmitter output will correspond to a liquid level of 7 feet times the error factor of 1.2054, or 8.4375 feet.

A good way to solve this problem is to apply the problem-solving technique of *simplification*. Imagine the two specific gravities being much simpler numbers: 1 and 2 instead of 1.12 and 1.35, respectively. It should be obvious now that a doubling of specific gravity will result in a doubling of level indication (i.e. the transmitter will register twice as much liquid level as there actually is inside the vessel). It should also be obvious that the error factor is 2:1, which is precisely the ratio of new:old specific gravity.

Alternatively, liquid level could be measured with a float, a capacitive sensor, ultrasonic or radar gauge, or some other instrument functioning on the detection of the liquid/vapor interface.

The transmitter output will stay the same.

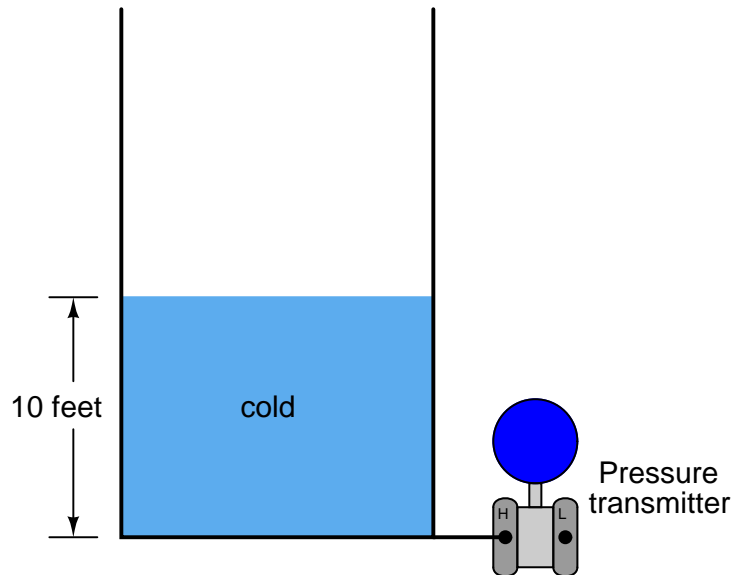
If you thought that the transmitter output would decrease due to the water becoming less dense, I recommend you explore the concept of density a little deeper with the following “thought experiment:”

- Imagine the vessel filled half-way with liquid.
- Imagine that liquid heating up and expanding until it is only *half* as dense as it was at the beginning of the experiment.
- Calculate the new hydrostatic pressure with the expanded, less-dense liquid.

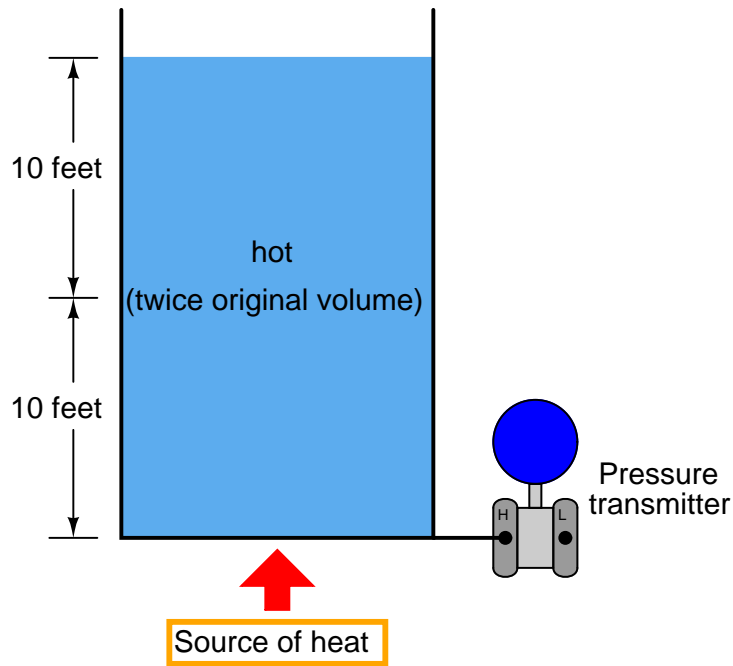
In a way, this is a “trick” question. As any given mass of water heats up, its volume will increase. This is what makes it less dense than before: increased volume with the same mass (weight). Knowing how to calculate hydrostatic pressure from height and specific gravity, you might have approached this problem by assuming the water column height would have stayed the same while its density decreased, resulting in a lesser hydrostatic pressure and decreased transmitter output. However, this answer is incorrect.

If the water volume expands as a result of a temperature increase, the level inside the vessel *must rise*, because it will require a higher vessel level to contain a greater volume of water. The level will rise by the same percentage that the density decreases, resulting in a cancellation of level increase with density decrease. As a result, the hydrostatic pressure at any point in the vessel remains constant.

If you have difficulty picturing this effect, consider an exaggerated example to make things simpler. Suppose that a vessel has been filled to a height of 10 feet with cold liquid:



Now, imagine that same vessel being heated until the liquid expands to exactly *twice* its former volume:



The liquid level must double to accommodate twice the volume in the same vessel, assuming a vessel of constant diameter, and its density will be cut in half (twice the volume with the same mass). Consequently, the two factors of liquid level change and liquid density change cancel each other out to give the exact same hydrostatic pressure as before. In other words, the transmitter will register the same liquid level as it did when the liquid was cold, and will output the exact same signal, even though the actual vessel level is quite a bit more than it was when cold. Pretty tricky, huh?

Answer 3

Any vapor pressure will be sensed by the transmitter and interpreted as increased liquid level!

Two solutions to this problem:

(1) Use two transmitters (one at top of vessel, one at bottom) and electronically subtract their output signals.

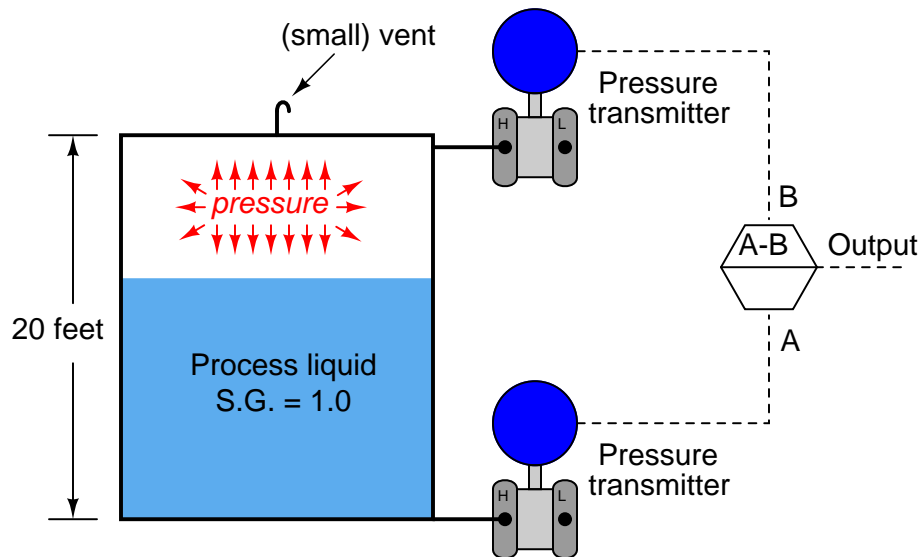
(2) Connect the “Low” side of the one ΔP transmitter to the top of the vessel to naturally compensate for vapor pressure.

Since the transmitter infers level from the amount of pressure sensed at the bottom of the vessel, any vapor pressure buildup inside the vessel will be falsely interpreted as additional liquid level, since the transmitter senses the *sum total* of hydrostatic pressure plus any vapor pressure trapped inside the vessel.

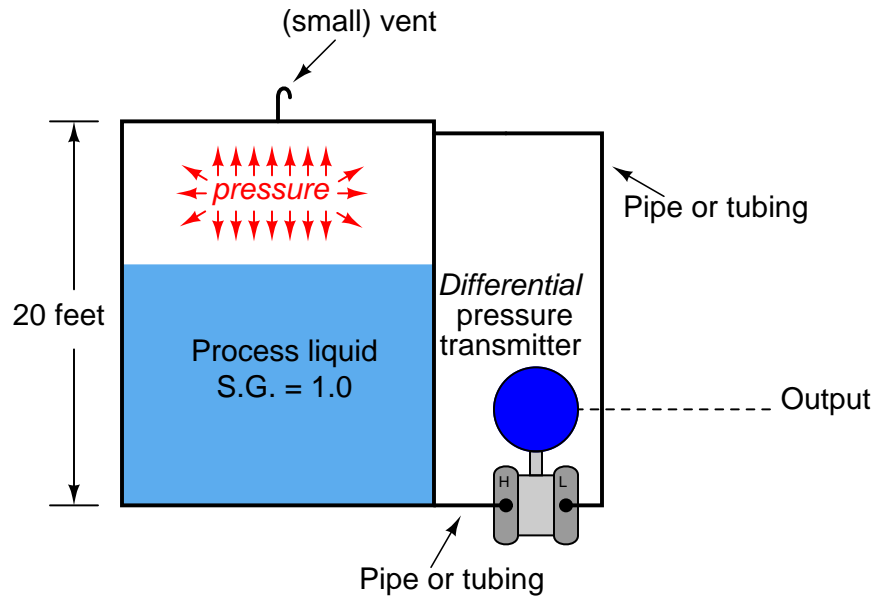
For example, if the process liquid level were at 10 feet (50% of range), the hydrostatic pressure generated by the liquid column would be 120 inches W.C., assuming a specific gravity of 1.0, equal to water. If, however, the vessel contained a vapor pressure equal to 15 inches W.C., this pressure would add with the 120 inches W.C. of pressure generated by liquid head to create 135 inches W.C. of total pressure sensed by the transmitter. As a result, the transmitter would “think” it was detecting a liquid level of 11.25 feet (135 inches high) instead of the true level of 10 feet (120 inches high). Essentially, any vapor pressure in the vessel results in a “zero” shift of the transmitter’s indication.

In many applications, the gas pressure inside a vessel far exceeds the hydrostatic pressure generated by the column of liquid inside of it, so this problem can be a very serious one in level measurement. We need to fully understand the nature of the problem and how to solve it in order to successfully measure liquid level in many industrial applications.

The solution to this dilemma is to measure the *difference* in pressure between the top and bottom of the vessel. We could do this by using two pressure transmitters, one at the top and one at the bottom, and detect hydrostatic pressure by subtracting the top transmitter’s measurement from the bottom transmitter’s measurement. A computer may be used to perform the mathematical subtraction of signals:



Another, more elegant method, incorporates a *differential* pressure transmitter with pipe connections to both ends of the vessel. This solution performs the subtraction mechanically, by directly exposing the transmitter’s sensing element to the *difference* of two applied pressures:

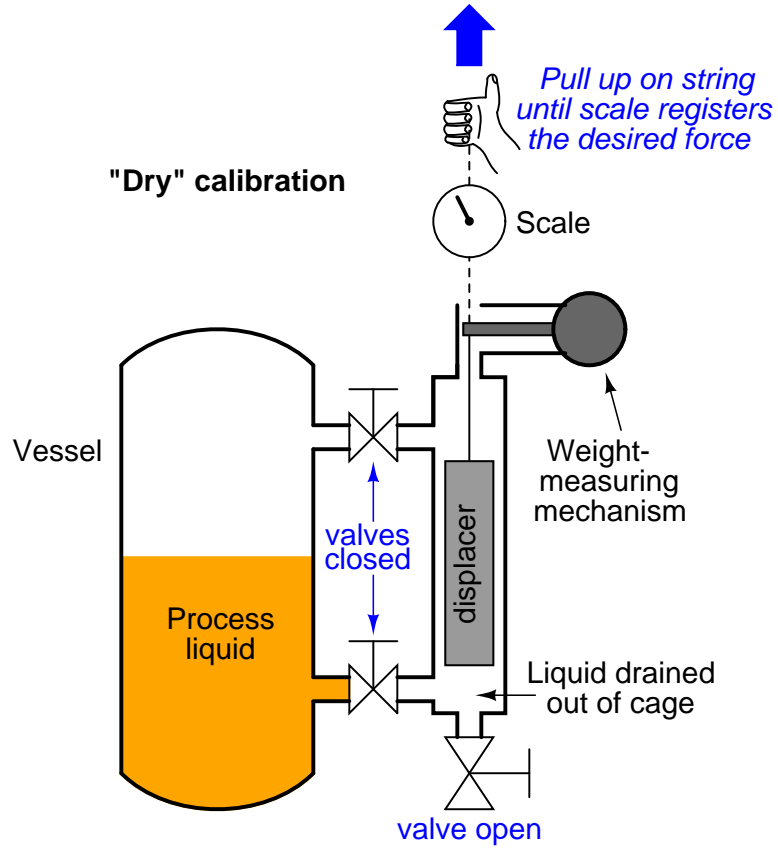


Because the differential pressure transmitter solution requires only one sensing instrument rather than two, and results in better accuracy because we are only dealing with the inaccuracies of a single instrument rather than the compounded inaccuracies of two instruments (three, if you include the subtraction unit), the differential, or “d/p” solution is the one more widely used.

In this particular level measurement application, a differential pressure instrument would have the exact same calibration points (lower and upper range-values) as a “normal” pressure transmitter connected to an open vessel.

Answer 4

One way to simulate a full condition is to use a *hand scale*:



Answer 5

Process level (ft)	Percent of span (%)	Δ pressure sensed ("W.C)	Output signal ideal (PSI)	Output signal min. (PSI)	Output signal max. (PSI)
8	0	156	3	2.88	3.12
8.4	10	160.8	4.2	4.08	4.32
9	25	168	6	5.88	6.12
10	50	180	9	8.88	9.12
11	75	192	12	11.88	12.12
11.6	90	199.2	13.8	13.68	13.92
12	100	204	15	14.88	15.12

Answer 6

The elevation for this transmitter (i.e. the total differential pressure applied by the height of fill fluid on both sides) is equal to the total height difference between the remote seal diaphragms multiplied by the specific gravity of the fill fluid:

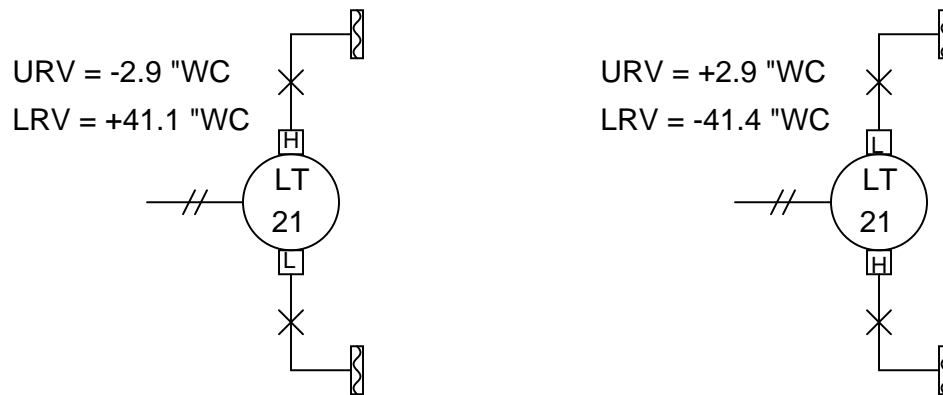
$$P_{elevation} = (44 \text{ in})(0.934) = 41.1 \text{ "WC}$$

In the LRV condition, this is the only pressure seen by the transmitter. Therefore, 41.1 "WC is the appropriate LRV setting for this transmitter. If we assume that the "H" port of this DP transmitter connects to the lower nozzle, the LRV will be -44.1 "WC. If we assume the "H" port connects to the upper nozzle, the LRV will be +41.4 "WC.

In the URV condition, we have the exact same amount of elevation (the fill fluid inside the capillary tubes) but on the lower nozzle we have the hydrostatic pressure of 44 vertical inches of water (i.e. the water inside the seal drum). Thus, in the URV condition the transmitter sees a differential pressure of:

$$P_{differential} = 44 \text{ "WC} - 41.1 \text{ "WC} = 2.9 \text{ "WC}$$

If we assume the "H" port of this DP transmitter connects to the lower nozzle, the URV will be +2.9 "WC. If we assume the "H" port of this DP transmitter connects to the upper nozzle, the URV will be -2.9 "WC.



Answer 7

Hydrostatic pressure when completely full of water = 4.769 PSI

Hydrostatic pressure when completely full of gasoline = 3.208 PSI

Hydrostatic pressure when water-gasoline interface is at the 50% level = 3.988 PSI

Answer 8

- (6 points) Transmitter ΔP at 0% water level = -38.832 "W.C.
- (6 points) Transmitter ΔP at 50% water level = -31.864 "W.C.
- (6 points) Transmitter ΔP at 100% water level = -24.896 "W.C.

Answer 9

The liquid has a density of 66 pounds per cubic foot.

Answer 10

Process level (in)	Percent of span (%)	Buoyant force (lb)	Output signal ideal (mA)
0	0	0	4
10	25	1.135	8
20	50	2.270	12
30	75	3.405	16
40	100	4.540	20

Answer 11

Process level (in)	Percent of span (%)	Buoyant force (lb)	Output signal ideal (mA)
0	0	0	4
5	25	0.567	8
10	50	1.135	12
15	75	1.702	16
20	100	2.270	20

Answer 12

Partial answer: (Transmitter range values only)

$$\text{LRV} = \underline{\mathbf{30.6}} \text{ "WC (@ 4 mA)}$$

$$\text{URV} = \underline{\mathbf{69.1}} \text{ "WC (@ 20 mA)}$$