Intro to Boyle's Law

Pressure Volume Relationships

We are used to living at 1 ATM of pressure, so we rarely even take notice of it. We normally don't feel the pressure on us because the human body is primarily made up of liquid, and liquids are basically non compressible. At times, however, we do notice changes of pressure, primarily in our ears. You may have noticed your ears "popping" when flying, driving in the mountains, or even going up and down in elevators. This is because our ears have an air space in them, and air, like all other gases, is compressible.

A gas will compress proportionately to the amount of pressure exerted on it. For example, if you have a 1 cubic foot balloon and double the pressure on it, it will be compressed to 1/2 cubic foot. Increase the pressure by 4, and the volume will drop to 1/4 the size etc. This theory was discovered by Sir Robert Boyle, a 17th century scientist. The theory known as Boyle's Law states: *If the temperature remains constant, the volume of a given mass of gas is inversely proportional to the absolute pressure.*

Let's follow an example...

Suppose you had a balloon measuring one cubic foot at the surface of the water. This balloon is under 1 ATM (14.7 psi) of pressure. If we push the balloon underwater, and take it to a depth of 33 feet, it is now under 2 ATM of pressure (29.4 lbs) - 1 ATM of pressure from the air, 1 ATM of pressure from the water. Boyle's Law then tells us that since we have twice the absolute pressure, the volume of the balloon will be decreased to one half. It follows then, that taking the balloon to 66 feet, the pressure would compress the balloon to one third its original size, 99 feet would make it 1/4 etc.

If we bring the balloon in the previous example back up to the surface, it would increase in size due to the lessening pressure until it reached the surface and returned to its one cubic foot size. This is because the air in the balloon is compressed from the pressure when submerged, but returns to its normal size and pressure when it returns to the surface.

We will achieve the same result with an open container, such as an inverted bottle, as we do with a balloon. By inverting a bottle at the surface and descending with it, the pressure from the surrounding water will compress the air and the bottle will start to fill with water. Even with no air escaping, the container will be half full of water at a depth of 33 feet due to the pressure compressing the air to half its original volume.

Along with the volume of air in the balloon or container, the surrounding pressure will affect the density of the air as well. Density, simply stated, is how close the air molecules are packed together. The air in the balloon or container at the surface is at its standard density, but when we descend to the 33-foot level where its volume is reduced to one half, the density has doubled. At 66 feet, the density has tripled. This is because the pressure has pushed the air molecules closer together.

Let's continue with this line of thinking and try an additional experiment. If we take our balloon and our open container down to 99 feet, we know that the density of air is four times what is was on the surface and the volume of air has been reduced to 1/4. Now at this depth, suppose we used a scuba tank and added air to the balloon until it returned to its original size. We will also blow air into the inverted container until it is completely full of air.

We know the air at this depth is 4 times denser than at the surface. This means when we ascend with our balloon and container, the lessening pressure will make the air expand. This will have two different effects. The balloon will increase in size. It will attempt to grow to a size of 4 cubic feet by the time it hits the surface. If this is beyond the capability of the balloon, it will pop. The inverted container, however, will simply "bleed off" the expanding air that will harmlessly float away as bubbles.

The main purpose of the proceeding material was to give you the theory behind the most important rule in scuba diving... "Never hold your breath!" Your lungs can act very much like a pair of balloons in your chest. As a breath hold diver (skin diver), if you fill your lungs with air at the surface, hold your breath, and dive to a depth of 33 feet, the surrounding pressure will compress your lungs to half of their original size. Upon ascending, they will return to normal size. If however, you descend to 33 feet and breath compressed air from a scuba tank, an ascent to the surface could cause you lungs to over expand and you could seriously injure yourself.

This is easy to avoid, however, by simply not holding your breath which will let your lungs act like the open container in the preceding example, and you will simply "bleed off" the expanding air and maintain a normal lung capacity.

Advanced Boyle's Law

Pressure Volume Relationships

We can take the knowledge we have gained thus far and figure out the volume of objects at any depth, not just at 33 feet, 66 feet etc. Boyle's Law tells us that there is an inversely proportional relationship between the pressure and the volume of gases. This means that the pressure (P) exerted on a gas times the volume (V) of the gas will always equal a constant (K). P x V = K.

If we take this one step further, we know that since this holds true for our balloon at any depth, the pressure times the volume at one depth must equal the pressure times the volume at any other depth. Or:

P1 x V1 = P2 x V2

where P1 is the pressure at the first depth and V1 is the volume at the first depth and P2 is the pressure at the second depth and V2 is the volume at the second depth.

Let's plug some numbers into this equation to see how it works. To make our first example easy, let's take an example we have already done. A balloon is 1 cubic foot at the surface, how big would it be it we took it down to 66 feet. We know the answer should be 1/3 cubic foot, but let's work through the formula.

The pressure at the surface is 14.7 psi and the volume is 1 cubic foot so the first half of our equation looks like:

14.7 x 1 = P2 x V2

Next we need to determine the absolute pressure at our second depth. (If you don't know about absolute pressure, check out Intro to Gasses.) To calculate the absolute pressure at 66 feet we multiply 66 times the pressure per foot in salt water, .445 and then add in 14.7 psi to give us the absolute pressure at this depth.

P2 = (66 x .445) + 14.7

P2 = 29.37 + 14.7 or

P2 = 44.07

Plugging the numbers into our formula then, we get

14.7 = 44.07 x V2

To solve for V2, we divide both sides of the equation by 44.07 that gives us the following:

14.7 / 44.07 = V2

Solving for this we then see that

V2 = 14.7 / 44.07 or 0.333 or 1/3.

Let's try another problem. If a balloon is 1 cubic foot in 20 feet of fresh water, how big would it be at a depth of 50 feet?

We use our formula P1 x V1 = P2 x V2 and start putting in the numbers. We know our V1 is 1. To determine P1 we multiply 20 times the pressure per foot in fresh water .432, then add 14.7. P2 would be 50 times .432 + 14.7 so our equation looks like this:

[(20 x .432) + 14.7] x 1

= [(50 x .432) + 14.7] x V2

Using a calculator we start doing the math:

[8.64 + 14.7] = [21.6 + 14.7] x V2

we add up the sides to give us:

23.34 = 36.3 x V2

Then we divide both sides by 36.37 to get:

23.34 / 36.3 = V2

or V2 = 0.6429752066116

rounding this number, we see that a 1 cubic foot balloon at 20 feet would be compressed to about .64 of a cubic foot at a depth of 50 feet.

As you can see, it is simply a matter of punching the numbers into the equation derived from Boyle's Law to calculate volumes and pressures of compressible objects at any depth.