The Buoyancy of a Flooded Dry-Suit, Archimedes Law and Dolphins' Bubbles

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Using a simple "barrel" model we address the question of how much buoyancy is lost when a drysuit is flooded. We show that, contrary to common ideas, this question does not have a straightforward answer though, in many relevant cases, a suit will not lose more than 30% of its buoyancy.

The dry-suit flooding issue is often discussed in various online forums. Most of the statements made on those public forums are, at the very least, misleading, contradictory, and most times just dead wrong. Examples are: water suspended in water (i.e., a flooded drysuit) does not add any weight to the diver, or "the weight of any water in the suit is nil, until you try and leave the water". These statements imply that suits do not lose any buoyancy due to flooding. One also finds statements that drysuits become excessively heavy due to tears. The loss of buoyancy is often mistakenly attributed to Archimedes law, which states that the buoyancy of a submerged object is equal to the weight of the fluid that is displaced. Of course, some comments made in those public forums are correct (e.g., a suit cannot lose more buoyancy that it originally had). Still, most statements do not seem to distinguish between scooters, which are not pressurized and have no net buoyancy, and suits, which are pressurized and have a lot of net buoyancy. It is perhaps not surprising that the various forums are full of confusing information—this is because the problem of buoyancy loss in a drysuit is not a trivial one.

We show here that the buoyancy of a flooded suit depends on three aspects:

(i) The location of the tear. By this we mean the upper part of the suit that faces upward, (i.e., toward the surface) or the lower part of the suit that faces downward.
(ii) The depth where the tear occurs.
(iii) Whether the ventilation valve is open or closed.

We shall show that, counter-intuitively, the greater the depth, the less water that penetrates into the suit. After illustrating these issues one by one using the conceptual barrel model (Fig. 1) and the pressures acting on it, we will point out that Archimedes law cannot always be applied to buoyancy issues associated with flooded suits. We do so using a conceptual barrel situated near a flat bottom and the recently observed "dolphin bubbles," which, peculiarly, even though they contained air, do not rise to the surface. The article involves some simple mathematical equations included for those who may wish to examine the conclusions in a controlled laboratory setup. The typical reader who may not be interested in those aspects can skip those equations.

Barrel model

Consider a conceptual barrel held fixed at mid-depth by a rigid mechanism whose details are not important for the present discussion (Fig. 1). The top of the barrel is situated a distance D away from the free surface, its radius is R, and its length is 2H. In analogy to a drysuit, the gas/air inside the barrel is pressurized so that its pressure $\hat{P}$ is equal to the mean hydrostatic pressure acting on the barrel from the outside, $r_w g(D + H)$, where r_w is the water density and g is the gravitational acceleration. Here, the pressure in the barrel is uniform but the outside hydrostatic pressure increases linearly with depth. Under such conditions, the inside of the upper half of the barrel is subject to a pressure greater than the mean outside pressure whereas the lower half is subject to a pressure lower than the mean outside pressure. This point is a key to understanding the buoyancy issue.

Due to these pressures differences, a hole punctured in the upper half of the barrel, will cause air to escape from the barrel whereas a hole punctured in the lower part of the barrel will cause water to rush in. We shall take these two issues one by one. Before doing so, however, we note that the buoyancy of the barrel is the difference between the downward (integrated) pressure acting on top of the barrel, $pR^2r_w gD$, and the upward integrated pressure acting on the bottom of the barrel from below, $pR^2r_w g(D+2H)$. The difference between the two gives the buoyancy in terms of the weight of the displaced water, $2pR^2r_w gH$, in agreement with Archimedes law.

(a) Hole in the bottom

Here, as mentioned, the water pressure outside the barrel is greater than the pressure inside so, in this case, water will rush into the barrel further compressing its gas until the pressure inside the barrel (P) equals the pressure exerted on it by the water penetrated from below. Taking the unknown length of the remaining air-filled fraction of the barrel to be L, this condition is,

$$r_w g(D+H)(2H/L) = r_w g(D+L),$$

where we have applied the linear compressibility law to the air inside the barrel. This is a quadratic equation for the unknown L. Denoting $a = L/2H$ and $b = D/2H$, its solution is,

$$a = \frac{1}{2}\left[-b+\sqrt{b^2+4b+2}\right],$$

where the negative root was rejected because $a \geq 0$. Two interesting limits are immediately noted. First, when the top of the barrel is right at the surface ($b = 0$), then $a = 1/\sqrt{2}$, implying that only ~ 30% of the barrel can get filled with water. This is the maximum amount of water that can penetrate into the barrel. Second, at great depth ($b \to \infty$, i.e., the depth D is much greater than the barrel height $2H$) $a = 0$, implying that no water penetrates into the barrel! For in-between depths, the barrel will be filled with an amount between zero and 30%. So, at the most, the barrel buoyancy loss is 30% and so will be the maximal loss of a drysuit buoyancy when the hole occurs on the bottom and the ventilation valve is closed. In the hole on top case, the pressure inside the barrel is greater than the surrounding water pressure so the air/gas will quickly escape and the barrel will lose most of its buoyancy.

Archimedes and dolphin bubbles

It is important to realize that Archimedes “law” is merely a statement related to an integration of the pressure forces acting on the submerged subject. In reality, it is the pressure, not the “law”, that the water senses and, in some cases, the “law” is just not valid. The simplest way to see this is to again consider our conceptual barrel model. Suppose that you think of some relatively small barrel in the laboratory submerged in a glass container with a very smooth and flat bottom. Suppose further that the barrel also has a smooth glass bottom, and that the weight of the water that it displaces when it is submerged (i.e., its buoyancy per Archimedes) is Q. The barrel will normally float because its weight is smaller than Q. When held in mid-depth it will have a tendency to rise, again because Q is larger than its own weight.

However, when the barrel is carefully placed vertically near the bottom making sure that there is no water between the smooth tank bottom and the smooth barrel bottom, the barrel will stay put and will not float even though its Archimedes buoyancy Q is still larger than its weight (Fig. 2, situation A). This is because there is no water under the barrel implying that there is no vertical pressure from below and, hence, no buoyancy at all. While this experiment has been repeated in the laboratory numerous times, it is easier said than done because any disturbances in the room will cause water to get in between the barrel and the bottom of the tank, causing the barrel to float. At best, the barrel will stay along the bottom for a while, until a disturbance occurs causes it to float to the top (Fig. 2, situation B). Nevertheless, it does show that the law is not universally valid.

A similar case where Archimedes law fails is that of dolphin bubbles. Recently, dolphins held in captivity developed a technique to form ring-like bubbles that do not rise to the surface even though Archimedes law says that, like all familiar bubbles, they should. (For a fascinating clip see *http://www.youtube.com/watch?v=TMCf7SNUb-Q&feature=related*. Kenyon (2011) recently suggested that the reason that the bubbles do not rise is, again, the distribution of pressure around them. He cleverly argues that the dolphins have learned to pressurize the bubbles in a manner that matches the outside hydrostatic pressure.

Summary

It is suggested that divers whose drysuits have flooded should attempt to keep the ventilation valve in the completely closed position and should anticipate that their suits will be flooded more and more as they approach the surface. This additional flooding is not necessarily because the suits had more time to get filled with water (which should happen in a matter of minutes or less) but rather because the surrounding pressure has decreased. When a suit is allowed to be continuously ventilated in the usual manner in order to adjust to the new lower depths, the pressure inside the suit is never large enough to arrest the penetration of water into it. Tightening the valve allows the establishment of an additional arresting pressure but it requires more water within the suit (and, hence, less buoyancy). Water penetration and buoyancy loss will be maximal near the surface where approximately 30% of the suit will be filled with water (assuming that the tear occurred in the lower part of the suit).

Finally, a clear distinction needs to be made between scooters, which are not pressurized and have no net buoyancy (and, hence, can indeed become excessively heavy) to suits, which are pressurized and have a lot of net buoyancy and, hence, are very unlikely to lose all of their lift. In a similar fashion to the two given examples (barrel on the bottom and dolphin bubbles), Archimedes law cannot be applied to water entering the suit without considering the pressure distribution within the suit.

Appendix: How fast will the water rush in or the air rush out?

This can be estimated using the so-called Bernoulli principle whereby the speed is equal to the square root of twice the pressure causing the motion divided by the density. For the hole in the bottom case, the speed of the water rushing in when the barrel is partially filled is,

$$W = \sqrt{2g(2H - L)}\ .$$

Taking the barrel dimensions to be similar to that of a diver (ignoring the diver's volume inside the suit), we use R = 15 cm (half a foot), and 2H = 1.8 m (six feet) to get a vertical speed of about 3.6 m/s (approximately 10 feet per second). Further assuming that the hole diameter is 3 cm (roughly an inch), we find that one third of the barrel will be filled in about one minute (50 seconds to be more precise).

When a hole occurs on the top, the excess pressure causing the air to escape so the speed is,

$$W = \sqrt{2gH\, r_W / r_A}\ ,$$

where we have taken into account that air (whose density is r_A), rather than water, escapes the barrel. As expected, this gives an enormous (theoretical) speed of 120 m/s implying that the entire barrel will be emptied in less than a second. To be more accurate, we really need to discuss here the problem of air rushing out and water rushing in to replace its space at the same time but this is a considerably more complicated problem, which is unnecessary for the purpose of our discussion. It is sufficient to say here that the whole process will take less than a minute or so.

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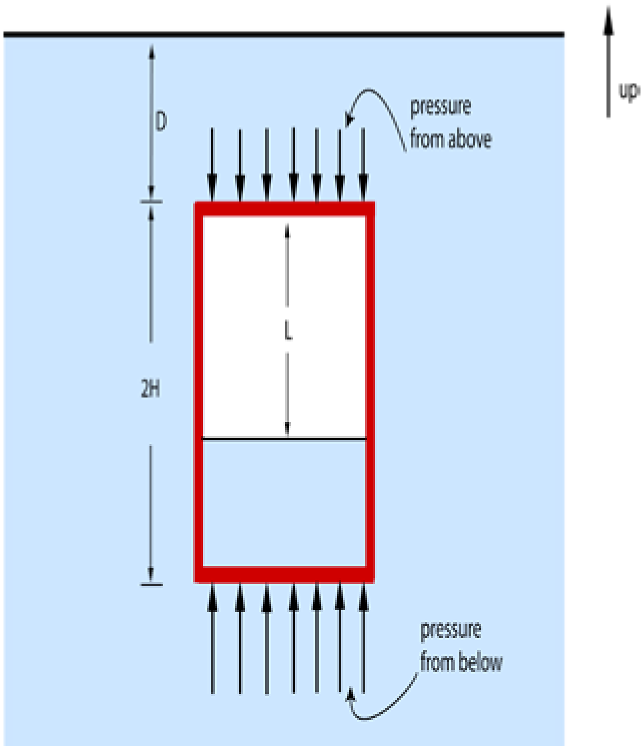

Fig. 1. The conceptual barrel model. The buoyant barrel has a radius R and height 2H; it is initially filled with gas/air and is artificially held underwater in a fixed position. This holding is done through some mechanical means (not shown) whose details are not important for our present discussion. The top of the barrel is situated a distance D below the free surface of the water. The barrel is sealed and, in analogy to a drysuit, is initially pressurized so that its air/gas pressure matches the mean pressure exerted on the barrel by the water outside, $r_w g(H + D)$*. At some later point in time, a hole is punctured on the bottom of the barrel. Water then rushes in to fill the barrel up to a distance L away from the top of the barrel, i.e., until the new compressed gas/air pressure inside matches the pressure of the water below,* $r_w g(D + L)$*. Aside from the puncture on the bottom, the barrel is completely sealed in analogy with a torn dry suit whose exhaust valve has been completely closed after the tear occurred.*

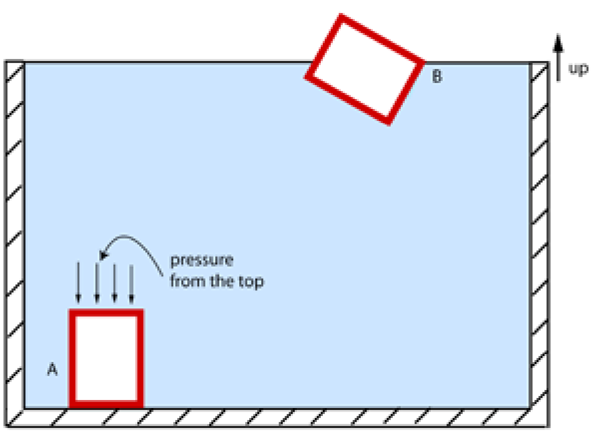

Fig. 2. An example where Archimedes law is violated. In situation A, a buoyant barrel with a perfectly flat bottom (say, glass) is placed near the bottom of a container that also has a perfectly flat bottom. No water can get under the barrel so the barrel does not float even though it displaces more water than its own weight (see text). However, once water does get under the barrel, the barrel does float (situation B).