GFD Lab Demo I Basic fluid properties: pressure, buoyancy, floating, eqn of state, phase change. 8i2004

Images from the experiments are posted separately

Introduction

Fluids surround us, and they are particularly well-suited to deliver and distribute the chemicals essential to life. We are carbon- and water-based creatures on an ocean planet, breathing the oxygen/nitrogen atmosphere created by our green co-conspirators.

In this collection of laboratory encounters with fluids, we will attempt to demonstrate the key properties of fluids, particularly those which matter for the oceans and atmosphere. We have found that meeting fluids in the lab, after or during a parallel course on theory, one can use other resources: eye, hand, even artistic senses, and that curiosity can once again come to life.

Pressure and buoyancy

Fluids sit, move and accelerate under the action of forces: both body forces like gravity, and surface-contact forces. A small cube-shaped region of fluid feels such surface forces on its faces, known as ‘pressure’ and ‘viscous stress’. The average (at a point, over all directions) of such forces normal to the cube’s faces is known as *pressure*, and the net force (the average of the normal vector force on all six faces) is the *pressure gradient*. It is this particular surface-contact force that tends to com*press*, the cube, changing its volume slightly. The surface forces tangential to the faces of the cube, which tend to deform its shape, are known as *viscous stress*.

Pressure is a difficult property to understand. It is a scalar, without direction; perhaps ‘compression’ might be a better name. In a simple gas, the pressure and temperature ‘express’ something about the activity of molecules. Temperature, T (in degrees Celcius, ^{0}C, or simply Kelvin, K), is a measure of their mechanical energy, per molecule: this is just kinetic energy, $\frac{1}{2}$ m V^2 for a monatomic gas. m is the molecular mass and V the speed. Pressure, p (in newton meter^{-2}, or Pascals), is a component of the *momentum flux* of all the molecules, or the rate at which momentum moves across a plane within the fluid. This momentum flux conveniently is also proportional to mV^2. For, a plane, solid wall in contact with the fluid feels molecular impacts; each impact exerts a force normal to the wall whose time integral is equal to twice the molecular momentum, mV_1, in that direction, whatever direction that normal might be. As impacts occur continually, the time-averaged normal force due to many (nV_1 per second) impacts is the momentum flux, nmV_1^2; n is the number of molecules per unit volume. nmV_1^2 is the same as 1/3 ρV^2 assuming that molecular speeds in the three directions are equal on average (ρ, the density in kg meter^{-3} is the name we give nm). Compare this statement

$$p = 1/3\ \rho V^2$$

with the equation of state for a perfect gas,

$$p = \rho RT$$

where R = 287.04 J kmol^{-1} K^{-1} for dry air. In words, the density multiplies the per-molecule kinetic energy to give the total momentum flux, per unit area, with a constant R which would be equal to 1/3 if temperature were really expressed in energy units. And that momentum flux is the force exerted on a wall. A fluid moving past a wall will exert forces *along* the wall as well, and these 'viscous stresses', also have molecular origin. They will be encountered in 'Stirring and Mixing', a later lab.
If the wall is not there, the same sort of molecular motion is still present, and this leads us to the idea that pressure is an intrinsic property of a fluid, a 'compression', which exerts a force on any object placed within it.

a BB model of fluid pressure

Apparatus:

- balance (classic beam balance or modern electronic balance)
- metal shot ('BB's or small steel ball bearings)

A quick lab demonstration can demonstrate these ideas. Set a cup on the balance and drop a single BB into it, so that it bounces out. Note the temporary deflection of the balance, or (probably unreadable) temporary change in the digital weight reading. Now drop BBs at intervals of about ½ second: experiment to find an interval for which a nearly steady deflection or digital reading is seen. If a digital camera and strobe light are available photograph the process with a strobe light, which will reveal the relevant speeds.

This simple, perhaps even tedious, experiment does have a point. Using Newton's laws, calculate the fall speed of a BB when it hits the cup, and hence estimate the average momentum flux, nmV^2. See if this indeed is equal (to within experimental error) to the apparent weight registered on the scale. The experiment forces us to think about the *continuum* model of a fluid: we can't worry about the details of each molecular impact but we stand back and see their net effect. This is reasonable, because both the molecular diameter [a few tens of angstroms (1A = 10^{-10}m) or a few nanometers (10^{-9}m)] and the mean free path of an oxygen or nitrogen molecule, between collisions [roughly 500 A] are so much smaller than the smallest interesting fluid motions which occur at about 1 mm (10^{-3}m).

(1) Hydrostatic pressure; U-tube oscillator

Immerse a solid in a liquid. It is com*press*ed by this pressure. But why is the pressure there? In an enclosed box filled with gas it is the confinement that creates pressure. But here the liquid is sitting with a free surface. Why doesn't it escape?

Of course, it does escape by evaporation. In the vacuum of outer space a beaker of water will turn into vapor and disperse, at least until gravity arrests the water molecules and puts them into some orbit or other. Gravity: that's it. Gravity is a body force holding the water in a beaker, and only a rare, energetic molecule can break the molecular bonds that maintain the fluid and escape.

So let us focus on the continuum balance between the body force, gravity, and surface-contact force, the pressure gradient. If the fluid is resting (macroscopically of course) there are no viscous stresses, and the entire force balance is the hydrostatic equation:

$$\frac{\partial p}{\partial z} = -\rho g \qquad (1)$$

where z is the vertical coordinate and g [9.8 meters sec^{-2}] is the acceleration due to 'gravity'. Why the ''? Because true gravitational force and the apparent centripetal force due to Earth's rotation combine in the quantity g.
Hydrostatic balance is the dominant part of the vertical momentum equation for most large-scale motions of the ocean and atmosphere, notably those whose horizontal length scale L and vertical length scale H obey $H/L << 1$: *flat*, *pancake* shaped motions.
The vertical integral of (1),

$$p(z) = p(z_0) + \int_z^{z_0} g\rho \, dz ,$$

says that the pressure is equal to the weight of fluid overhead (plus whatever pressure is exerted at the top of the fluid). This gives the very useful result that the elevation of water surface acts as a 'pressure gauge', for when (2) holds for a uniform density fluid,

$$p(z) = \rho g(\eta - z)$$

where $z=\eta$ is the height of the water surface (we assume here that the atmospheric pressure is effectively constant). This graphic result for long gravity waves and flows with a free surface will be exploited in Lab. 3.

It would be wonderful if we could *see* pressure, perhaps by a change in color of the fluid, but this is the next best thing [in fact, specialized paint exists which changes color in response to pressure; it is used in wind tunnels to give a complete picture of the pressure field on the surface of an airplane in high-speed flow].

Apparatus:

1m. long plastic tubing

Bend the tubing into a U-shape and fill it half-way with water. Holding the two vertical segments together note how the free-surfaces seek each other out. As the U-tube is moved side-to-side oscillations occur, about this mean position. Estimate the natural frequency of the oscillations, comparing with a hydrostatic theory for an idealized U-tube made up of vertical and horizontal arms meeting at right angles: the height increment, η, of either of the two water columns provides a hydrostatic pressure difference $2\rho g\eta$ to accelerate the horizontal arm of fluid. This is the ‘F’ of F=ma. The ‘ma’ is $\rho L d^2\eta/dt^2$. Solving this o.d.e.,

$$d^2\eta/dt^2 + (2g/L)\eta = 0$$

the natural frequency is $(2g/L)^{1/2}$, where L is the length of the horizontal segment. By the hydrostatic assumption, all the inertia of the oscillator is in the horizontal segment, and the vertical acceleration is neglible in the vertical arms. The problem can then be solved more exactly, allowing the vertical acceleration to modify the hydrostatic pressure in the vertical arms; this gives a frequency $(2g/(L+2H))^{1/2}$; that is $(2g/\text{total length of fluid})^{1/2}$. Thus it is found that only if the horizontal arm is long compared with the vertical, does the hydrostatic theory work. This is the same as ‘$H/L \ll 1$’ above. A quick way to the exact result is to use Hamilton’s principle

$$\frac{\partial}{\partial t}\frac{\partial L}{\partial \dot{\eta}} - \frac{\partial L}{\partial \eta} = 0$$

where $\dot{\eta} \equiv \frac{d\eta}{dt}$, $L \equiv T-V$, where T is kinetic energy and V the gravitational potential energy. Here $T = \frac{1}{2}\rho L_1 (d\eta/dt)^2$ and $V=\rho g L_1 \eta^2$, where $L_1 = L+ 2H$ is the total length of fluid. V is calculated as $\int \rho g z\, dl$ along the length of the fluid, which if the arms of the U-tube are vertical, involves just

$$\int \rho g z\, dz = \textit{difference in } \tfrac{1}{2}\rho g[z^2] \textit{ between left and right.}$$

giving equation (1) with L replaced by the total length of fluid, L_1.

Of course a little deception is useful to enliven a laboratory, and carefully filling one arm of the U-tube with salt water and the other with fresh will give a puzzling error in the equality of the respective free surface heights.

Explosive hydrostatic forces. Despite the gentle nature of hydrostatic pressure force in the lab, one should remember that at the bottom of the sea, say 5000 m depth, the pressure is about 5000 *decibars* or 500 times the atmospheric pressure. This is 5 x 10^7 Newton meter^{-1}, or ‘Pascal’. It is great enough to crush oceanographic instruments. Remarkable species of fish and cetacians (whales, dolphins) can move through great changes in pressure without suffering; whales dive rapidly to depths of 800m or more in search of food.

The idea of the hydrostatic pressure field suggests that, in a fluid-filled vessel of complicated shape, the pressure should be the same at all points along a level. This leads to strange, rather uncanny results. Consider the pressure in a flask with a tall, vertical ‘chimney’ (a narrow vertical tube) connected to a wide glass cylinder beneath. Since it is proportional to the height of the chimney, the net force on the bottom of the flask, ρgAh, is not related to the weight of the water, but exceeds it greatly. A is the area of the bottom, and h the height of the fluid column. Where does this, possibly huge, force come from? The hydrostatic pressure tries to burst open the flask, with outward force in all directions. This is true, no matter how narrow the chimney is: it could be as thin as a soda straw.

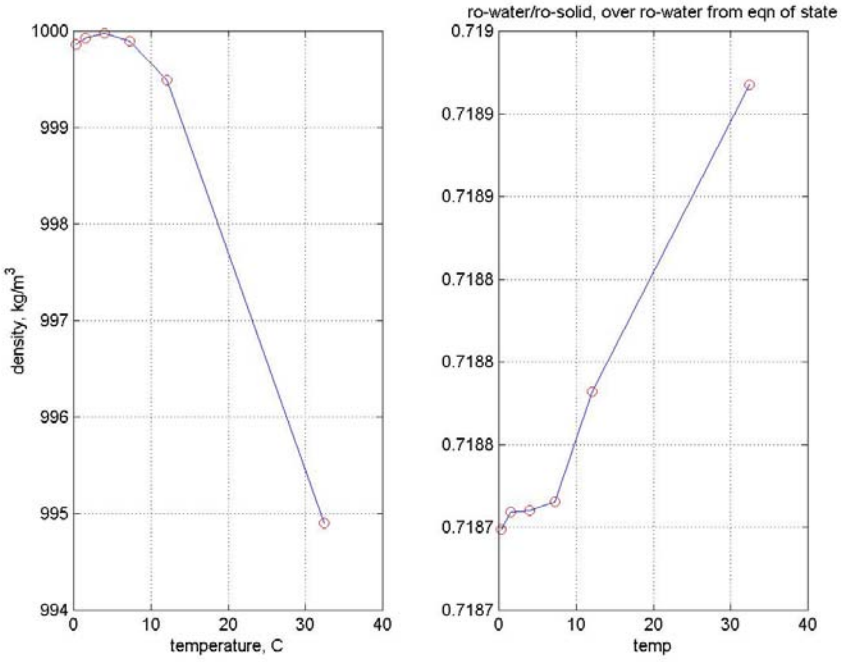
(2) Thermally driven fluid loop

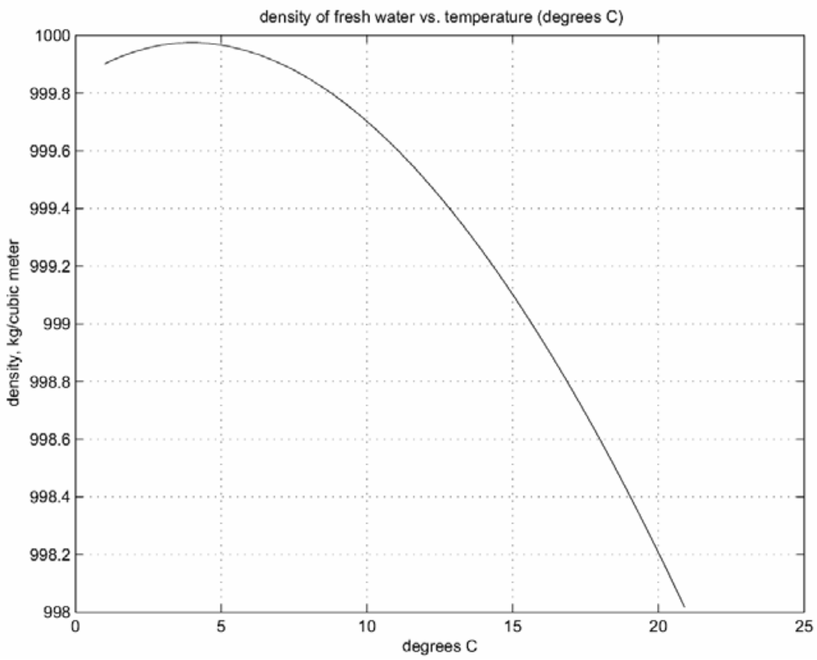
A U-shaped copper tube connects two cylindrical vessels at their bottoms. Fresh water fills the system. The U tube is heated. What happens? Think about the buoyancy forces involved as the water in the copper tube warms up. If a slight asymmetry exists, this buoyancy will push water up one side of the U, and flood one of the cylinders. This will continue for some time, but the process increases the water level in one cylinder at the expense of the other. A pressure difference develops from the difference in free-surface height (think about the hydrostatic pressure field). This will eventually stop the flow, and drive it the other way. So, this is an oscillator though much slower than the pendulum-like oscillator in experiment 1. Measuring the temperatures in this experiment using an infrared radiation thermometer is very rewarding. The expansion coefficient for water, $\alpha = - \rho^{-1} \partial\rho/\partial T$, is about about 10^{-4}, but decreases greatly with temperature (the slope of the curve $\rho(T)$ shows this). What would happen if we used temperatures near 4^0 C in this experiment?

The U tube and cylinders have interesting geometry, and that is what controls the experiment. Prof. Seelye Martin in Oceanography once discovered a remarkable oscillator that is also ‘geometrically determined’; it is a cylinder with a tube draining it in the center. If the cylinder is filled with salt water and then immersed in a bath of fresh water, the system develops oscillations, with the salty and fresh water fighting to occupy the tubular drain.

(3) Basic Buoyancy

An experiment that demonstrates buoyancy and also gives us quantitatively the equation of state is as follows: take a glass bulb of known weight and immerse it in water, hanging it from a thin wire. The wire is attached to a precision scale, sitting on a step-ladder above. Now change the density of the water by heating or cooling with ice. The weight of the bulb will change, according to Archimedes. We have done this experiment for many GFD classes, and it always works...qualtitatively...but is difficult to make it agree precisely with the calculation based on the 'official' equation of state. This is often due to air bubbles that form on the bulb and lift it slightly. Using ice, last year we came closer (fig. the righthand panel would be a constant for perfect accuracy; the fractional error is small, $4x10^{-3}$)). The calculation takes the observed temperature and weight of the bulb in water and in air, and derives the density of water. The figure shows an offset which we do not yet understand, but the shape of the curve looks very good. Note the maximum density near 4C. This effect means that fresh-water lakes 'turn over' as they cool to 4C, but with further cooling the coldest water remains at the surface. This encourages smooth freezing, good skating, and helps preserve life below. Also, water is anomalous in having its solid phase less dense than its liquid phase. If ice were denser than water, the world would be very different: a far-reaching quirk of Nature.




density of fresh water vs. temperature (degrees C)
density, kg/cubic meter
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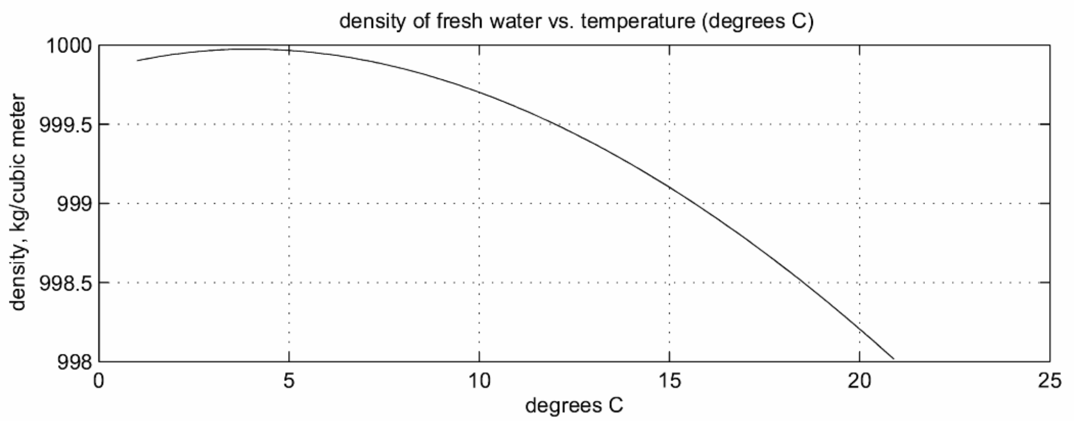
density of fresh water vs. temperature (degrees C)
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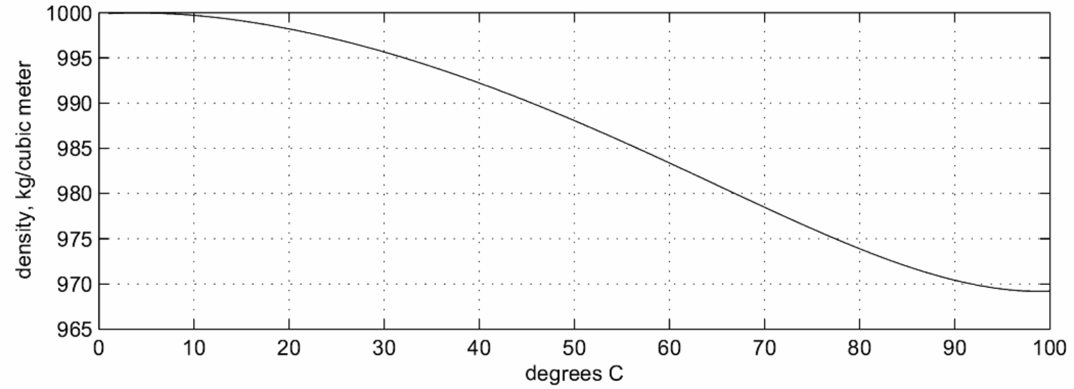
density, kg/cubic meter
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degrees C

(4-5) Floating: more buoyancy, and rotation as a contribution to 'gravity'

Apparatus:

rectangular glass or plexiglass tank (any size)
rectangular blocks of wood and styrafoam

Archimedes principle is based on the assumption that if we place a rigid body in a fluid, the molecular rebounds from its surface will have the same momentum as would the molecular flux from the fluid previously there, and hence the vertical force on the rigid body must equal (minus) the weight of the fluid previously there. This is simply a symmetry argument for an ideal gas, but is a more touchy assumption for a fluid. Perhaps we should just say that if it is not true, we can blame 'chemical reaction' between the fluid and solid molecules. But, it seems to work: the net 'buoyancy' (the force due to pressure exerted on an immersed object) is equal to the weight of fluid replaced by it. So Archimedes was handed a crown of complex shape and asked to measure its density to determine whether it was gold or some more base metal. He could have weighed it, and then immersed it in water to measure its volume by the amount of water displaced, but a simpler procedure is to weigh it in (W_1) and out of (W_2) water. Now, $W_1 = g\rho_{crown}V$ and $W_2 = W_1 - g\rho_{water}V$, where V is the volume of the crown. Two eqns. in two unknowns, so

$$\rho_{crown}/\rho_{water} = W_1/(W_1-W_2)$$

and the kingdom was saved.

This is the basis of floating and buoyancy. A partially immersed 'spar buoy' of mass M has a hydrostatic pressure force supporting it, and if it is displaced upward or downward and then let go it will oscillate. A model can be constructed by assuming the hydrostatic pressure law is correct even in the presence of motion. This gnores the inertia of the water movement and is thus approximate (questions of the stability of floating objects, whether they float 'vertically' or 'horizontally', can be worked out using simple hydrostatic pressure ideas, and have application to the rolling over of icebergs, and the floating of 'dead-heads' (logs that float nearly vertically in Puget Sound).

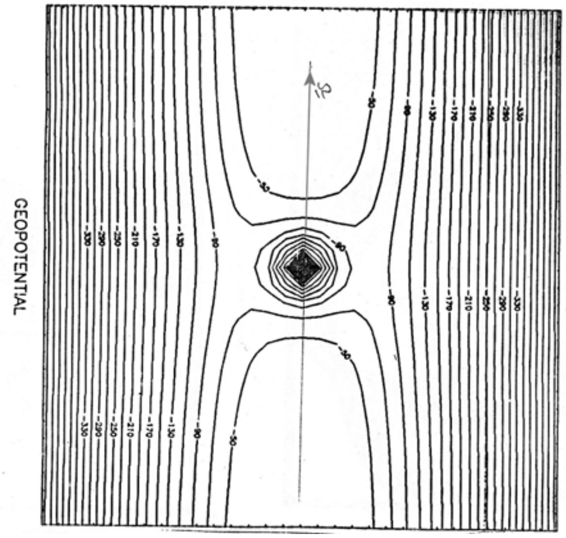
Implicit in all this is hydrostatic vertical force balance. For a fluid at rest, the two active forces (per unit mass) are the pressure force $-\nabla p/\rho$ and the gradient of the geopotential field, $-\nabla\Phi$. Φ is best thought of as the potential energy of a particle moving in the Earth's gravity field, yet in the rotating frame of the Earth, giving the two contributions

$$\Phi = -\frac{GM_{Earth}}{r_3} - \frac{1}{2}\Omega^2 r_2^2$$

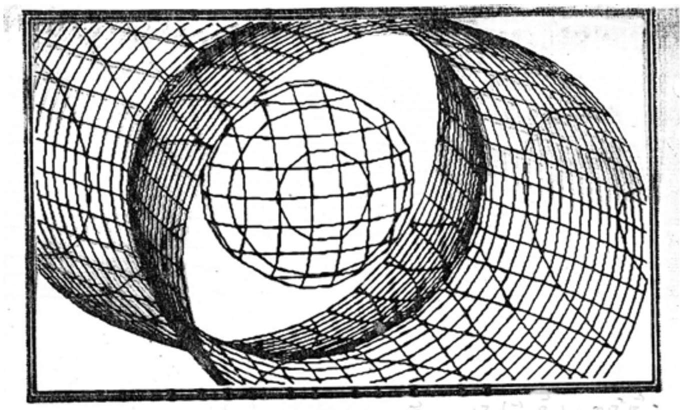
where G is the gravitational constant, Ω is rotation rate, r_3 is spherical radius, and r_2 is cylindrical radius measured from the rotation axis. This point-mass approximation works if the Earth is approximately spherical. The true-gravity part dominates near the Earth's surface, and we write

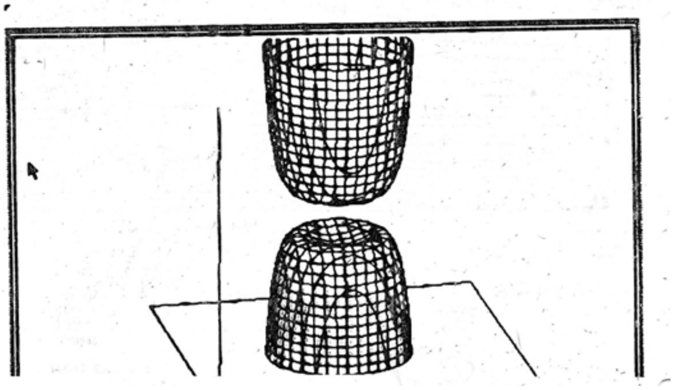
$$\Phi \approx gz$$

where g = 9.8 m sec^{-2} (at sea level, ± 0.3% variation with latitude) and z is the local vertical coordinate. The Φ=const surfaces are slightly distorted spheres (with an equatorial bulge, the equatorial radius, 6378km, exceeding the polar radius by about 21.4 km,) while further out they turn into cylinders. At a radius about 36,000 km above the Equator, the gradient of Φ vanishes, and there sit geostationary satellites.



Views of the Earth's geopotential (Φ=const) surfaces.





On a laboratory rotating table (radial coordinate r), by contrast, the appropriate geopotential is

$$\Phi_{lab} = -\tfrac{1}{2}\,\Omega_{table}^2\, r^2 + gz$$

so that equipotentials (the fluid free surface being one) are just paraboloids of revolution.

Hydrostatic balance is

$$\nabla p/\rho = -\nabla\Phi$$

which can only be satisfied if p and ρ are constant along geopotential horizons, Φ=const. (hence $\partial p/\partial\Phi = -\rho$)

In a stratified ocean or atmosphere these buoyancy effects are subtle indeed. We showed a column of salt-stratified water in which the density ranged from about 1.2 g cm^{-3} to 1.0 g cm^{-3}. This is enough to float a piece of plexiglass! In the oceans, the density is 1.035 g cm^{-3} to within about 2%, and most of this 2% is dynamically inactive, as it is just adiabatic compression. A typical water column has about 2×10^{-3} fractional change in potential ('dynamically active') density from top to bottom. This corresponds to an empirical equation of state $\rho(T,S,p)$ with 'slope' coefficients

$$\alpha \equiv -\frac{1}{\rho}\frac{\partial \rho}{\partial T} = 0.75\mathrm{x}10^{-4} \quad (T = 2C, S = 35ppt, p = 0)$$

$$= 2.75\mathrm{x}10^{-4} \quad (T = 22C, S = 35ppt, p = 0)$$

$$\beta \equiv \frac{\partial \rho}{\partial S} = 0.75 \quad (T = 22C, S = 35ppt, p = 0)$$

Note how small the thermal expansion becomes at low temperature. This means that in subpolar regions thermal convection is reduced in intensity, and ‘haline’ (salt-driven) convection is particularly important. In the tropics, the thermal expansion of water is great, but so too is the evaporation, which leaves more saline water behind when the surface is warmed. Convection can involve both effects.

A perfect gas is much simpler than water, with $p=\rho RT$, α is just 1/T at constant pressure; the vertical density profile is exponential, $\rho=\rho_0 \exp(-z/H)$ for a choice of isothermal, resting atmosphere (the e-folding scale H being RT/g ~ 8 km).

More active pressure. In a steadily flowing fluid, constant-density, inviscid fluid there is a first integral of the momentum equation, showing that $B \equiv p/\rho + ½ |\mathbf{u}|^2 + gz$, the Bernoulli function, is conserved along streamlines. Ignoring gravity for now, this shows how the pressure falls as fluid accelerates into a constriction in a channel (with rigid surface). It is somewhat counterintuitive, for we think of jets of fluid ‘blowing’ solid objects in their path, but it must be true, because the pressure gradient that accelerates the fluid along its path is then in the right sense. That force comes from the slow-flow region near the stagnation streamline, however. Low pressure regions exist elsewhere (and can causes houses to ‘explode’ in violent winds). A ping-pong ball tethered to a thread is sucked into a stream of air or water, proving this point (sketch the streamlines to see the region of fast flow). Likewise, the ball suspended in an air jet is stabilized by this effect; if it wanders out, the fast-flow region is on the side nearest the jet, and this sucks the ball back into the stream. You can pick up a piece of paper by blowing an air jet on it!

In GFD the use of hydrostatic balance gives the free surface a special role in interesting flows: the height of the surface is proportional to pressure, and for an unstratified flow, this height profile maps out the horizontal variation of pressure below. We will see many examples of this effect in channel flows later in the term; here we looked at tornado vorticies produced by swirling flow in a cylinder. If (roughly) angular momentum is conserved for rings of fluid moving inward, we have rv=const (v=swirl velocity, r=radius). Now the radial mom. balance is $\partial p/\rho\partial r = v^2/r$, so together we have

$$p = \text{const}/r^2$$

where we use the fact that the atmospheric pressure is nearly constant along the water surface.

With hydrostatic vertical balance, the surface height h is given by

$$gh = \text{const} + p/\rho = \text{const} - \text{const}/r^2.$$

Now, I said 'roughly' above because in fact friction forces in the lower boundary layer are important and a significant part of the radial inflow occurs in that layer (as in a real tornado). Recall the cylinders of dye orbiting round the core, and only slowly flowing out the drain. Nevertheless, a 1/r (irrotational!) swirl profile is not a bad approximation, and in nature leads to wind-speeds in excess of 100 m $\sec^{-1}$ and very low core pressures. The *ex*plosive effects of tornados on buildings can be seen in videos like *Cyclone* by National Geographic (whereas all the tornadoes in the movie *Twister* are computer graphics).

In the sunlight you can often see vividly the vortices near the surface of a swimming pool, the deflections of the free-surface acting as lenses.

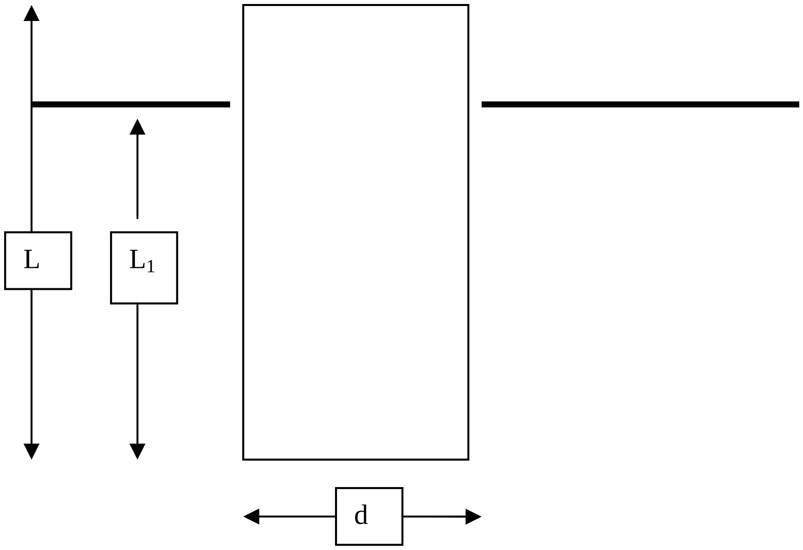
Stability of floating objects. If a rectangular polyhedron floats on a water surface, will it also float happily, after being rotated 90^0 to the vertical? A log floats lying on the sea-suface, yet sometimes you see logs floating vertically ('dead heads') or at an angle. A very light solid of foam rubber floats either way. The stability can be studied by tipping the solid slightly, and seeing whether it erects itself or tips completely over. This can be worked out by calculating the moment of the hydrostatic pressure-force about the center of mass of the object: this torque will either restore equilibrium or cause a tip-over. For the rectangular floating solid sketched below, the result of this calculation is that for stability:

$$d^2 > 6L_1(L-L_1)$$

which implies that the aspect ratio obeys

$$\frac{d}{L} > \left[6\frac{L_1}{L}(1-\frac{L_1}{L})\right]^{1/2}$$

The lesson is that objects float stably if they are short and squat, or if they float low in the water (their specific gravity ≡ density of solid/density of water is close to 1), or if they are very buoyant with small specific gravity, $L_1/L \ll 1$. This latter case is easy to see with styrafoam blocks.



(6) Rising bubbles and breakable water

Bubbles of air rise in a fluid due to the buoyancy force. Think about the way their diameter increases as they rise. How does it depend on atmospheric pressure? Investigate this in a cylinder of water, and then in a glass tube in which most of the air has been removed, yet there is water. The evacuated tube has nearly zero atmospheric pressure and this has many interesting effects.

The water breaks apart (evaporating in one place, condensing in another) and gaps open up readily. As the tube is tipped back and forth, the water 'clinks' like metal or glass, as air bubbles and their cushioning effect are then absent. It is interesting that if a small amount of residual air is present, the apparatus acts and 'feels' like normal water until it is shocked (accelerated abruptly), whence the phase change and 'clinking' are induced. The process of boiling and condensing very quick...effectively instantaneous compared to other atmospheric time scales (but, could a standing sound wave induce a regular pattern of vapor bubbles?).

Note also how a rising bubble in this apparatus grows in size as it comes to the top of the liquid. This is expected, as the hydrostatic pressure varies with depth below the free surface. At atmospheric pressure, the height scale over which the pressure in a water column varies is about 10m (~ 10 decibars ~ 1 bar of pressure). So in a glass of beer, the rising bubbles would not appear to increase in size noticeably (if it were not for the bubbles 'scavenging' more gas from the beer as they rise). Here however the pressure is much reduced: you could use the observed bubble expansion to measure the pressure! The trick in all this is to know when the bubble is adding more water vapor by phase change, and when it is not. Rapid shaking of the tube produces dynamic pressures that force a lot of fluid to 'boil' and become gaseous; however a more gentle experiment the water vapor can be in equilibrium with the liquid, so that the vapor pressure (and amount of vapor) is a function of temperature only.

something useful: the siphon

The hydrostatic pressure principle, and Bernoulli's equation for more general flows, explain the wonders of the siphon: in an inverted U-tube, water rises a great distance before falling down the other arm and exiting. The siphon is such an important tool in the laboratory that it deserves a brief introduction. It is useful for transferring water from source buckets to experimental apparatus, and in providing a continuous inflow to model jets and rivers. Making a siphon work is an exercise in humility. Some rules: wide diameter tubing makes for a fast-flowing siphon, yet is difficult to start (and stop!). Thin tubing works fine but is slow. Start a siphon by filling the tube with fresh water, pinching in firmly near the middle (which will prevent flow everywhere in the tube) and immersing one end in the source water. Both ends should be secured, for example guiding them loosely through a pinch clamp. The normal accident is that the tube is not secured, the inflow end flips up above the water surface and the siphon is 'broken'. Sucking fluid from one end, the siphon can be reestablished but only at the expense of a large mouthful of (perhaps salty) water. It is not necessary, and may even be dangerous, to suck fluid into tubing. By holding the tube under a water tap or immersed in water, it can filled without oral contact.

When stratified fluid is involved, usually salt- and fresh water, it will be necessary for the outflow to be gentle; a diffuser is described in a later lab, which holds the top on the floor of the tank and spreads the outflow to reduce turbulence.

Large-diameter siphons are useful for rapid draining of tanks. These can be filled in a sink, and carried to the tank, holding an end in each hand. Often a bubble will appear at the high point, stopping the flow. It can in fact be removed by threading a much smaller tube into the large one, and sucking the air bubble out.

Pinch clamps, to control the flow rate in a siphon, are indispensable, yet it is not easy find good ones. Medical apparatus provides a useful family of thumb-roll controlled valves. A small C-clamp works, but is somewhat unstable. Spring clamps, used with thin tubing doubled over, work also. Having a good clamp means that the siphon can be set up and then pinched off, so that an experiment can be started and stopped quickly.

The siphon is rather difficult to get right; wouldn’t it be nice to invent a ‘self-priming’ siphon that would start up whenever the water level exceeded a certain height? Imagine how this might be done. One way is to use capillary fluid-surface effects, which cause fluid to climb up a wick. A piece of string draped over the edge of a beaker of water will eventually drain it out! Try it.

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