Lighter than air

The expression **lighter than air** refers to objects, usually aircraft, that are buoyant in air because they have an average density that is less than that of air (usually because they contain gases that have a density that is lower than that of air). Examples include balloons, airships, and aerostats. The opposite expression, heavier than air, refers to aircraft, such as aeroplanes and helicopters, that have a greater density than air.

Derivation

At low densities, the behaviour of gases is well approximated by the ideal gas law

$$pV = nRT$$

where p is pressure, V is volume, n is the number of moles of gas, T is absolute temperature, and R is the universal gas constant.

Dividing both sides by V, R and T gives

$$p / RT = n / V.$$

Now multiply each side by A, the molecular mass of the gas in question:

$$pA / RT = nA / V$$

Notice that nA, the number of moles multiplied by the mass per mole, is simply the total mass of the gas. And mass divided by volume is density. So,

$$\rho = pA / RT$$

where ρ is the density of the gas. This equation shows that a gas with low density can be achieved by:

- Lowering p, the pressure;
- Lowering A, the molecular mass;
- Raising T, the absolute temperature; or
- Some combination of the above.

R is a physical constant and so cannot be changed.

Low pressure

The average density of an aircraft can be reduced, at least in principle, by creating a partial vacuum. The concept of an airship supported by the buoyancy of a vacuum has been explored in science fiction, but in practice the strength of the envelope must be so great in order to resist crushing by external atmospheric pressure that its weight exceeds the lift created by the vacuum. It may be possible in the future to construct a vacuum airship from advanced materials.

High temperature

The density of a gas can also be reduced by raising its temperature. Heated air is widely used in practice as a lifting gas in hot-air balloons (although, to be strictly accurate, the gas in a hot-air balloon is not just air, but also the products of combustion of the balloon's burner).

Low molecular mass

Since the average molecular mass of air is 28.8, any gas with a lower molecular mass will be lighter than air, even at the same temperature and pressure. This makes it possible to create a balloon with a thin, light envelope, and no need for constant heating. Assuming:

- the gas is composed of normal elements (i.e. no strange matter); and
- appropriate materials are chemically stable, and gases at reasonable temperatures

then the laws of chemical valence enable all of the possible choices to be enumerated quickly.

The heaviest possible atom that could meet these criteria is silicon. Silicon has an atomic mass of 28.1, so with just 0.7 atomic mass units left over, it would have to be a monatomic gas. Unfortunately, silicon does not become a gas until it reaches a temperature of over 2,000°C. The next lightest atom is aluminium, with an atomic mass of 27. The spare 1.8 units gives room for just one hydrogen atom, but AlH would not be stable, and plain Al is not a gas until 2500°C. Next would be magnesium, mass 24.3. With 3.5 units spare, it could combine with up to 3 hydrogen atoms. The stable number would be two, giving magnesium hydride, MgH_2. Unfortunately, neither magnesium hydride nor magnesium are gases at reasonable temperatures.

Proceeding in the same way through progressively lighter elements produces the following list of all stable materials with a molecular mass under 28.8 and a boiling point under 800°C:

Compound	Formula	Mass	Comments
Nitrogen	N_2	28	Majority component of air (~78%)
Carbon monoxide	CO	28	Toxic, flammable
Ethylene	C_2H_4	28	Flammable, reactive
Diborane	B_2H_6	27.6	Spontaneously flammable in air
Hydrogen cyanide	HCN	27	Very toxic, flammable, and water soluble
Acetylene	C_2H_2	26	Extremely flammable, reactive
Methyllithium	$LiCH_3$	21.9	Extremely flammable and reactive, explodes on contact with moisture
Neon	Ne	20.2	Noble gas
Hydrogen fluoride	HF	20	Very toxic, very corrosive, and water soluble
Water	H_2O	18	Boils at 100°C at sea level
Ammonia	NH_3	17	Somewhat toxic, slightly flammable, and water soluble
Methane	CH_4	16	Flammable
Helium	He	4	Noble gas
Hydrogen	H_2	2	Very flammable

All of these 14 gases—and no others!—are lighter than air at the same temperature and pressure. A number of them are clearly unsuitable to use as a lifting gas in a balloon, however. There are seven (carbon monoxide, ethylene, diborane, hydrogen cyanide, acetylene, methyllithium and hydrogen fluoride) which combine poor lift (mass close to 28.8) with highly objectionable properties. Nitrogen has negligible lift. Neon is harmless, and offers a modest degree of lift; however it costs roughly the same as helium, another noble gas with far superior lift. Four of the remaining five (ammonia, methane, helium, and hydrogen) have been used as balloon gases. Ammonia and methane have generally only been used for small scale experimental uses, since they are inferior to hydrogen on nearly every account. In particular, ammonia has sometimes been used to fill weather balloons, while methane—in the form of town gas or illuminating gas—has been used when nothing better was available. However, due to its relatively high boiling point, ammonia could potentially be refrigerated and liquified, allowing for an airship to easily reduce lift and add ballast.

Hydrogen and helium have been the most common choices for lifting gases. Hydrogen offers slightly superior lift, but the difference is negligible; helium is usually preferred whenever it can be obtained because it is not flammable. Many countries have banned the use of hydrogen as a lifting gas. The German Zeppelin Hindenburg is the frequently cited example for risks posed by hydrogen. However Addison Bain in 1997 published a paper discounting the role of hydrogen as a cause of the fire on the Hindenburg. Instead he focused attention on the role of the skin material of the Zeppelin which contained the ingredients used in Thermite, a rocket propellant ingredient. There is an ongoing debate about Bain's analysis and the safety of hydrogen as a lifting gas. Other researchers have recently conducted analyses and experiments that substantially refute Bain's theory. (See Hindenburg disaster for a detailed discussion of this controversy.) The relatively high cost of helium compared to hydrogen has led several researchers to reinvestigate the safety issues of hydrogen as a lifting gas with some positive conclusions regarding its use given sufficient crew and ground handling team training.

The one remaining gas, water, is worth a comment. Although it is not a gas at normal temperatures, its vapour pressure may allow it to contribute significantly to the lift of other gases, such as the combustion products in a hot air balloon. Unfortunately this situation is unstable; if the air cools, then lift-generating water vapour may become lift-sapping water droplets. However this process should occur quite slowly owing to water's high latent heat capacity. At higher altitudes—where the boiling point of water is below the ambient temperature—a pure water vapour balloon is easier to implement. Nonetheless, two research efforts are currently underway to build steam-based aircraft (See section below.)