Pressure changes in Rigid Inflatable Boats – the Nitrogen/humidity debate

Introduction

Nitrogen fills on car tyres are primarily for maintaining tyres at optimum pressure over a long period of time – i.e. the life of the tyre. Much like a balloon will shrivel over time, the gases in a tyre will diffuse (escape) through the rubber over time.

Diffusion of oxygen through of rubber faster than nitrogen. Pure oxygen diffuses around 3 to 6x more rapidly than pure nitrogen. Air (~78% N_2, ~21% O_2), therefore leaks out ~1.7 times faster than pure nitrogen. This varies with the construction of the tyre

Source: http://home.comcast.net/~prestondrake/N2_FAQ_Q04.htm

This long term stability is the main advantage to filling tyres with nitrogen.

This is for butyl rubber. You have to decide whether the diffusion through hypalon, polyurethane is comparable. The relative rates of diffusion of oxygen and nitrogen I would think are the same, but perhaps the absolute permeability is less (e.g. a nitrogen filled polyurethane rib would lose less pressure over a year than an air filled polyurethane rib, but compared to a rubber rib then both gases lose less pressure)

Above ~94% nitrogen, oxygen diffuses INTO the tyre, and this may offset the loss in nitrogen until it reaches equilibrium, but I would expect the rate of diffusion inbound to be minimal.

For tyre manufacturers, other claims are made in support of Nitrogen– noteably corrosion and degradation of rubber due to oxidation.

http://www.getnitrogen.org/pdf/Bridgestone.pdf

What we are really concerned about is the shorter term stability of pressure in the tubes over the course of a typical day – where the tubes are heated by the sun when it is on the driveway, then when the tubes are cooled as the boat sits on the water. Over this timescale we can assume that very little gas escapes the tubes due to diffusion, so any change in pressure is solely due to heat being added or taken away from the gas.(ignoring work done on the gas through compression and mixing as the tube bumps on the sea)

Abstract:

A tube filled with nitrogen would maintain more of its pressure 6 months down the line than a rib filled with dry or damp air (if you measured the tube pressures on days with the same temperature and atmospheric pressure). A common question is whether nitrogen aids with stabilising the

pressure in tubes or tyres when heated, and whether this affect is different for nitrogen, dry air and moist air.

Given a chance to equalise in temperature with the surroundings (the rib tube fabric) , heating tubes that started at the same pressure and filled with *any* gas will reach the same end pressure eventually .

However, what we care about is how the pressure changes throughout the course of a day – as the tubes heat up to their highest temperature in the sun on the driveway, and cool down to their lowest on the water.

It is the RATE at which the temperature – and hence pressure – changes that is dependent on the type of gas inside the tube. Left for a long enough time in the same conditions, the pressure in a rib tube will reach a level regardless of the type of gas inside the tube.

Introducing an identical amount of heat energy into the tubes that doesn't bring the temperature up to that of the surroundings, you would actually see a smaller change in pressure with damp air than either dry air or nitrogen, and the difference between nitrogen and dry air is negligible. An example might be recovering a rib from the cold sea and driving a short distance home on a hot day before reaching your boatshed. The gas in the tubes hasn't had opportunity to reach equilibrium temperature with the surroundings (the hot tubes heated by the sun), so upon reaching the boatshed, tubes filled with different gases will be at different pressures.

We will show below that air and nitrogen perform similarly in terms of pressure rise for a given quantity of heat added to a fixed volume of gas and that damp air heats up approximately 20% slower than either air or nitrogen for a typical RIB

Method:

We have three identical ribs

- Rib A is filled with pure nitrogen
- Rib B is filled with DRY air
- Rib C is filled with water vapour (to represent our rib filled with air on a humid day or with some residual moisture on the inside)

Each rib is filled to 2 psi gauge pressure, and has sat in a garage at 15 degrees C for a long time, on a day where atmospheric pressure is 1013 mb. We then take each rib out of the garage on a sunny day and drive 10 minutes to the slipway before dunking it in the sea. In the TIME it has taken us to get to the slip, the POWER of the sun has added a fixed amount of ENERGY to our tubes.

What will the pressure be of the tubes when we get to the slipway?

Each rib is ~5m long, with ~70cm diameter tubes, so contains ~ 4 cubic metres *volume* of gas.

Our ideal gas laws tell us that

$$P1.V1/T1 = P2.V2/T2. \qquad (1)$$

Where P1,V1,T1 are the starting pressure, volume and temperature, and P2,V2,T2 are our end pressure,volume,temperature.

For a fixed volume of gas, if we increase the temperature of our gas (by adding heat),then the pressure will increase if the volume is kept constant. We can work out the end pressure of the tubes if we know the start pressure, and the start and end temperature.

$$P2 = P1.T2/T1 \qquad (2)$$

Source: http://en.wikipedia.org/wiki/Ideal_gas_law

So it's all about temperature – if all ribs are at the same temperature, then the pressures will be the same regardless of what gas is inside them. If the tubes all sit out in the sun and have enough time to get into a steady state temperature – no longer heating, no longer cooling -then the end pressures reached will all be the same.

The key here is *how quickly* the different tubes change temperature.In our scenario Each rib has been exposed to the sun for the same amount of time, so has received the same amount of ENERGY from the sun, and hasn't had chance to reach its maximum temperature and pressure.

How much has each rib tube increased in temperature in the 10 minute drive to the slipway?

Observation 1) - - surely if one rib contained more *mass* of gass, it would take longer to heat up (increase the temperature) and therefore the pressure wouldn't fluctuate as FAST if heated by the same source.?

- ⇨ We have to work out how much MASS of gas is in each of the tubes at rest in the garage

Observation 2) surely if it took more energy to heat up a kilo of one gas compared to another gas, then again the temperature wouldn't increase as much if we gave it a fixed amount of energy?

- ⇨ We have to work out how much a gas' temperature rises for each unit of energy we give it.

Observation 3) what if one gas conducts heat better than the other – won't it heat up quicker in contact with the hot tube?

- ⇨ We have to consider the conductivity of each gas

Observation 1 explained:

The ideal gas law tells us the relationship between pressure, volume, the number of moles of a gas and the temperature

$$PV=nRT \qquad (3)$$

P=absolute pressure (in Pa)

V= Volume (in cubic m)

n = number of moles of a gas

R = universal gas constant (same for all gases)

T = absolute temperature (in kelvin).

We are comparing Air, Nitrogen, and water vapour which have different Molecular Weights (M), therefore we can define a new constant *Ri* being the individual gas constant for our given gas

$$Ri = R/M \qquad (4)$$

We can incorporate the individual gas constant into equation 3 and re-arrange to calculate the density of a gas at a given temperature

$$\text{Density} = P / Ri.T \qquad (5)$$

We can look up the values of Ri for Air, Nitrogen and water vapour, and therefore work out the density and hence MASS of gas in each of our ribs:

Gas	**Ri**	**density(kg/m3)**	**Mass of gas in our tubes (kg)**
AIR	287	1.39	5.57
Nitrogen	297	1.34	5.38
water vapour	461	0.86	3.47

So the rib with water vapour in it is less dense and has less MASS! So if we gave each of our tubes the same amount of energy would we expect the one with water vapour to reach a higher temperature because we don't have to heat up as much stuff? This may be the case if the specific heat capacities were identical, however…

Observation 2 explained:

… it depends on how much heat you have to give the gas to cause a given change in temperature. This is called the Heat Capacity Or, if we want to know how much energy it takes to raise one kilo of matter by one degree, we call it the Specific Heat capacity SHC. There are actually two values of specific heat capacity– one for if you let the gas expand as you heat it –(constant pressure (Cp)) and one for if you keep the volume the same as you heat it (Cv). It is the latter we are interested in as we are keeping our tube volume fixed.

The change in temperature *dT* of a mass *m* of gas, with SHC of *Cv*, when heated by an amount of energy *Q* is given as

$$dT = Q/m.Cv \qquad (6)$$

We are giving each of our ribs the same amount of energy (the sun's *power* gives an amount of *energy* in a given *time*), so the temperature rise is dependent on how much gas we have, and also the SHC of the gas. The more mass, and the higher the SHC, the smaller the change in temperature

The SHC of Nitrogen and Air are pretty similar (0.718 vs 0.743 kJ/kg.K), but water vapour is a whopping 1.46 – so it requires almost twice as much energy per unit mass to heat water vapour up by 1 degree than it does Nitrogen or Air.

So we have a tradeoff here –on one hand our water vapour rib has less MASS to heat up, but it takes nearly twice as much ENERGY to heat a given quantity of the water vapour up by the same temperature.

How does this work out? Lets assume we give each tube 100kJ of energy.(Instead of the sun, we use a 1kW fan heater, and somehow stick it inside each tube for just under 2 minutes). Equation 6 gives:

	Mass of gas in our tubes (kg)	SHC (Cv)	Temperature RISE (degrees C or K)
AIR	5.57	0.718	25.00104
Nitrogen	5.38	0.743	25.00162
water vapour	3.47	1.46	19.74916

So in our case it is heat capacity that is the greater influence than the mass of the gas in the tubes. As it happens, heat capacity always wins in this situation, because the densities of the gases are a fixed ratio for a given temperature. No matter what starting temperature or pressure or volume or amount of energy we give our ribs, the temperature rise of the water vapour rib is around 21% lower than the air rib.

What does this do to our pressures? Using Equation 2 to work out our end pressures:

	T rise	P1 (Pa)	T1 (K)	T2 (K)	=P2 (Pa)	=P2(psig)
AIR	25.00	115115	288	313.001	125108	3.449316
Nitrogen	25.00	115115	288	313.0016	125108.3	3.44935
Water Vapour	19.74	115115	288	307.7492	123008.8	3.144864

So after applying our heater, our air and nitrogen ribs are now sat at around 3.45 psi, and our water vapour rib is just 3.14 psi.

Crucially there is very little difference between air and nitrogen.

Observation 3 explained

The thermal conductivity of air, nitrogen, and water vapour at temperatures under 50 degrees C is practically identical, so if the sun is shining on a tube, the heat exchange between the gas and the tube material occurs at the same rate regardless of gas (air, nitrogen, water vapour) .As temperatures rise, humid air conducts heat less well than dry air, so if anything, humid air again doesn't heat up as quickly as dry air and therefore the pressure doesn't increase as quickly.)

http://www.electronics-cooling.com/2003/11/the-thermal-conductivity-of-moist-air/

Conclusion:

- A water vapour filled rib will experience a smaller change in pressure for a given input of energy than for air or nitrogen.
- Air and nitrogen experience practically identical pressure changes given the same energy input.
- Specific heat capacity of water vapour is the significant factor in determining pressure increase, as opposed to the density of the gas in the tubes.

Interpretation;

Tubes filled with 100% water vapour would a) weight less, and b) change pressure more slowly in sunlight / on the water. If it was a hot day and you quickly took the rib from your cool garage to the cool water (quick enough that the temperature on the journey does not reach a steady state), then the peak pressure reached by the tubes filled with water vapour would be lower than that of those filled with air or nitrogen. Leave all sets of tubes out in the sun for long enough and they will eventually get to the same pressure.

We've made lots of assumptions here – that no heat is lost from the tubes as they are being heated, that the tubes do not expand as the pressure increases, and that the gases absorbs heat from their surroundings at the same rate.