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P3_3 Vacuum Dirigibles

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Abstract

A concept for a vacuum dirigible based upon a membrane stretched over a rigid frame is discussed. An expression is derived for the maximum possible size of this design based upon the membrane properties. It is shown that even using a graphene membrane the maximum size achievable is on the order of tens of micrometres.

Introduction

The idea of a vacuum balloon has been around since before the first manned balloon flights. If possible, it could be the most effective displacement lifting technology. However, enclosing a vacuum is a substantial problem. It is fairly obvious that a steel vacuum chamber will never be lighter than air, so recently a proposal[1] has been made that stretching graphene sheets over a rigid frame could contain a vacuum, utilising graphenes impermeability to gases[2], and its record breaking ultimate tensile strength of 130GPa[3]. For the purposes of the investigation the support structure will be neglected, but it can be assumed this would add additional mass onto the overall load.

Lift Condition

First consider the effective criteria for lift,

$$\rho_a > \frac{Total\ \ Mass}{Total\ \ Volume},$$

essentially that the density of air must be greater than the density of the balloon. If we assume a thin walled balloon, we can assume that the total mass is given by

$$M_T = S \times t \times \rho_w,$$

where S is the surface area, t is the wall thickness and ρ_w is the wall density. Assuming a spherical balloon, we can write the lift condition as:

$$\rho_a > \frac{4\pi r^2 t\rho_w}{\frac{4}{3}\pi r^3},$$

which leads to the condition that

$$\frac{t}{r} < \frac{\rho_a}{\rho_w}\ (1).$$

Inserting densities for carbon and air into (1), the ratio is around 2000:1, which confirms that the wall must be very thin relative to the radius of the balloon.

Membrane Tension

In order to determine the tensile strengths acting on the material the basic design model needs to be fleshed out a little. The simplest design would be a golf ball like design, where the membrane stretches into dimples in the gaps in the frame. Then the tension in the sheet can be derived from the Young-Laplace equation,

$$\Delta p = \gamma \nabla . \hat{n}\ [4],$$

where γ is surface tension and Δp is the pressure at the interface. This can be solved for a spherical surface to give

$$\Delta p = \frac{2\gamma}{R}\ (2),$$

where R is the radius of curvature of the sphere. This now allows calculation of the tension on the surface membranes.

Dirigible Parameters

The ultimate tensile strength quoted above is the maximum stress which graphene can withstand without inelastic deformation. This can be related to tension using

$$Stress = \frac{Tension}{Thickness}.$$

There are a range of possible conditions now which determine possible dirigible sizes. Firstly, there is the situation where the radius of curvature is much larger (~10x) than the dirigible radius. Then from substituting R=10r into equation (2) we have the condition

$$r = \frac{130\times10^9\times t}{\Delta p\times 10}\ m.$$

If we substitute in appropriate values for pressure (100kPa) and thickness (1 Angstrom for a single graphene layer) the value of r calculated is 10^{-5}m.

Discussion

It is possible to increase the possible radius by reducing the radius of curvature of dimples, but this would lead to increased need for support structure, and increased mass. Another possibility is using multiple layers of graphene. Whilst this is an obvious method for increasing the possible size, stacked graphene is only loosely bound by van de Waals forces[5], meaning its effective tensile strength would be considerably lower than monolayer. Above around 10-15 layers its properties also gradually become more similar to that of bulk graphite[5], which is not flexible enough to be used as a membrane.

Conclusion

Despite the allure (for some) of a vacuum dirigible, it appears to be impossible to achieve using the strongest known materials. This investigation has also not touched upon the question of what internal support structure could be used, which probably requires extreme material properties.

A vacuum dirigible would lift more than a hydrogen or helium filled balloon of equivalent volume, it would have a very low mass and hence be easy to accelerate and it would have no risk of exploding into flames. However, even if it were possible to produce, the vehicle would still only have a lifting power of the density of the air it displaced. In this light then, the impossibility of a vacuum dirigible is not overly troubling.

References

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