BUOYANCY ESTIMATION OF A TITAN AEROSTAT

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ABSTRACT

Based on terrestrial laboratory experiments, estimates are presented for the buoyancy of a Titan Montgolfière with a single-wall natural-shape envelope. Using the experimental results, the internal free convective heat transfer rate derived was found to be significantly lower than has previously been assumed. Preliminary estimates of the down force caused by rain and downdrafts are made. Modulation of buoyancy is also briefly addressed.

1. INTRODUCTION

1.1 Titan Montgolfière

Titan has a thick atmosphere that permits that world to be explored by a variety of aeronautical platforms. The use of such platforms would permit *in-situ* investigation and high-resolution aerial remote-sensing of Titan's diverse surface geomorphology including lakes and seas as well as rugged, fluvially-incised terrain and vast dune-fields. The atmosphere has many climatological parallels with the Earth's, albeit much colder and with methane as a cloud-forming greenhouse gas instead of water.
Titan aerial platforms have been advocated in a range of mission studies [1-6] including the 2007 NASA Titan Explorer Flagship mission study [2], and the joint NASA/ESA Titan-Saturn-System-Mission Flagship study [3]. The actual platform advocated in both these studies was a Montgolfière balloon where Titan atmospheric gas is warmed by the 'waste' heat from a Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) of the type currently flying to Mars on MSL: this unit yields about 100 W of electrical power with a thermal heat output of about 2 kW.

1.2 Key Research Issues

For the preliminary design of a Titan Montgolfière, three key research issues are:
i) Accurate prediction of the aerostat buoyancy for a prescribed MMRTG heat output at quasi-steady equilibrium [3, 4, 7].
ii) Worse-case prediction of the downward force that would arise if and when storms with methane precipitation are encountered [3].
iii) Estimation of the buoyancy modulation that could be achieved using appropriate (low risk) devices.
This paper presents some recent experimental and theoretical efforts to tackle these key issues.

1.3. Further Background

Samanta et al. [7] have conducted buoyancy experiments using a near-spherical envelope in a cryogenically cooled nitrogen gas test facility intended to approach Titan atmospheric conditions. At cryogenic temperatures radiation heat transfer effects are relatively unimportant and may be ignored. Good matches were reported between experiment, computational models and existing free convective heat transfer correlations. This led Samanta et al. to conclude that the buoyancy of an aerostat with a single-wall envelope varies approximately with the (MMRTG) heat output raised to the 3/4 power. However, their experimental results appear to show a significant departure (or deviating errors) from this rule. There is also some disagreement concerning the most accurate heat transfer correlations that should be adopted [8]. Consequently, a reinvestigation of buoyancy estimation models is worthwhile.
Section 2 offers a preliminary report of a low cost aerostat buoyancy experiment that was performed using an electrical heater unit to warm air within a "natural-shape" envelope in ordinary laboratory conditions. Of course, external radiation heat transfer becomes dominant at room temperature. Despite this drawback, good agreement was found between the experiment and an analytical heat transfer model. The approximate 3/4 power rule was confirmed, although the extrapolated buoyancy at cryogenic conditions was found to be about 30% greater than predicted by Samanta et al. for the single-wall case [7].
Whilst this particular result eases the overall design challenge, the issue of Titan storms raises a major problem. According to Barth and Rafkin [9] storms are likely to exist, mainly in the polar areas of Titan. Based on their simulations, methane precipitation rates of up to 130 kg m^{-2} over a 5 hour period with downward winds as high as 3 ms^{-1} are possible. If such conditions

were encountered, then they would pose a significant mission risk to a Titan Montgolfière. It was therefore deemed necessary to predict the resulting heaviness and down-force.

Section 3, offers a preliminary report of a simple laboratory-based “drizzle experiment”. This work was conducted in order to estimate how much heavier a near-spherical balloon becomes when placed in a light shower of water. The results were subsequently used to partly verify a simple analytical relation derived through dimensional analysis. Although approximate and in need of verification, the analytical relation presented in Section 3.1 is subsequently used to extrapolate the heaviness that would result when a Titan Montgolfière encounters methane rain. The actual increase in heaviness is predicted much more than previous estimates [4]. Furthermore, the downward force caused by associated vertical storm winds is too large to be manageable, i.e. such storms would have to be avoided.

Section 4 speculates on a possible buoyancy modulation scheme. During the buoyancy experiments described in Section 2, the test configuration was found to be an important factor. When the heater was placed inside the envelope, the buoyancy was about 11% larger than when it was placed below and outside the envelope. However, in the latter configuration it was possible to easily modulate the buoyancy by placing an obstruction in the thermal plume rising from the heater to the envelope. This basic observation suggests that it may be possible to eliminate the crown valve of a Titan Montgolfière and replace it with a simple valve-like device placed just above MMRTG.

Section 5 offers some brief recommendations and motivational comments for future work.

2. BUOYANCY AND HEAT TRANSFER

2.1 Overview

At equilibrium conditions, the heat transfer from the MMRTG is known: about 2 kW. The estimation of the buoyancy of a Titan Montgolfière requires knowledge of the average internal gas temperature. This temperature essentially depends on two processes: first, the free convective heat transfer between the MMRTG, and the inside surface of the envelope (through the enclosed internal gas); second, the external free convective heat transfer between the outer envelope wall surface and the ambient atmosphere. (The heat transfer through the envelope wall itself only results in a negligible temperature difference, unless some form of insulation is employed.) These two processes are fundamentally coupled, but to simplify modelling in previous studies [3, 4, 7] they are effectively disconnected by assuming the envelope wall has a uniform (or average) wall temperature.

To estimate the external heat transfer, the Nusselt-Rayleigh correlation of Churchill [10] has been used previously [e.g., 4]. Although the applicability of this correlation should be re-questioned for natural-shape envelopes with non-uniform wall temperature distributions, it is assumed that the likely variation of the coefficients involved would not result in large changes in derived buoyancy.

To estimate internal free convective heat transfer, Samanta et al. [7] used an unsubstantiated correlation quoted by Carlson and Horn [11] which was based on another offered by Kreith [12]. Evidence from the experiments outlined herein suggests that the correlation used by Samanta et al. over-estimates the heat transfer rate.

2.2. Similarity Conditions

The net buoyancy of the aerostat may be written as,

$$B = (\rho_a - \rho_b)gV = \rho_a gV\left[1 - \frac{P_b R_a T_a}{P_a R_b T_b}\right] \qquad (1)$$

where: P_a is the ambient pressure at a datum height, P_b is the average internal pressure inside the aerostat envelope, R_a is the ambient gas constant, R_b is the internal gas constant, T_a is the ambient temperature at the datum height, T_b is the average internal gas temperature, ρ_a is the ambient density, ρ_b is the average gas density inside the envelope, V is the aerostat envelope volume, and g is the gravitational acceleration. Ignoring pressure and composition differences between the ambient atmosphere and the gas contained within the envelope, Eq. (1) reduces to,

$$B = (\rho_a - \rho_b)gV = \rho_a gV\left[1 - \frac{T_a}{T_b}\right] \qquad (2)$$

When $\Delta T = T_b - T_a$ is much smaller than T_a,

$$B \cong \rho_a gV\Delta T / T_a \cong \rho_b gV\Delta T / T_b \qquad (3)$$

The Grashof number for the internal free convection heat transfer may be written as,

$$Gr = \frac{gL^3(T_b - T_w)\rho_b^2\beta}{\mu_b^2} \qquad (4)$$

where μ_b is dynamic viscosity of the internal gas and $\beta \cong T_b^{-1}$ (for an ideal gas), L is the diameter (or some representative length-scale) of the envelope and T_w is the average wall temperature. Again assuming small temperature differences (resulting in small differences in gas properties), and assuming that the internal heat transfer is the dominant thermal resistance such that, $T_b - T_w \cong \Delta T$, combining Eq. 3 and 4, it follows that $Gr \approx \lambda^3 B\rho_a / \mu_a^2$ where $\lambda = L/V^{1/3} \approx 1$.

In order to achieve similarity conditions between Titan and any representative test conducted on Earth (with a similar geometry), it would therefore be necessary to match the product, $B\rho_a / \mu_a^2$.

At 8 km altitude, the pressure, temperature and density of the Titan atmosphere are $P_a \cong 97500$ Pa, $T_a \cong 85.5$ K, $\rho_a \cong 3.85$ kg m^{-3} (Huygens Atmospheric Structure Instrument, L4 profile as archived on the PDS Atmospheres Node) respectively. For a nitrogen plus methane mixture with a CH_4/N_2 mass ratio of 0.025 [13], NIST-14 software yields a dynamic viscosity of $\mu_a \cong 6.2$ μPa s. Hence, for a total float mass of 200 kg (say) with $g \cong 1.34$ N/kg, $B\rho_a / \mu_a^2 \cong 2.7 \times 10^{13}$.

(Note: to match this condition in an Earth-based test using air, at sea-level, would require testing an envelope with $B \cong 7000$ N. Assuming $\Delta T = 5$ K, this implies a test envelope with a volume of about 36,000 m^3, i.e. with a radius of about 20 m.)

The Prandtl numbers for Earth and Titan conditions are both close to 0.75. Hence, in order to match Titan conditions, tests at Rayleigh numbers of about 2×10^{13} are required. The only experiments that have been conducted at such high *Ra* values have been done in closed vessels containing cryogenic helium gas. For example, Niemela et al. [14] report measurements in the range $10^6 \le Ra \le 10^{17}$. The Nusselt relation they give is, $Nu = 0.124 Ra^{0.309}$, i.e. the Nusselt number expected would be about 1600. Samanta et al. [7] use the relation $Nu = 0.325 Ra^{1/3}$, which yields a Nusselt number of 9700 (i.e. a predicted heat transfer rate that is about 6 times higher).

2.3 Experimental Apparatus

Figures 1 and 2 depict two experimental rig configurations that were used to measure the buoyant lift force of an electrically heated balloon in laboratory (room temperature) conditions. The so-called "natural-shape" envelope was selected since it was considered more representative of any likely flight geometry than a sphere. The envelope shape was calculated using the method given in ref. [15]. The envelope material was a laminate of aluminised polyvinyl-fluoride and a polyester scrim, with a mass-to-area ratio of 40 g/m^2. The reflective aluminised side was placed on the inside of the envelope. Gores were taped and then stitched together with the seams on the inside. The envelope's maximum diameter varied with changes in buoyancy and was measured to be 5.05 ± 0.05 m. The open neck of the envelope had a diameter of approximately 800 mm. The envelope volume was estimated to be 56 m^3.

In "Configuration 1", the electric heater was placed about 2 m below the envelope neck in a slanted box made from Cogemicanite 505M panels. Four spring balances attached to box and the envelope neck were used to measure the buoyant lift. This method proved to be less accurate than was expected. Also, no measurements were made of the heat loss to the laboratory floor or box side walls. Consequently only one quantitative result from this configuration test is reported below.

In "Configuration 2", the electric heater was mounted inside the envelope on top of a tower passing through the neck. The tower was a lightweight aluminium-alloy truss structure with a height of z_h = 2.6 m. Heat conduction from the heater through the truss was assumed to be negligible. The balloon was free to drift up and down the tower (without touching the neck) within a prescribed vertical limit of ± 0.1 m. The height of the neck was nominally z_{neck} = 2 m above ground, i.e., the vertical distance between the base of the heater and the envelope was nominally 0.6 m. However, the experiment was also repeated at heights of z_{neck} = 1.6 m and 2.5 m.

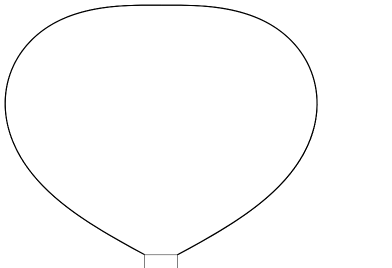

Fig. 1. Electrically heated balloon "Configuration 1", see acknowledgements.

For Configuration 2, the electrical load to the heater (actually 4 heater units) was varied in a stepwise manner between 3.2 kW and 6.1 kW allowing at least 1 hour for equilibrium to be reached after each step change. The thermal output from the heater was assumed to equal the electrical input power (i.e. power cable thermal losses were ignored). Weights were carefully added to the neck rim, until a state of near-neutral buoyancy was achieved. The accuracy of the total weight measurement (including the balloon itself) was deemed to be ± 2 N. Errors in fluctuating electrical power were less than 1%. The temperature of the envelope was measured using K-type thermocouples on the crown and maximum diameter flank. External pictures of the envelope were also taken using a Forward Looking Infra-Red (FLIR™ E60) thermal imager. In order to match the thermocouple measurements, the imager was set-up with a emissivity setting of $\varepsilon_w =$ 0.75, which was thought to be close to the actual external wall value. Finally, the vertical flow velocity was measured immediately above the heater-units using an Omega HHF-SD1 hot-wire anemometer.

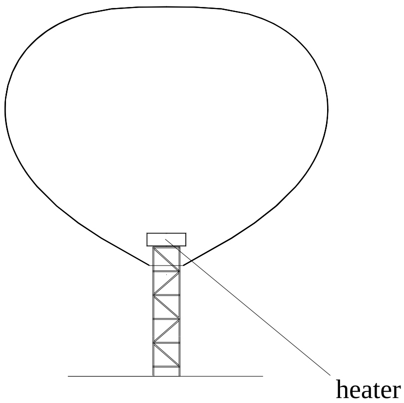

Fig. 2. Electrically heated balloon "Configuration 2".

2.4 Results

For Configuration 2, as the electrical power input P_e to the heater was slowly decreased (as described above) from about 6.1 kW to 3.2 kW, the buoyant lift decreased as $P_e^{0.7}$. A similar variation was found when P_e was subsequently increased back up to 5.8 kW, see Fig. 3. Varying the heater height above the neck (as specified in the previous section) only altered the buoyancy by ± 1 N.

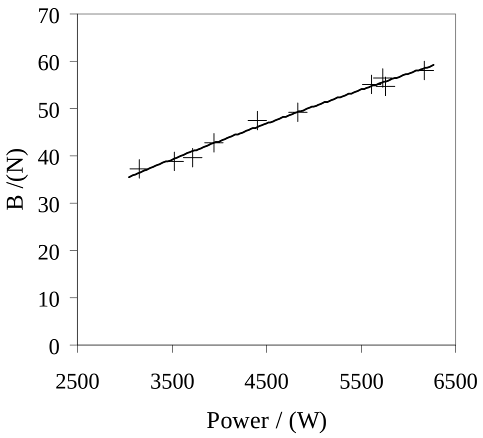

Fig. 3. Buoyant lift *vs*. electrical power input, for "Configuration 2".

As might be expected, the thermal distribution of the envelope was far from uniform. The highest wall temperature measured, at the crown, was about 41°C (20 K above the ambient temperature) when $P_e \cong 6.1$ kW. The wall flank temperature at the maximum diameter at this condition was 29°C (8 K above ambient). A thermal image is shown in Fig. 4. This casts considerable doubt on the validity of using heat transfer correlations based on an average wall temperature condition, e.g., as done in ref. [3]. Flow velocities immediately above the heater were typically about 0.5-1 m/s.

For Configuration 1, shown in Fig. 1, the buoyancy variation was similar, although the confirmed buoyant lift was 10-11% lower at $P_e \cong 6$ kW. It was also noticed with this configuration that it was also possible to easily modulate the buoyancy by obstructing the convective flow above the heater units with a small baffle (see Section 4).

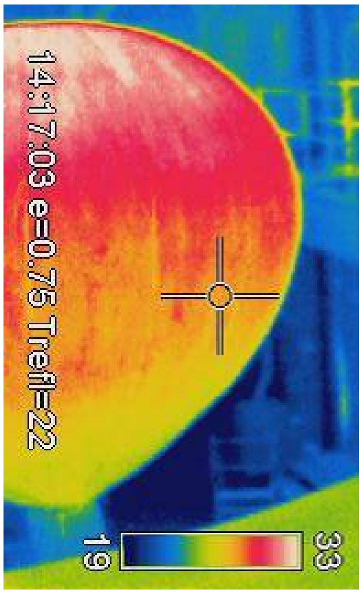

Fig. 4. Infra-red image of heated envelope ("Configuration 2"), showing increase in wall temperature towards the crown.

2.5 Comparison with Theory

A theoretical model including radiation heat transfer was developed in order to derive the internal convective heat transfer rate. For Configuration 2, the best fit between model and experiment was found using a Nusselt-Rayleigh relation lying between that of the relation given by Niemela et al. [13] and the one used by Samanta et al. [6]. The exact coefficient values were sensitive to the emissivity value assumed (which still needs to confirmed), but the use of Kreith's correlation [11] resulted in a buoyancy prediction than was within 5% of the experimental results shown in Fig. 3. However, in reporting this result, it should be stressed that the model used the external free convective heat transfer correlation of Churchill [9], whose applicability in this case must now be questioned.

Extrapolating these preliminary results to Titan conditions, at 8 km altitude with a thermal conductivity of 0.0091 $Wm^{-1}K^{-1}$ [16], predicts that a natural-shape envelope with a maximum diameter of 17 m, would be capable of lifting 200 kg with a MMRTG thermal output of Q = 1800 W and B would vary with $Q^{0.73}$.

3. HEAVINESS CAUSED BY PRECIPITATION

3.1 Analytical prediction

The fall and accumulation of liquid methane drizzle on any Titan aerostat envelope will result in a down-force, and the resulting need for a buoyancy margin to prevent the aerostat from drifting downward.

In order to determine the down-force, a non-dimensional drizzle parameter is defined as,

$$N = \frac{\dot{m}_A^3}{\rho_L^2 \mu_L \; g} \qquad (5)$$

where $\dot{m}_A$ is the mass flow rate of drizzle per unit of sky area, and ρ_L and μ_L are the density and dynamic viscosity of liquid methane, respectively. Assuming the steady down-force on a spherical envelope is only dependent on these drizzle properties, the gravitational acceleration and the envelope radius, r, then dimensional analysis indicates a possible expression for down-force is,

$$F_L = g\dot{m}_A r^2 \left(\frac{\mu_L}{\rho_L g^2} \right)^{1/3} f(N) \cdot \qquad (6)$$

However, it should stressed Eq. 6 is just a preliminary suggestion, primarily intended to provoke scientific discourse on the topic.

3.2 Experimental Apparatus

In order to investigate the validity of Eq. 6, a simple apparatus was set up to create a reasonably uniform water drizzle flow over a near-spherical latex balloon whose inflated radius was varied from about 0.4 to 0.7 m, see Fig. 5.

The resulting down-force was recorded by hanging the balloon from a digital balance above the shower head. Drizzle mass flow rate was varied between 0.01 and 0.03 $kgm^{-2}s^{-1}$.

3.3 Results

The drizzle experiment consistently revealed a thin continuous liquid layer on the upper part of the balloon, followed by transition to trickle flow, always near the maximum diameter, see Fig. 6.

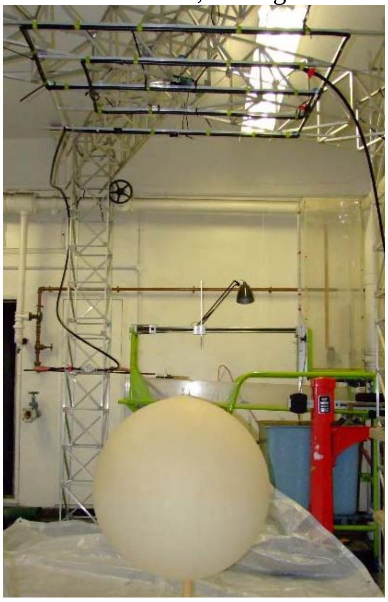

Fig. 5. Drizzle experiment set-up by Nevzat Atakan, see acknowledgements.

A reasonable fit between the experimental results and Eq. 6 was found when using, $f(N) \cong 161 N^{-0.244}$.

A numerical example is useful: for r = 0.5 m and a mass flow of 0.0322 $kgm^{-2}s^{-1}$, Eq. 5 gives $N \cong 3.4 \times 10^{-9}$ and $f(N) \cong 18{,}750$. Hence the down-force is predicted to be 3.23 N. The actual measured value at this flow rate was 3.17 N (corresponding to the weight of a film of water with average film thickness of about 0.2 mm over one hemisphere). Whilst similarly good agreement was obtained over the measured range, further work is required to verify the generality of this result. In particular, the influences of droplet fall speed, liquid surface tension and wall surface properties need to be investigated.

Fig. 6. Drizzle experiment using 0.7 m latex balloon using red-dyed water, showing transition from sheet flow to trickle flow, courtesy of Nevzat Atakan, see acknowledgements.

3.4. Flight in Titan (Storm) Conditions

In Section 2.5 it was estimated that a natural-shape envelope with a 17 m diameter would be sufficient to lift a total balloon mass of 200 kg at 8 km altitude. However, a buoyancy margin would be needed to cater for methane precipitation (see section 1.3).

Using a liquid methane density and viscosity of 447 kgm^{-3} and 1.8×10^{-4} kg m^{-1} s^{-1}, respectively, r = 8.5 m, $\dot{m}_A = 0.008$ kg $m^{-2}s^{-1}$, and Eq. 6 with $f(N) \cong 161N^{-0.244}$, predicts $F_L \cong 67$ N (corresponding to an average film thickness of 0.25 mm over hemisphere with the same diameter). This result is far higher than a previous estimate [4]. Furthermore, this precipitation level would also be accompanied by downdrafts [8]. In the case of a steady downward wind, the additional buoyancy needed to overcome both the weight of the liquid methane accumulated on the envelope and downward drag would be,

$$\Delta B = \tfrac{1}{2}\rho_a \pi r^2 C_D \left|w_a\right|^2 + F_L \qquad (7)$$

where C_D is the drag coefficient and w_a is the downward wind velocity. Again assuming, r = 8.25 m, with w_a = 3 m/s and $C_D \cong 0.55$, gives $\Delta B \cong 2.2$ kN. Clearly, this is a problematic result. Adding the required margin would lead to a prohibitively large envelope. Without the margin, in such a strong downdraft, the aerostat would be pushed down to surface level.

Although even in the peak season (polar summer) such storm activity is rare [17], to be assured of avoiding the risk of being swept downwards, the flights of a Titan Montgolfière should therefore be limited to the winter hemisphere, or to low latitudes away from the Equinox.

4. DISCUSSION

The use of a crown valve [2, 3] to permit buoyancy modulation presents several risks. In particular, the valve may not close completely (when required) resulting in unnecessary spillage of warmed gas and loss of buoyancy. Note: during preliminary tests, for the experiments described in Section 2.3, a small hole (approximately 10 mm by 50 mm) appeared near the envelope crown and resulted in a significant loss of buoyancy.

It was also found to be feasible to significantly reduce the buoyant lift of Configuration 1, by obstructing the thermal plume from the heater. It therefore seems likely a valve system could be used immediately above the RTG of a Titan Montgolfière. When fully open, the valve would not obstruct the flow significantly. When partly closed (or slanted), the plume would be partly diverted sideways away from the envelope neck opening, resulting in 'thermal spillage'. Experiments are needed to quantify the magnitude of the effect, but based on the observations already made the buoyancy could probably be modulated by 50% without difficulty. Placing the RTG below the envelope in the gondola, as opposed to placing it above the envelope neck, may offer significant design advantages, provided the resulting buoyancy decrease is acceptable.

5. CONCLUDING REMARKS

The preliminary work that led to the experiments reported here (including the early tests of Configuration 1) was undertaken by university 4th year engineering students, see acknowledgements. It is strongly recommended that other similar (low cost, room temperature) experiments should be conducted elsewhere to verify the findings. Specifically, it would be useful to extend the Rayleigh number range of the buoyancy experiment by testing larger envelopes with higher heat inputs. Investigations into use of double walls and other envelope thermal insulation schemes are needed. The drizzle experiment and associated analysis also require independent verification. All these activities are within the scope of typical university undergraduate projects (or even school outreach programmes). Furthermore, there is also considerable scope for significant (and novel) postgraduate research.

Whilst there is a rich history of long-distance hot-air ballooning on Earth, much of this heritage is based around visceral experience and anecdotal evidence. The experiments reported here represent a small step to providing a secure quantitative foundation - to support realistic design efforts - that could lead to the efficient, near-future exploration of Titan.

We believe that such an aerostatic exploration venture is well within engineering capability, and yet it would capture the interest and imagination of millions of people, young and old.

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