

FEASIBILITY STUDY OF A HOT-AIR TETHERED AEROSTAT SYSTEM

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The lifting gas used in Lighter-than-Air systems is usually Helium or Hydrogen. Helium is a rare gas and hence very expensive and Hydrogen, though relatively less expensive and easily available, is highly inflammable. Hot air has been used as an LTA gas since the first flight of a balloon in the 18th century, but its utilization in tethered aerostat systems has been limited. The objective of this project is to examine the feasibility of using hot air as the LTA gas in a practical tethered aerostat system. In this study, the thermal analysis of hot air envelope was conducted to predict heat losses and power requirements. This was followed by an experimental study to validate the theoretical values obtained from the thermal model, in which an electrical heating system was inserted inside a spherical envelope made of rip-stop nylon with a fire-retardant coating. Heat loss predictions were extrapolated for a larger size working prototype and feasibility studies were performed. The experimental heat loss predictions were far higher than those obtained using the thermal model available in literature. The power requirement for the smallest possible spherical working prototype made of Polyurethane coated envelope, with a radius of 2.3 m was estimated to be more than 66 kW. However, for an envelope fabricated with a proprietary material named aerofabrix®, around 33% reduction in the power requirement was estimated. These results show a promise for a hot-air based tethered aerostat system, but with several design and operational challenges, which will be highlighted in the paper.

Nomenclature

LTA	=	Lighter Than Air
CFD	=	Computational Fluid Dynamics
T _g	=	Glass Transition Temperature
GSM	=	Gram per square meter

I. Introduction

Tethered aerostats are an outcome of Lighter than Air (LTA) technology, where static lift production is based on Archimedes' Principle. Thus, an aerostat does not require any additional energy to reach to a certain height. For a given volume of envelope that contains lighter than air gas, the most common ones being Helium or Hydrogen, displaced weight of air creates a vertically upward force that leads to the lift. The volume is so designed that the displaced air should be able to produce sufficient lift to balance all weight groups of an aerostat system i.e. envelope, fin, nose battens, and pivot mechanisms etc. This is followed by design aspects as suggested by other disciplines such as aerodynamics, aerostatics, materials and manufacturing techniques that lead to a most desirable aerostat system design.

The conventional LTA gases i.e. Hydrogen and Helium suffer from safety, availability & cost issues. LTA gases other than Helium and Hydrogen that have been tried before include Ammonia¹ and superheated steam². Bormann et al.³ have shown numerical and experimental investigations of a steam balloon giving a survey of the design process and focusing on material characteristics. Banerjee et al.⁴ have discussed the application of hot air and steam aerostats in low cost ferry across rivers. The conceptual design and other structural issues have been discussed by Nachbar et al.⁵. Several early patents⁶⁻⁸ have discussed ideas of aerostats with hot air as an LTA gas, but without any detailed theoretical or experimental studies.

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Marion⁹ performed calculations for estimating fuel requirements of a hot air balloon and gave experimentally determined heat transfer coefficients. Analytical thermal model for performance prediction in balloon was given by Stefan¹⁰. Lighter-Than-Air exploration of Titan concepts have been presented and analytical and numerical thermal models been discussed in several works¹¹⁻¹⁵. Scientific ballooning has been on the rise with NASA's ballooning program¹⁶. Carlson et al.¹⁷ have developed a computer program for predicting the thermal behavior and trajectory of stratospheric balloons. Cathey¹⁸ presented a more accurate thermal model by accounting for the non-uniformities of balloon surface. Recent works^{19,20} have shown better analytical and CFD models for predicting thermal behavior in high altitude balloons.

The literature survey showed that though alternative buoyancy concepts have been tried before, hot air has never been studied for use in tethered aerostat systems. Also the theoretical models and experimental coefficients available regarding hot air balloons is not adequate to determine the feasibility of hot air as an LTA gas. Thus, the main objective of the project was to design a hot air tethered aerostat along with the heating system and study its feasibility with respect to other conventional aerostats.

II. Electrical heating system design

The heating system is a crucial element of hot air tethered system. Its design, fabrication and integration with the envelope presented a big challenge. The first trial involved suspending a high resistance Nichrome coil at two ends using ceramic beads as shown in Figure 1. But the testing showed huge expansion of the wire when heated. Since the heating system was to be covered with envelope, a dangling structure was considered an unsafe option. The first few trials with a polythene envelope actually resulted in a small fire when envelope came in direct contact with the coil. Considering the safety issues, a structure for supporting the coil was essential.

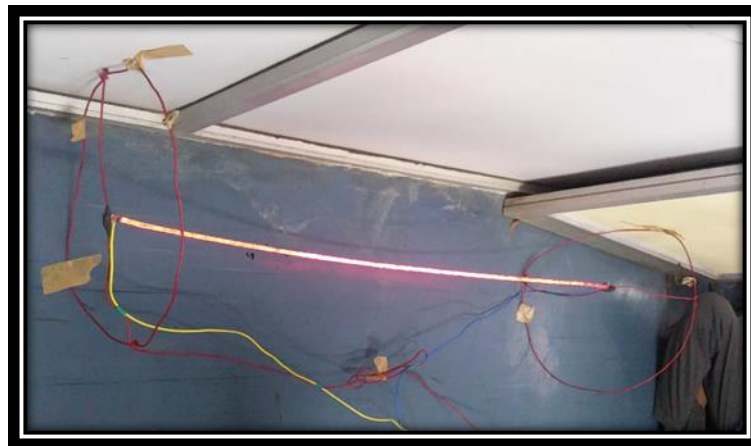


Figure 1 Linear configuration for heating system

The next concept evolved from the commercially available systems used in hot air blowers. In these systems, a nichrome coil is wound over Mica sheet structures as shown in Figure 2.



Figure 2 Hot air gun heating system

Another consideration while designing the system was to protect the envelope material from coming in contact with the heating coil due to any gust wind/or during inflation and deflation. This was achieved by adding a protective structure around the coil such that it doesn't interfere with the heating coil and also protects envelope in case of envelope collapse.

The final requirement was the attachment of heating system to the envelope. This needed to be easily detachable from the envelope. The idea was to have the structure supporting heating coil and the protective structure to be connected to a central hollow pipe. The pipe is hollow to allow air to enter from bottom through convection. The pipe connects to a flat plate structure which keeps the whole system upright when on ground.

The conceptual design was modelled in Solidworks as shown in Figure 3.

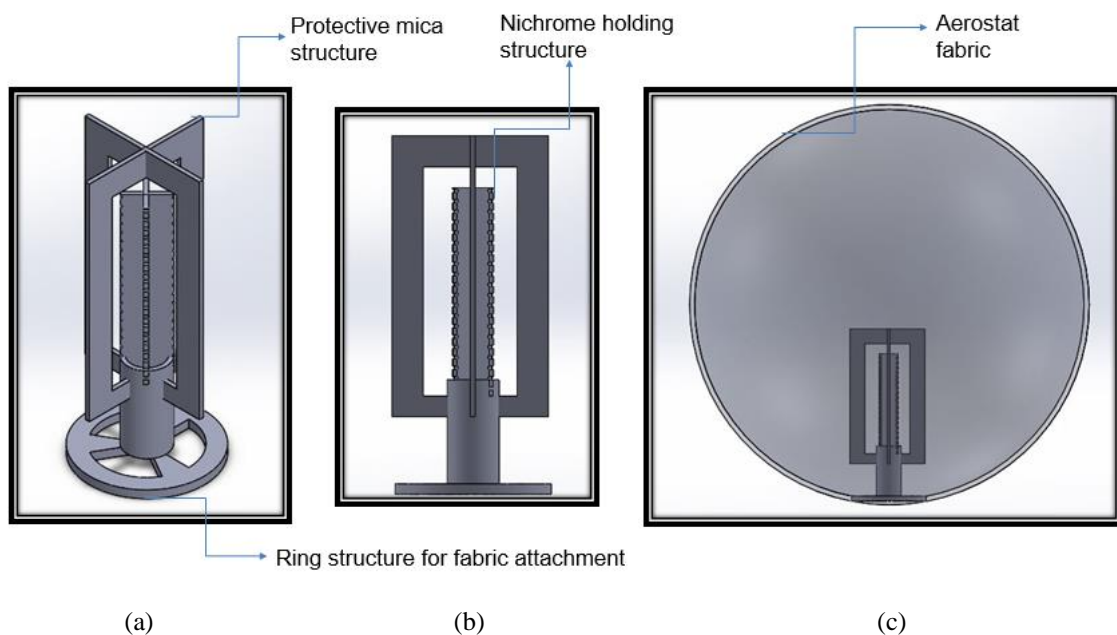


Figure 3 (a) Isometric view (b) Side view (c) Heating system integrated with the envelope

III. Fabrication and testing

Fabrication techniques utilized for the envelope and heating system is discussed here. The testing involved experimental estimation of glass transition temperature and heat losses.

A. Envelope

For material and heat loss testing procedures, a 1m X 5m Polyurethane coated fabric was used. The largest feasible spherical envelope was made using this fabric for the experimental heat loss testing. This envelope had a radius of 0.3 m and was made with petals that were heat sealed together. The envelope fabrication was carried out using the methodology described in this section.

Any inflatable LTA envelope is fabricated out of fabric pieces which are cut out from a flat piece. Since, the shape is non-conic and non-cylindrical, the following two flat pattern techniques are used to generate patterns for fabrication of LTA envelope :

1. Gore method

Long tapering sections as shown in Figure 4 are called gores. Several identical gores are sealed edge-to-edge to form the envelope. Also each gore can be made out of smaller pieces called panels. Thus panels make gores and gores make the envelope.

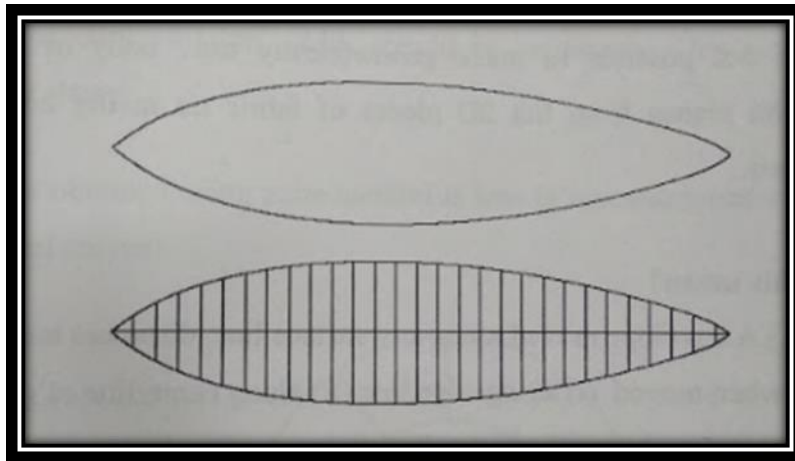


Figure 4 Gore Method

2. Zone method

In this method the body of revolution is cut by plane perpendicular to the center line. Each section is assumed as a conic section. At high curvature area conic section width should be minimum. Shape obtained using zone method is true in cross-sections with straight lines in longitudinal curves as shown in Figure 5Figure 5.2.

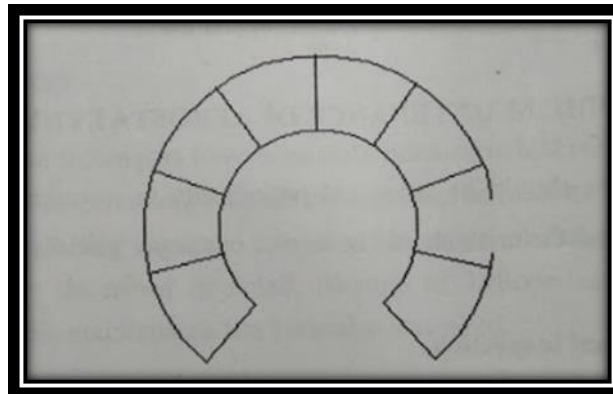


Figure 5 Zone method

B. Procedure

Gore method is the most suitable method with regard to ease of fabrication and is generally used. The size and shape of each gore is to be marked on the fabric to be cut out.

SolidWorks 2016® is used to obtain the gore geometry and the steps followed are described with figures as under -

- Since the envelope is symmetrical about the centerline, one half of the side view cross section is sketched using sketch tools as shown in Figure 6.

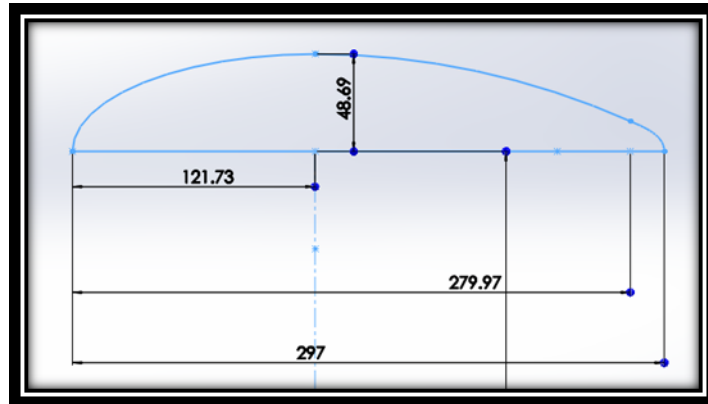


Figure 6 Half cross section sketch

- The sketch so obtained is converted into a surface and revolved around the centerline by a particular angle, to obtain a section of the solid envelope geometry. This is achieved using the 'Revolved Boss' feature. The angle is based on the number of gores that will be used to make the envelope. For e.g. 12 gores correspond to an angle of $(360^\circ)/12=30^\circ$. The solid obtained will be as shown in the Figure 7.

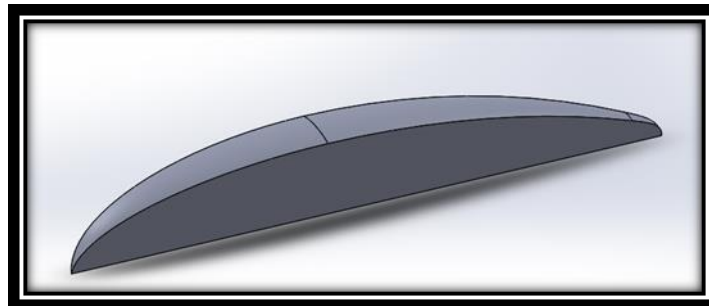


Figure 7 Solid section

- Since only the top surface is required as a gore, a new surface is created using the 'Surface Offset' method. An offset of 0 mm is given to the top surface of the envelope section. A new surface is thus created as shown in the Figure 8.

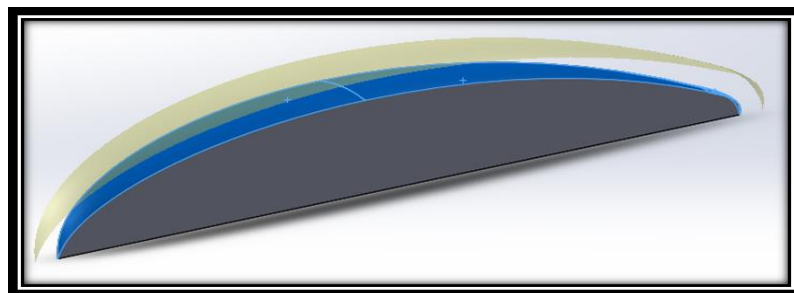


Figure 8 Surface Offset

- The surface thus obtained is flattened about the envelope nose tip using ‘Surface Flatten’ Option as shown in Figure 5.6. The accuracy is set to maximum to obtain an accurate gore shape.

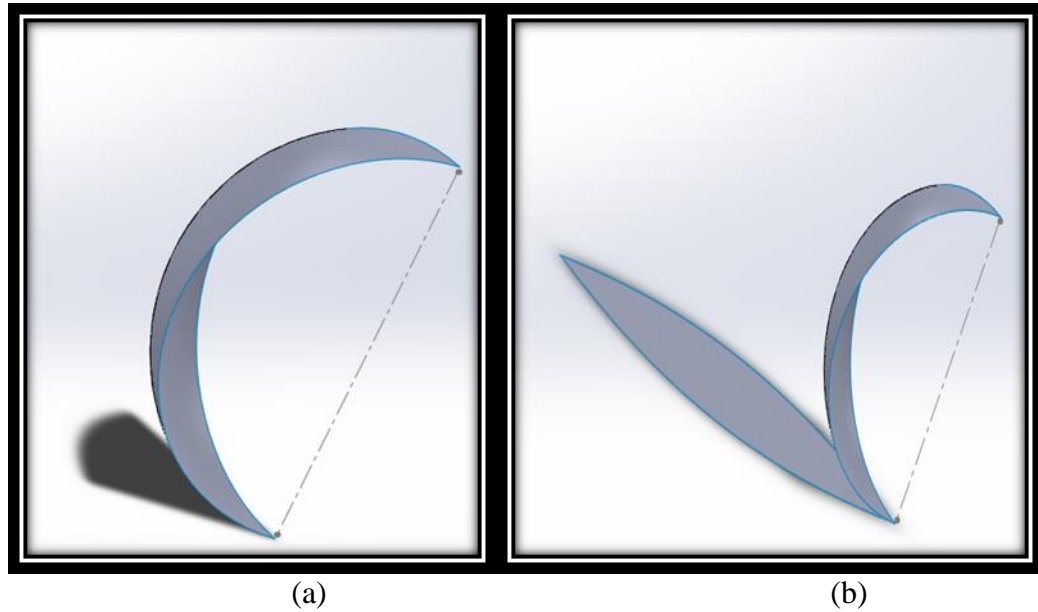


Figure 9 (a) Offset surface (b) Surface flattening

- The surface thus obtained is exported to drawing format as shown in Figure 10 and the page size is adjusted for printing on a flex paper. An offset is given to the outline for the weld margin. This is typically between 2-5 cm.

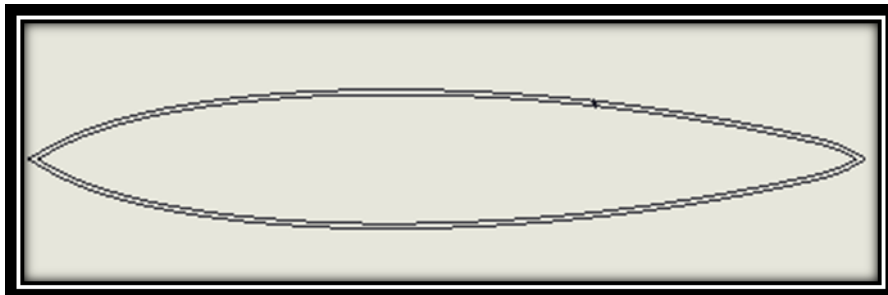


Figure 10 2D petal drawing with margin

- The gore outline was printed on a flex and then cut out. This cut out was then placed on the chosen fabric and gores were cut. This is shown in Figure 11.

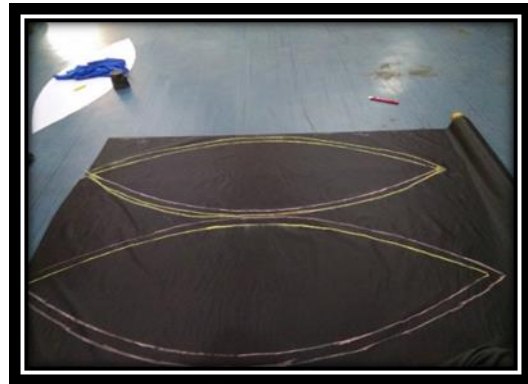
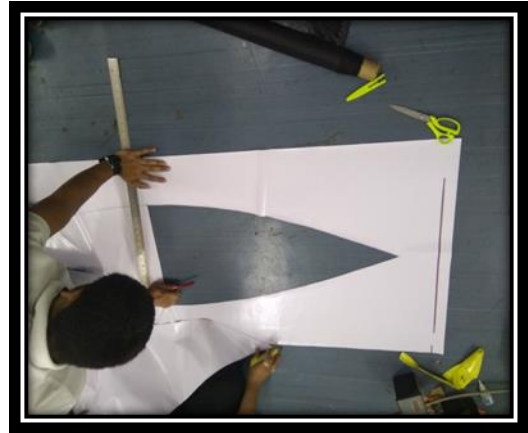
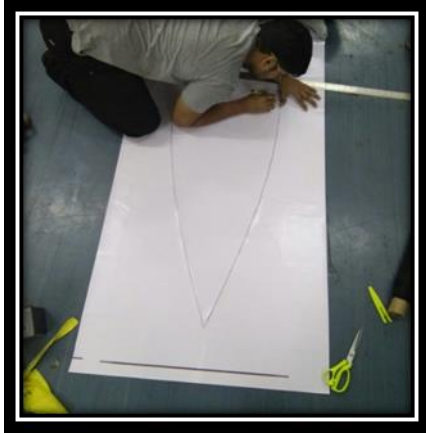


Figure 11 (a) Flex marking (b) Flex cutting (c) Petal marking (d) Weld margin

The heat sealing and the final inflated structure is shown in the Figure 12.



(a)



(b)

Figure 12 (a) Heat sealing (b) Inflation

C. Heating system

As discussed in section II, the conceptual design of heating system was finalized. The central supporting structures are made from mica sheet as they have melting point of around 1500-1800 °C. In addition to that, they are very lightweight and considerably strong structures.

Both the central and outer structures are made using mica sheets. The sheets are cut out and connected orthogonally to generate the central support for Nichrome coil. Similarly, the outer protection is made by joining two sheet cut outs. Both of them are attached to a hollow cylindrical cardboard structure on the base. The whole process is shown in the Figure 13.

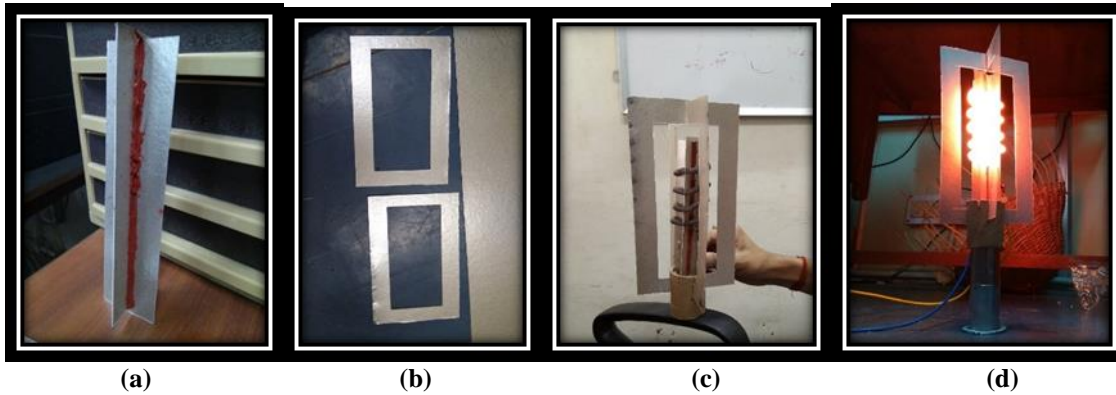


Figure 13 (a) Central mica structure (b) Cut outs for outer structure (c) Fully assembled system (d) Functional heating system

Velcro strips are used to attach the envelope and the heating system. In addition, a flat base plate is attached on the base to provide it stability when on ground.

The terminals of nichrome coil are connected to a wire which runs through a dimmerstat. A dimmerstat as shown helps in varying the AC voltage supply and hence the power supply to the coil. Thus the temperature at steady state can be controlled using this arrangement.

D. Testing

The main aim of testing was to determine the following two parameters –

- Glass transition temperature of the fabric used.
- Heat losses and power requirements.

Glass transition temperature estimation

The Glass Transition Temperature (T_g) is an important thermal property of any epoxy and is the temperature region where the polymer transitions from a hard, glassy material to a soft, rubbery material. As epoxies are thermosetting materials and chemically cross-link during the curing process, the final cured epoxy material does not melt or reflow when heated, but undergoes a slight softening at elevated temperatures.

In order to generate buoyancy with hot air, the envelope structure must hold even at high temperatures. Hence the steady state temperatures should be considerably lower than the glass transition temperature of the material or coating used.

In the present case, the material used is a nylon base with coatings of Polyurethane. To ensure that the material will withstand high temperatures, it was attached to a stick and held in the close vicinity of heated nichrome coil as shown in Figure 14. Simultaneously, a thermocouple probe was used to measure the surface temperatures at various intervals.

The testing showed that at temperatures above around 150 °C, the fabric material started crumpling and softening. This temperature was taken as the limiting surface temperature to which the fabric could be subjected. This sets the limit to be considered while designing the temperature ranges of hot air during aerostat operation.

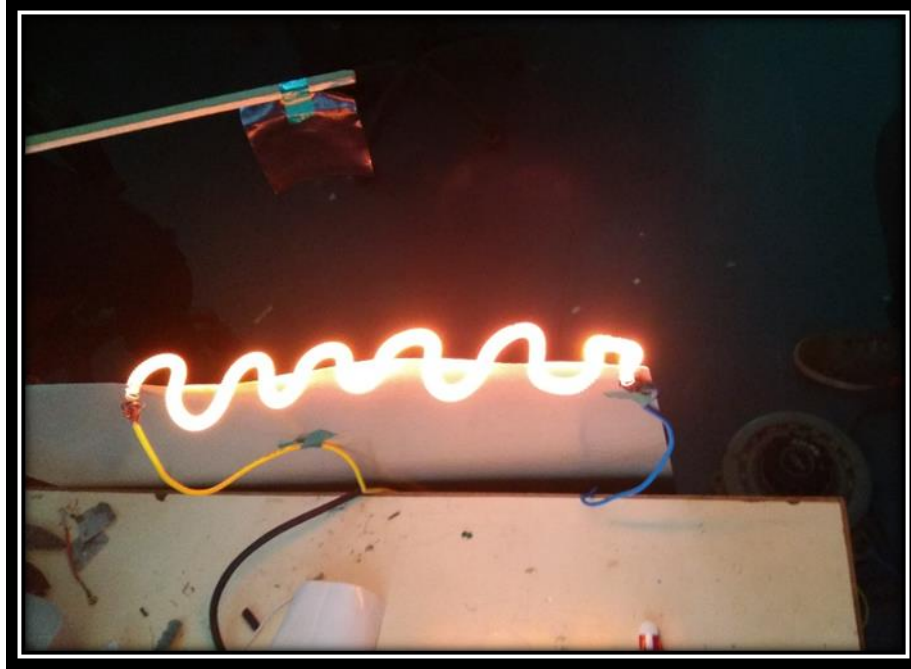


Figure 14 Test for glass transition temperature

The important thing to be noted here is that the average hot air temperature inside the envelope cannot be the same as the T_g calculated experimentally. It should be considerably lower than the T_g . This is because the temperature distribution that gives an average temperature of 150 °C inside the whole envelope will result in surface temperatures quite higher than 150 °C at several locations on envelope. This will result in envelope softening at those locations, and might result in structural failure. An example of temperature distribution for an average temperature difference of 140 °F from the ambient temperature for a hot air balloon is shown in Figure 15. As can be seen from the figure, for an average ΔT of 140 °F, several places have higher ΔT than 140.

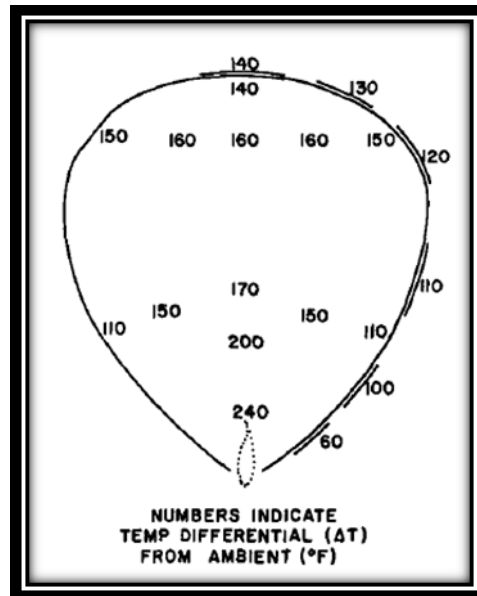


Figure 15 Temperature contour of a typical hot air balloon⁹

Heat losses and power requirements

Heat loss from the fabric is one of the most important factors while considering the feasibility of hot air tethered systems. Although theoretical calculations are performed using the methodology and heat transfer coefficients available in Marion's work⁹, but since the material used was quite different in our case, an experimental measurement was considered essential to have an accurate prediction of heat losses.

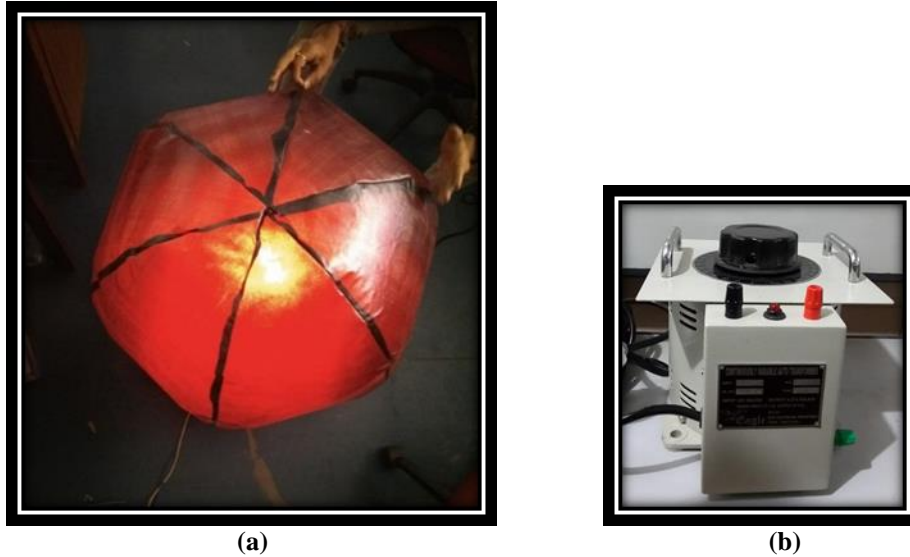


Figure 16 (a) Heat loss testing (b) Dimmerstat for voltage control

Once the envelope is fabricated, it is then integrated with the heating system and power is supplied to the system as shown in Figure 16(a). A dimmerstat as shown in Figure 16(b) was used to control the AC voltage supplied to the heating system and the current flowing was measured for different voltages. The voltage was increased in steps and a time of 10-15 minutes was given for the temperatures to reach a steady value. Inside temperature measurements were taken as shown in Figure 17 using a thermocouple probe at different points along one of the circumference and averaged.



Figure 17 Temperature measurement with K-type thermocouple

Since a critical temperature of 150-160 °C was identified during the glass transition test for the fabric, readings were taken for a maximum average temperature of 120 °C as temperatures at certain points reached 150 °C. The observations for different voltages are given in Table 1.

Table 1 Temperature and power measurements for different voltages

Voltage (V)	Average Temperature (°C)	Power Supplied (kW)
100	69	0.45
110	75.6	0.54
120	81	0.64
130	90.3	0.75
140	101.4	0.87
150	112	1.00
160	120.2	1.14

IV. Results and discussions

The styles and formats The results obtained from experiments are used to calculate heat losses. These values are then extrapolated to obtain the requirements for larger surface areas. Sizing of a working prototype is done by a break-even point analysis and then the feasibility of fabrication and testing is discussed.

E. Extrapolation

For reaching an average temperature of 120 °C, power requirement is 1.14 kW for a balloon of 0.6 m diameter. Assuming that the heat transfer coefficient remains same for the given geometry, material and heating configuration used, the values are extrapolated for a larger balloon. Since heat transfer coefficient and temperatures are constant, heat losses vary with the surface area of balloon as shown in Figure 18.

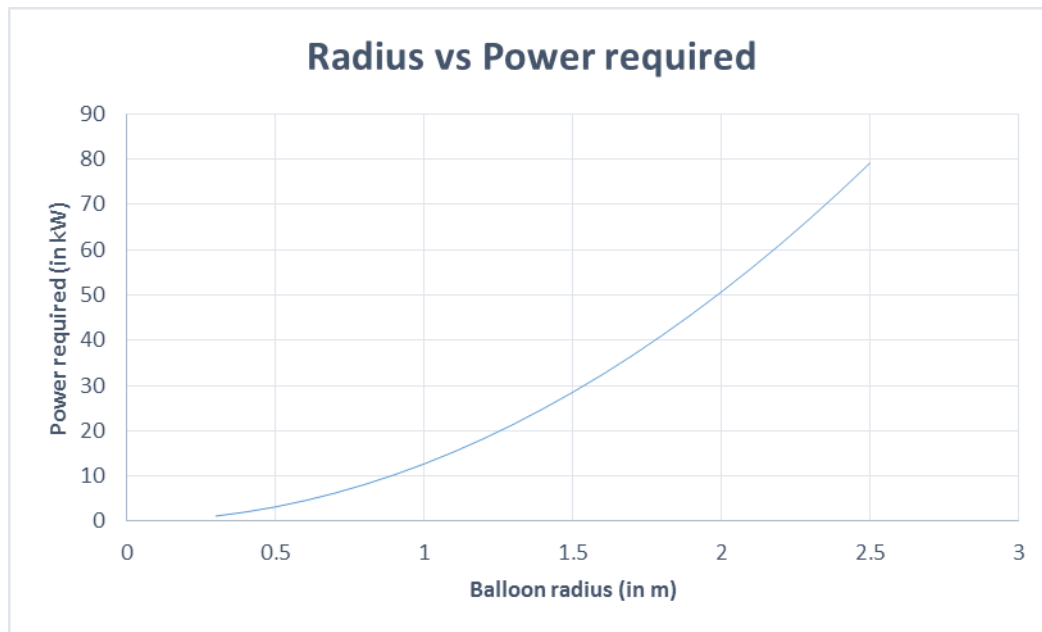


Figure 18 Balloon radius vs Power required

F. Prototype sizing calculations

The minimum size required for the envelope so that it can lift itself is limited by the fabric weight. Given the GSM (Gram per square meter) of fabric, a break-even point can be determined beyond which the fabrication of a working type is feasible. A plot showing the same for the currently used fabric (GSM = 115) is given in Figure 19.

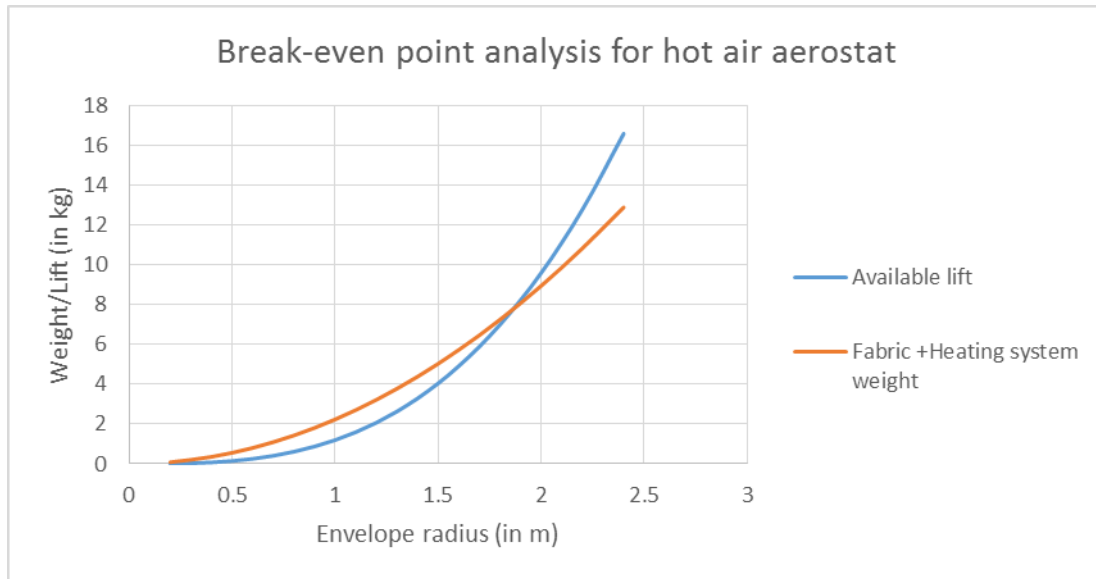


Figure 19 Break-even point analysis

As can be observed from the plot that break-even point is around the radius of 1.8 m. This analysis does not take into account the payload, heating system and other miscellaneous weights that will be included. When all these parameters are taken into account, the minimum radius of envelope that is feasible for a working prototype comes around 2.3 m.

Fabricating and testing a 2.3 m radius envelope prototype would have presented the following problems:

- Heat losses are estimated to be around 66.58 kW. Continuous power supply of such high magnitude is very difficult and costly.
 - Dangers of working with such a huge amount of AC power was a safety issue. Also, safety fuses do not allow such high power applications.
 - Handling a big hot air balloon before it achieves enough buoyancy to lift itself also presented a problem.
- Considering all the above reasons, fabrication of a working prototype was not attempted.

G. Cost analysis

Apart from safety and size issues, cost is an important factor deciding the feasibility of hot air aerostat. A comparison of estimated operational cost of aerostats using different LTA gases is made.

Assumptions-

- Net available lift of 1 kg.
- Spherical aerostats.
- Fabric weight of 115 gsm for Hot air and 120 gsm for hydrogen and Helium aerostats.

Operating cost

Cost due to gas leakage/heat losses is given in Table 2.

Table 2 Operating cost table

S. no.	LTA gas	Leakage rate/Heat loss rate	Cost per m ³ /kWh	Total Cost for 1 day continuous operation
1.	Hydrogen	5 lit./m ² /day	Rs. 357.14	Rs. 14.25
2.	Helium	5 lit./m ² /day	Rs. 1571.43	Rs. 68.18
3.	Hot air	52.64 kW	Rs. 4.50	Rs. 5685.49

As can be seen from this comparison, hot air aerostats require a very large investment in terms of operational costs. However, the costs involved in storage infrastructure is minimal as compared to conventional systems. Also,

in terms of portability, hot air aerostat saves a lot of money as compared to Hydrogen/Helium systems where the gas has to be wastefully released to the atmosphere before envelope can be transported.

H. Conclusions

The aim of the present work was to design and study the feasibility of a hot air tethered aerostat system. Though the materials used for fabrication and testing are very specific but they also allow several general conclusions to be drawn regarding hot air aerostats. Based on the literature reviewed, experiments conducted and analysis performed, the following conclusions can be drawn from the present work:

- The minimum possible working prototype size of an aerostat that could be fabricated with the materials tested was a 2.3 m radius spherical aerostat.
- The glass transition temperature for the PU coated nylon was found to be around 150 °C and hence the average envelope temperature was limited to 120 °C.
- A continuous electrical power supply of 66.58 kW was required to sustain the aerostat.
- Huge amount of heat losses is a major drawback for this concept making it cost ineffective.
- It is also concluded that using electrical power for heating contained air in the envelope is both a cost and safety issue too.
- Hot air tethered aerostat is a viable alternative in the absence of other conventional options.

I. Scope for future work

From the work done so far, it has been realized that making use of hot air as LTA gas for tethered aerostat systems can be made viable only if the heat losses from the balloon surface is minimized. This requires research in two important areas-

- Experimental testing of fabric materials/coatings that have high thermal resistance, minimum air permeability and are lightweight.
- Development of a better thermal model to have an accurate estimate of heat losses from the surface.
- Computational fluid dynamic analysis to have a better understanding of the temperature profile for different envelope shapes. This would help in optimizing the heating mechanisms and structure.
- Methods of heating other than electrical should be experimented which may give cost effective results.
- Safety system to cut off power supply in case of structural failure of the heating system can also be included.

Acknowledgments

The project was supported by Indian Institute of Technology, Bombay under the Industrial Research and Consultancy Centre (IRCC) research internship programme. The fabrication and testing was carried out at the Lighter than Air (LTA) lab in the department of Aerospace Engineering, IIT Bombay.

Fabric material for hot air envelope was provided by Kusumgarh Corporates®.

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