IMPACT OF HELIUM PERMEABILITY ON ENDURANCE AND ALTITUDE CONTROL OF GEOSTATIONARY STRATOSPHERIC AIRSHIP - A MATHEMATICAL MODEL

Anuj Kumar Garg, Santosh Kumar Burnwal, Asish Pallapothu, Rohit Singh Alawa and A.K. Ghosh
Department of Aerospace Engineering
Indian Institute of Technology Kanpur
Kanpur-208 016, India
Emails : anujgarg.iitk@gmail.com, akg@iitk.ac.in

Abstract

A geostationary stratospheric airship is lighter than air platform to be used for several civil and military purposes. In this study, the impact of Helium permeation through the hull and ballonet skin is considered. Mathematical modeling of the system is being done to estimate the amount of Helium and air transmission through the hull and the ballonet skin for a general airship system. Impact of permeation mainly affecting its ability to maintain constant altitude and a minimum level of differential pressure is shown in this study. A method is also devised so as to develop an open loop control system to maintain the altitude of the airship by maintaining the net vertical force due to buoyancy and weight on the airship as zero. Both the cases with and without the altitude control are simulated by numerically solving the model using RK4 algorithm. The results obtained are discussed and appropriate conclusions are drawn from the analysis.

Nomenclature

A = Area
A_1 = Hull skin area between region 1 and the atmosphere
A_2 = Ballonet skin area in between region 1 and region 2
A_3 = Hull skin area between region 2 and the atmosphere
F = Flux of gas through membrane in m^3/m^2/day or moles/m^2/day
k = Proportionality constant
k_{a_1} = Permeability constant for air for Hull skin material
k_{a_2} = Permeability constant for air for Ballonet skin material
k_{a_E} = Effusion constant of air
k_{He_1} = Permeability constant for helium for Hull skin material
k_{He_z} = Permeability constant for helium for Ballonet skin material
k_{He_E} = Effusion constant of Helium
M_a = Molecular weight of air
M_{He} = Molecular weight of Helium
n = Moles
n_1 = Moles of gas on side 1 of the membrane
n_2 = Moles of gas on side 2 of the membrane
$n_{a_{b,t}}$ = Moles of air in region 2 i.e. in ballonet at time t
$n_{a_{h,t}}$ = Moles of air in region 1 i.e. in hull at time t
$n_{He_{h,t}}$ = Moles of Helium in region 1 i.e. in hull at time t
$n_{He_{b,t}}$ = Moles of Helium in region 2 i.e. in ballonet at time t
P = Gas pressure
P_1 = Gas pressure in region 1
P_2 = Gas pressure in region 2
P_{atm} = Atmospheric pressure
P_{diff} = Differential pressure across the Hull
p_1 = Partial pressure of gas on surface 1 of the membrane
p_2 = Partial pressure of gas on surface 2 of the membrane
R = Gas constant
T = Gas temperature
t = Time

Paper Code : V64 N3/743-2012. Manuscript received on 28 Feb 2011. Reviewed and accepted as a Full Length Contributed Paper on 03 May 2012

V = Gas volume
V_1 = Volume of gas in region 1
V_2 = Volume of gas in region 2
Vol = Total volume of the airship including hull and ballonet

Introduction

Airship is very large controlled balloon which remains airborne using the buoyancy force up in the atmosphere. It has several applications in civilian and military areas like hosting communication transponders, surveillance, etc [1, 2]. Some of these applications demand that the airship remains stationary at a desired location for a period of more than 6 months giving it the ability to even host the geostationary satellites. This also necessitates that the airship should remain at a considerable altitude. Hence, the modern airships are better known as geostationary stratospheric airships or Lighter Than Air (LTA) platforms.

The prolonged flying duration subject the airship to harsh atmospheric conditions like ultraviolet rays, drastic fluctuations in temperature over day and night, etc [3]. Also the gas typically Helium, inside the airships permeates out through the airship skin and the air from the atmosphere permeates in the airship resulting in the drop in the purity level of the Helium inside the airship. This also is the case of the aerostat currently in operation round the globe. However, the aerostat differs to that of airship in the case that in aerostats, an initial excess buoyancy, typically 15% of the total weight, is ensured and its altitude is maintained with help of the tether [4]. As the time passes and the purity of Helium decreases, the weight of the aerostat increases but this increase still remains less than the excess buoyancy and therefore aerostat is able to maintain its altitude by adjusting its tether tension appropriately [5]. However, in case of stratospheric airships no such tether is present and the weight of the airship increases due to the decrease in the purity level of the Helium with time. This puts a constraint on the duration till which the airship can maintain its altitude. Therefore, the airship has to maintain its altitude by maintaining the net force due to buoyancy and weight as zero irrespective of the Helium diffusion. Further, an altitude monitoring system has to be placed on the airship which releases the appropriate amount of the air in the atmosphere to maintain its constant weight. The research in this area is still in nascent stage and a lot need to be done before the LTA platforms become a reality.

This study gives a mathematical model for estimating the amount and rate of gas (es) permeation through the airship skins in the most general form. An attempt is also made to estimate the amount of reserve air to be kept in the ballonet and the appropriate quantity to be leaked in order to maintain a desired constant altitude of the airship. This mathematical model is validated by simulating an airship system by numerically solving the equations using a RK4 algorithm [6].

Theory

Geostationary stratospheric airships are designed as lighter than air systems which remain airborne due to the buoyancy forces. This is made possible by inflating the hull of the airship with a gas substantially lighter than air like Hydrogen or Helium. As the airship is launched for the ground station and it starts rising, the density of the atmosphere continuously drops. In order to reach its destination station the airship releases air filled in its ballonet to simultaneously reduce its weight. As it moves up, for a given size and weight of the airship, there is a ceiling height at which the buoyancy forces and the weight balances each other. At this height the airship theoretically, can be stationed for unlimited period of time. Though, in practice, the permeation of the gases in and out of the hull through the polymer based hull skin puts a limit on the time up to which the airship can be kept airborne. This property of polymers of allowing gases to diffuse through them in both directions lead to the permeation of the Helium out of the airship and air into the hull of the airship. Over a period of time, the purity of Helium decreases and the weight of the airship gradually keep on increasing. To overcome this, the airship maintains a reserve of air in the ballonet which is released with the same rate as the rate of increase of the weight thereby keeping the net forces due to buoyancy and weight as zero since the buoyancy remains constant. Due to the permeation and the release of the gas in the atmosphere the differential pressure in the airship decreases. Both the amount of reserve air in the ballonet and the required minimum differential pressure puts a constraint on the time up to which the airship can be kept at a given altitude.

The transmission of gases through a polymer can be specified in terms of the three processes namely, solubility of gases in the polymer, diffusion and permeation [7, 8, 9]. As the gas is brought in contact with one surface of the polymer membrane, it gets adsorbed on the surface of the polymer. In the second step, the adsorbed gas diffuses through the membrane to the other surface and there it gets desorbed from the surface resulting in the net permeation of the gas. In general, the simultaneous occurrence of these processes leads to the overall transmission of the gases through the polymer membrane. In case of the airship, the volume of gas is typically of the order of two to three hundred thousand cubic meters and the membrane thickness is in sub millimeter range hence the decrease in the Helium concentration due to adsorption on the polymer surface can be objectively neglected. By the same reason the gas trapped in the membrane during the process of diffusion can also be neglected without having any considerable effect on the Helium concentration in the airship hull. It can also be assumed that the steady state is quickly reached as the membrane is very thin and hence all the derivations made are done assuming the steady state condition. Further, the temperature across the different regions is assumed to be constant for the simplicity of the derivation.

In the derivation, steady state is assumed and the steady state permeation flux is taken directly proportional to the difference in the partial pressure of gas across the polymer membrane [9].

$$F \propto (p_1 - p_2) \tag{1}$$

Where F is the flux through a surface either measured as volume of gas percolated through unit surface area in unit time or as moles of gas percolated from unit surface area in unit time i.e. m^3/m^2/day or moles/m^2/day respectively.

The number of moles of gas and air in airship are independent of other physical conditions like temperature and pressure hence the flux is measured in moles/m^2/day for the purpose of this study. Therefore, the rate of change of the number of moles in the hull/ballonet is directly proportional to the difference in the partial pressure of the respective gases Eq. (2).

$$\frac{dn}{dt} \propto (p_1 - p_2) \tag{2}$$

Equation (2) can be written in terms of the moles, volume and temperature by substituting the pressure using the ideal gas equation (Eq. 3) as given by Eq. (4).

$$PV = nRT \tag{3}$$

$$\frac{dn}{dt} \propto A\left(\frac{n_1 RT}{V_1} - \frac{n_2 RT}{V_2}\right) \tag{4}$$

Using Eq. (4), the expression for the rate of change of moles of Helium and air in the region 1 and region 2 (Refer Fig.1) can be written by using the principle of superposition i.e. the net change in moles of Helium is equal to the addition of moles transmitted out to the region 2 from the region 1 (first term in Eq. (5)) and of the moles transmitted out to atmosphere from the region 1 (second term in Eq. (5)).

$$\frac{dn_{He_{h,t}}}{dt} = k_{He_2} A_2 \left(\frac{n_{He_{b,t}} RT}{V_2} - \frac{n_{He_{h,t}} RT}{V_1}\right) + k_{He_1} A_1 \left(0 - \frac{n_{He_{h,t}} RT}{V_1}\right) \tag{5}$$

Similarly expressions can be written for the transmission of Helium and that of air by using the principle of superposition and the Eq. (4). The respective equation for air in the hull (region 1) and for helium and air in ballonet (region 2) are equation from 6 to 8 respectively.

$$\frac{dn_{a_{h,t}}}{dt} = k_{a2} A_2 \left(\frac{n_{a_{b,t}} RT}{V_2} - \frac{n_{a_{h,t}} RT}{V_1}\right) + k_{a_1} A_1 \left(P_{atm} - \frac{n_{a_{h,t}} RT}{V_1}\right) \tag{6}$$

$$\frac{dn_{He_{b,t}}}{dt} = k_{He_2} A_2 \left(\frac{n_{He_{h,t}} RT}{V_1} - \frac{n_{He_{b,t}} RT}{V_2}\right) + k_{He_1} A_3 \left(0 - \frac{n_{He_{b,t}} RT}{V_2}\right) \tag{7}$$

$$\frac{dn_{a_{b,t}}}{dt} = k_{a2} A_2 \left(\frac{n_{a_{h,t}} RT}{V_1} - \frac{n_{a_{b,t}} RT}{V_2}\right) + k_{a_1} A_3 \left(P_{atm} - \frac{n_{a_{b,t}} RT}{V_2}\right) \tag{8}$$

Total volume of the airship is equal to the sum of the volume of the hull and that of the ballonet as given by Eq. (9).

$$V_1 + V_2 = Vol \tag{9}$$

Using gas law Eq. (3), the volume of the hull and that of ballonet can be written in terms of the pressure, temperature and the moles of the gases present in the individual region as in Eq. (10) and Eq. (11).

$$V_1 = \frac{(n_{He_{h,t}} + n_{a_{h,t}})RT}{P_1} \tag{10}$$

$$V_2 = \frac{(n_{He_{b,t}} + n_{a_{b,t}})RT}{P_2} \tag{11}$$

Ballonet skin divides the region 1 and region 2. In case of the stratospheric airship, the volume occupied by the ballonet during the launch will be almost 94-95% of the net volume depending upon the stationing altitude. Due to this the ballonet skin will be almost equal to half of the total hull skin and will not get strained and act like a free surface as it is sufficiently large. Therefore, pressure in the hull and the ballonet will be equal as both the regions are separated by a free surface formed by the ballonet skin. However, the outer hull skin of the airship will be subjected to a differential pressure which is required to maintain the shape of the airship and to avoid deformations like bending, etc due to wind gushes.

$$\therefore \; P_1 = P_2 = P_{atm} + P_{diff} \tag{12}$$

Substituting Eq. (10) and Eq. (11) in Eq. (9)

$$\frac{(n_{He_{h,t}} + n_{a_{h,t}})RT}{P_{atm} + P_{diff}} + \frac{(n_{He_{b,t}} + n_{a_{b,t}})RT}{P_{atm} + P_{diff}} = Vol \tag{13}$$

Using Eq. (13)

$$(P_{atm} + P_{diff})\, Vol = (n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}})\, RT \tag{14}$$

Rearranging Eq. (14)

$$Vol = \left(\frac{n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}}{P_{atm} + P_{diff}} \right) RT \tag{15}$$

From Eq. (10), Eq. (11) and Eq. (12)

$$\frac{n_{He_{h,t}} + n_{a_{h,t}}}{V_1} = \frac{n_{He_{b,t}} + n_{a_{b,t}}}{V_2} = \frac{n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}}{Vol} \tag{16}$$

From Eq. (16)

$$V_1 = \left(\frac{n_{He_{h,t}} + n_{a_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}} \right) Vol \tag{17}$$

$$V_2 = \left(\frac{n_{He_{b,t}} + n_{a_{b,t}}}{n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}} \right) Vol \tag{18}$$

Typically, the material used to fabricate the hull and ballonet skin is same and both the hull and ballonet skin differ only in terms of thickness. Therefore, the ratio of permeability of the Helium and air is only a function of nature of the gas molecules as the membrane material is constant, thereby implying that

$$\frac{k_{a_1}}{k_{He_1}} = \frac{k_{a_2}}{k_{He_2}} = k \tag{19}$$

Substituting Eq. (17) and Eq. (18) in Eq. (5)

$$\frac{dn_{He_{h,t}}}{dt} = \left[k_{He_2} A_2 \left(\frac{n_{He_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} - \frac{n_{He_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} \right) - k_{He_1} A_1 \left(\frac{n_{He_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} \right) \right] \times \left[\frac{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}})RT}{Vol} \right] \tag{20}$$

Substituting Eq. (17), Eq. (18) and Eq. (19) in Eq. (6)

$$\frac{dn_{a_{h,t}}}{dt} = k \times \left[\begin{array}{c} k_{He_2} A_2 \left(\dfrac{n_{a_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} - \dfrac{n_{a_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} \right) \\ - k_{He_1} A_1 \left(\dfrac{P_{atm}\, Vol}{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}})\, RT} - \dfrac{n_{a_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} \right) \end{array} \right] \times \left[\frac{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}})RT}{Vol} \right] \tag{21}$$

Substituting Eq. (17) and Eq. (18) in Eq. (7)

$$\frac{dn_{He_{b,t}}}{dt} = \left[k_{He_2} A_2 \left(\frac{n_{He_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} - \frac{n_{He_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} \right) - k_{He_1} A_3 \left(\frac{n_{He_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} \right) \right] \times \left[\frac{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}})RT}{Vol} \right] \tag{22}$$

Substituting Eq. (17), Eq. (18) and Eq. (19) in Eq. (8)

$$\frac{dn_{a_{b,t}}}{dt} = k \times \left[\begin{array}{l} k_{He_2} A_2 \left(\frac{n_{a_{h,t}}}{n_{He_{h,t}} + n_{a_{h,t}}} - \frac{n_{a_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} \right) \\ - k_{He_1} A_3 \left(\frac{P_{atm} Vol}{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}) RT} - \frac{n_{a_{b,t}}}{n_{He_{b,t}} + n_{a_{b,t}}} \right) \end{array} \right] \times \left[\frac{(n_{He_{h,t}} + n_{a_{h,t}} + n_{He_{b,t}} + n_{a_{b,t}}) RT}{Vol} \right] \quad (23)$$

Using Eq. (20 to 23) the variation of the moles of Helium and air, both, in the hull and ballonet can be determined if no intervention is made to keep the weight of the airship constant. A term each in the ballonet equations can be incorporated while numerically solving the equation to estimate the amount of gas to be released from the ballonet in order to maintain constant weight. This is done by calculating the increase in the total weight of the airship by taking the difference of the weight at time t and the initial weight at each step of the iterative process. Gases equal to the weight of difference is then released only from the ballonet thereby maintaining the total weight. The rate of release of Helium and air from ballonet will not be independent but will sharply follow the Daltons law of effusion and will be related as

$$\frac{k_{He_E}}{k_{a_E}} = \sqrt{\frac{M_a}{M_{He}}} \quad (24)$$

Using Eq. 24 and taking the effusion constant in terms of mass per unit time the moles/mass rate of release of Helium and air can be determined which forms an open loop control expression for the system.

Results and Discussion

The mathematical model derived in section, theory is numerically solved using the RK4 algorithm for a system with 18000 Kg as the total weight for the altitude of 22000m. The area of the ballonet skin is taken equal to half of the area of the total hull skin. In first case of analysis, no gas was released to maintain the total weight of the airship. In second case, the gas in the ballonet was released so as to maintain constant weight of the gases in the airship implying constant total weight of the airship necessary to maintain the constant altitude of the airship. The various parameters feed into the system are given in Table-1 and Table-2.

The permeability constant used in this study are taken after a detailed survey of the literature [10, 11, 12]. However, these constant are directly dependant on the material used for the hull and the ballonet skin and also on the conditions such as temperature, etc and are still in the development stages. Therefore the results in this study are only indicative of the trends followed by various parameters and may not have significance in absolute. But the results produced in this analysis are sufficient to prove the significance of the model and to ascertain the models ability to give useful results once the actual material characteristics are known.

Without Maintaining Constant Weight

Figure 2 and Fig.3 shows the variation of the moles of Helium and air in hull and ballonet respectively. The moles of Helium in the hull decreases continuously as the concentration of Helium in hull is always higher than that of the surrounding regions. The concentration of Helium increases in the ballonet as the initial concentration of Helium in the ballonet is taken as zero and hence increases with time due to permeation from the hull. The rate of air

Table-1 : Atmospheric Conditions

Altitude (m)	Pressure (Pa)	Density of Air (Kg/m^3)	Density of Helium (Kg/m^3)	Temperature (K)
22000	4026	0.0672	0.0093	199

Table-2 : Airship and Material Parameters

Total Mass (Kg)	A1 (m^2)	A2 (m^2)	A3 (m^2)	Initial He Purity	Initial Inflation Ratio	k_{He_1} (m Moles /Pa/m^2/ day)	k_{a_1} (m Moles /Pa/m^2/ day	k_{He_2} (m Moles /Pa/m^2/ day)	k_{a_2} (m Moles /Pa/m2/ day)
18000	10038	10038	10038	0.99	0.9	0.00325	0.00121	0.00456	0.00169

permeation though decreases with time and even changes direction with time if the simulations are done for higher period of time. This is due to the fact that the initial concentration of air in ballonet is equivalent to the surrounding air and the partial pressure of the air in the ballonet is higher than that of the ambient air as a higher differential pressure is maintained in the airship. Owing to this the air permeates out of the ballonet into the hull and into the atmosphere and gradually the partial pressure of the air in ballonet decreases below the atmospheric level. Beyond that the air starts to permeate inside the ballonet from the atmosphere whereas the rate of transmission of air from ballonet to the hull decreases due to increase in the partial pressure of air as result of the permeation of air into the hull both from the ballonet and from the atmosphere. After a certain period of time, the net permeation of air inside the ballonet takes place resulting in the increase in the moles inside the ballonet.

Figure 4 shows the decrease in the purity level of the Helium in the airship hull as can be expected from the permeation process and also from the flight data of the aerostats. Since the total number of moles decreases in the airship the differential pressure in the airship also decreases as shown in Fig.5. This is one of the most critical factors that put a limitation on the total endurance of the airship. This is due the fact that a minimum differential pressure is required at all time inside the airship to prevent it from deformations due to wind gushes, especially in case of a blimp. Hence, the minimum allowable differential pressure is to be determined and from this analysis the maximum day up to which an airship can be kept airborne can be determined using the differential pressure data.

Inflation ratio is the ratio of the hull volume to the total volume of the airship and should always be less than one. Fig.6 shows the variation of inflation ratio with time. As contrary to the common belief, the inflation ratio decreases with time. It is so because Helium permeation from the hull into the ballonet is significantly higher than the air permeation out of the ballonet into the hull and the atmosphere. The reason for this is that the permeation constant for Helium is significantly higher than that of air owing to the small size of the Helium atom. Hence the net moles of gases in the ballonet increases with time leading to the increase in the volume of the ballonet implying decrease in the hull volume as the total volume is constant. This leads to the decrease in inflation ratio with time.

If no intervention is made in the airship to keep the total mass of the airship as constant the total mass of the airship increases with time. This is due to the fact that the Helium permeates out and air permeates in to the airship as the partial pressure of Helium in the hull is very high as compared to the partial pressure of the Helium in the ambient air and also the partial pressure of the air inside the airship is significantly low as compared to the partial pressure of the air in the atmosphere outside the airship. The mole rate of Helium permeation out of the airship is much more than the air and this leads to the net decrease in the moles of the gases in the airship as depicted in Fig.7a and also indicated from the drop in the differential pressure as shown in Fig.5. But the molecular weight of the air is much higher as compared to the molecular weight of Helium leading to the increase in the net weight of the airship as can be seen in the Fig.7b.

Maintaining Constant Weight

This case is similar to the one discussed in section, without maintaining constant weight, except that a certain amount of Helium - air mixture is released to maintain total constant weight of the airship. This is done by computing the total excess weight after every computation and then releasing the excess amount of Helium - air mixture from the ballonet. The individual quantity of Helium and air from the Helium - air mixture that will effuse out of the opening in the ballonet is estimated using the Dalton's Law of Effusion as mentioned in section, theory. It can be seen from the Fig.8 and Fig.9 that no significant difference can be observed in the quantity of Helium and air in the hull and the ballonet. This is owing to the fact that the quantity of gases is very large and the difference though present is not as much noticeable from the graphs. Similarly, Fig.10 also remains the same and the purity of Helium is marginally affected.

Figure 11 shows the inflation ratio with time and it can be observed that the drop in inflation ratio is less as compared to the drop in earlier case Fig.6. The reason for this that the mixture of gases is released only from the ballonet to maintain the constant weight thereby decreasing the total number of moles in the ballonet hence reducing its volume relative to the previous case as other parameters such as pressure and temperature are same both for hull and ballonet.

Figure 12 gives the rate with which the gas should be released in the atmosphere so as to maintain the constant weight which in turn would lead to the maintenance of the constant altitude as the buoyancy remains constant for the system. Fig.13 gives the total moles and the mass to be released till the day i.e. the cumulative amount of Helium - air mixture released.

However, in Fig.14 a considerable change can be observed and the pressure drop is even sharper in this case as compared to the previous one in Fig.5. This is because considerable moles of gases are now released from the ballonet Fig.13a thereby decreasing the total number of moles even sharply as compared to the previous case as seen from the Figs.15a and Fig.7a respectively.

Figure 15b shows that the total mass of the gases in hull and in the ballonet is constant thereby maintaining constant altitude in contrast to the Fig.7b where the mass of the gases increases thereby forcing the airship to lose altitude and stabilize at the point where the weight equals the buoyancy.

Conclusion

In this study the impact of Helium permeation through the hull and the ballonet skin is considered. An open loop control method for estimation of the amount of Helium - air mixture to be released is also suggested and simulated. Following conclusions can be drawn from the analysis:

- Helium permeation limits the endurance by increasing the total weight of the airship and also by decreasing the differential pressure across the airship hull skin affecting the ability of the airship against the impact of gushes.
- The moles of gases inside the airship hull and ballonet continuously decreases with time but still the weight of the airship increases owing to significantly large molecular weight of air as compared to that of Helium.
- The inflation ratio first decreases with time and thereafter starts increasing mainly because of the high rate of transmission of Helium from the hull to the ballonet.
- The differential pressure continuously decreases with time due to the overall decrease in the number of moles of gases present in the airship.
- The mathematical model developed confirmed the expected results which are also in coherence with the flight data of the aerostats.
- The airship system is feasible to fly for periods more than 6 months against the limitation applied by the helium permeation on its endurance.

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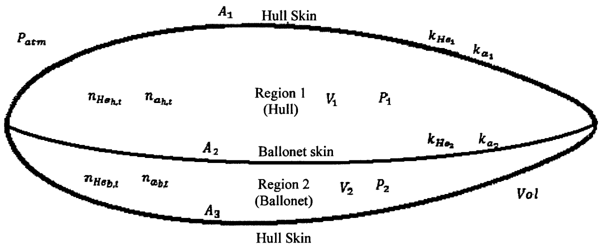

Fig.1 Airship Model and Parameters Used in the Study

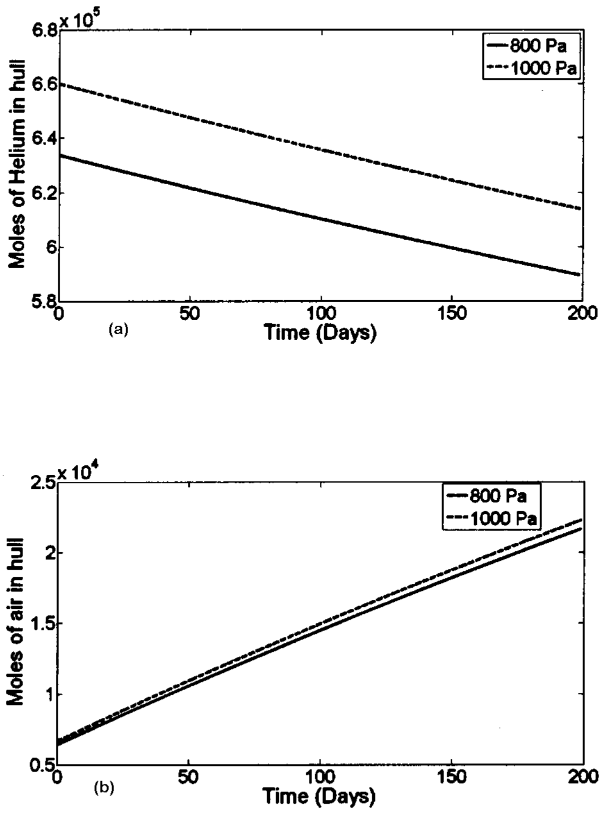

Fig.2 Moles of (a) Helium (b) Air in Hull vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

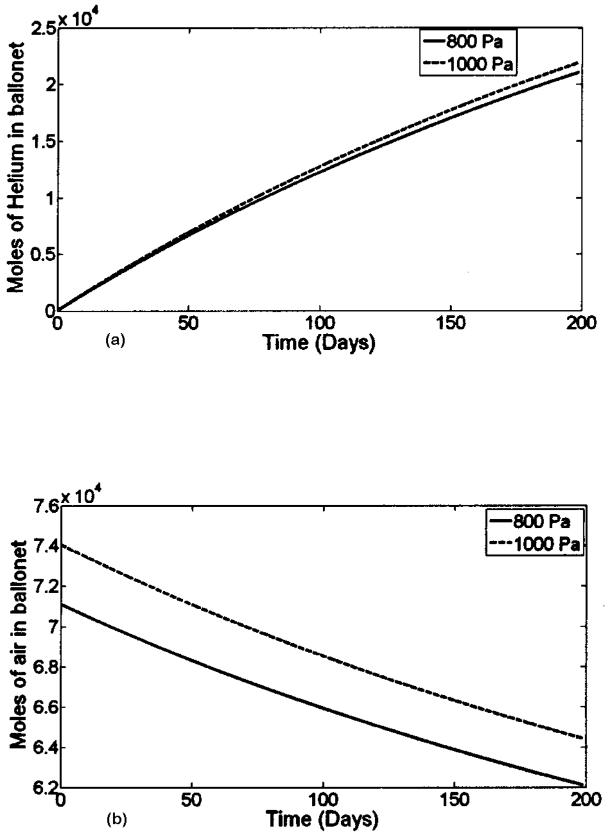

Fig.3 Moles of (a) Helium (b) Air in Ballonet vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

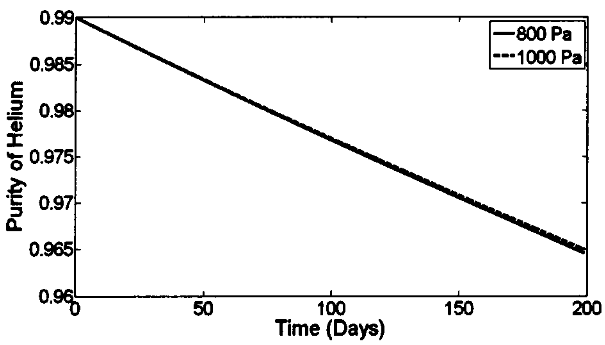

Fig.4 Purity of Helium in Hull vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

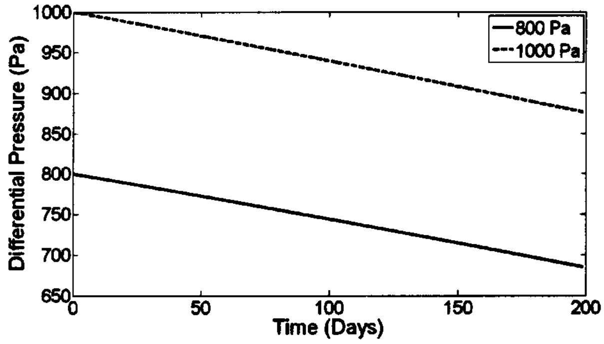

Fig.5 Differential Pressure in Airship vs Time

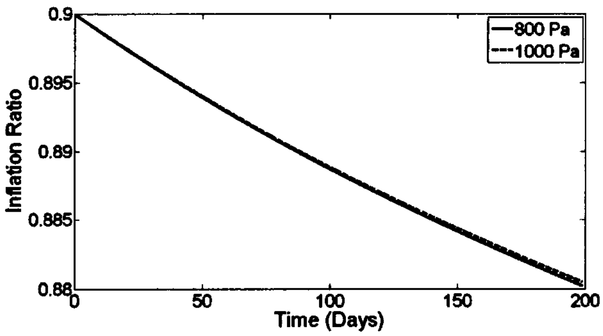

Fig.6 Inflation Ratio vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

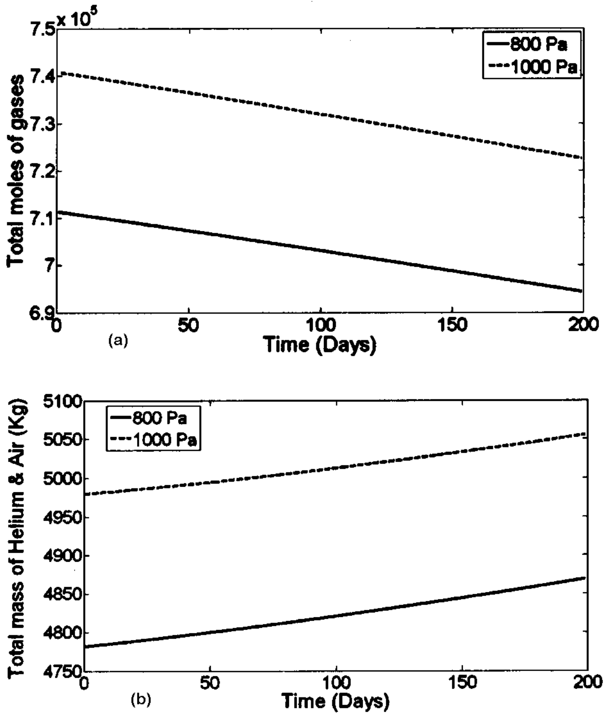

Fig.7 (a) Total Moles (b) Total Mass of Helium and Air vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

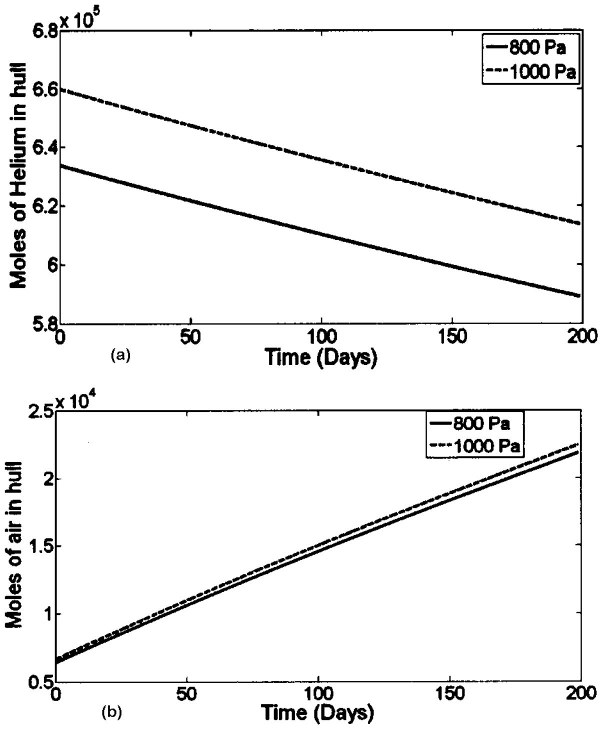

Fig.8 Moles of (a) Helium (b) Air in Hull vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

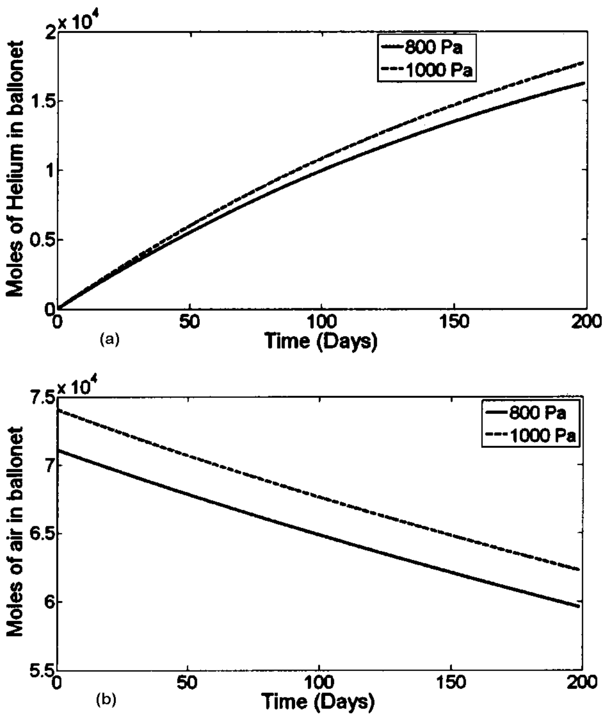

Fig.9 Moles of (a) Helium (b) Air in Ballonet vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

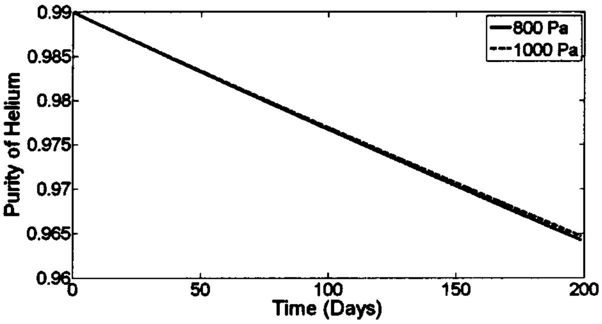

Fig.10 Purity of Helium in Hull vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

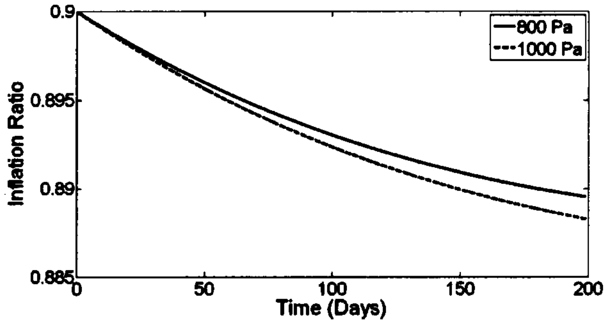

Fig.11 Inflation Ratio vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

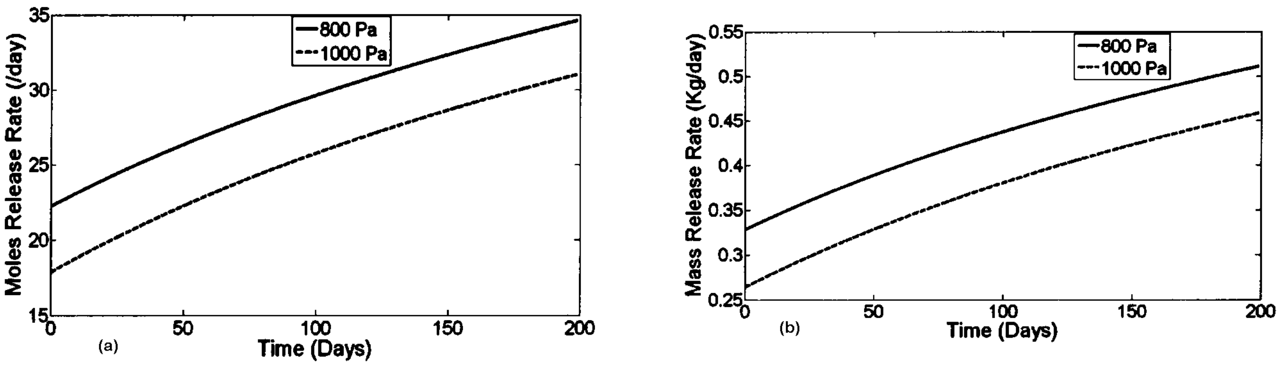

Fig.12 (a) Moles Release Rate (b) Mass Release Rate of Helium - Air Mixture in Ballonet vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

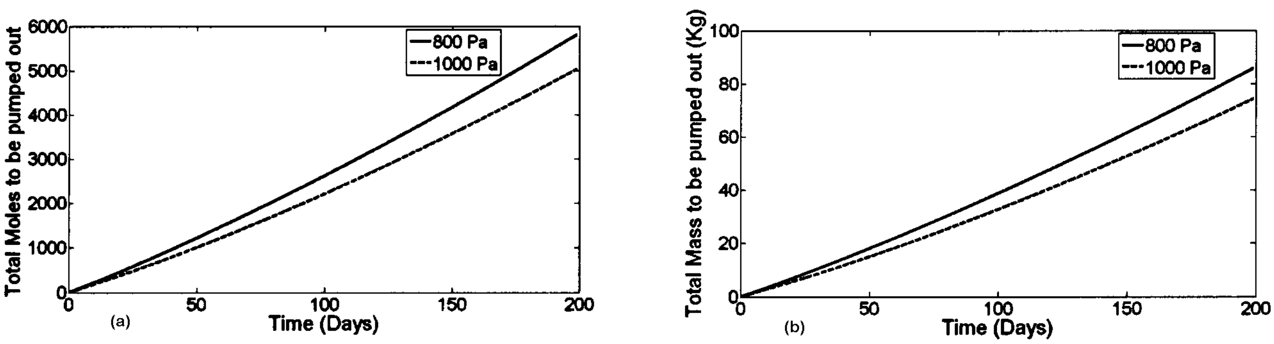

Fig.13 (a) Total Moles to be Released (b) Total Mass to be Released of Helium - Air Mixture in Ballonet vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa

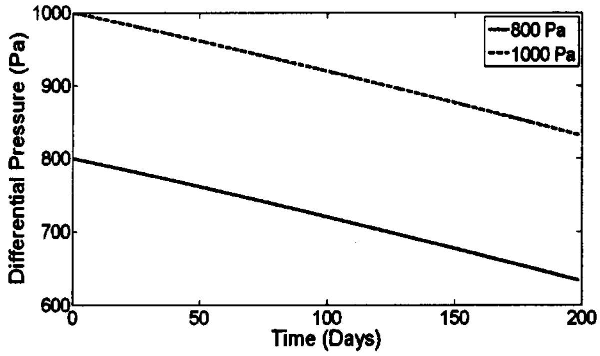

Fig.14 Differential Pressure in Airship vs Time

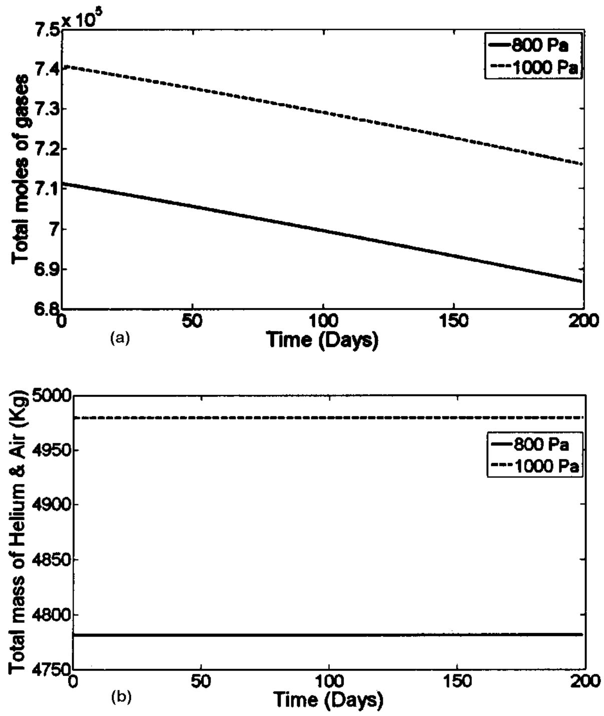

Fig.15 (a) Total Moles (b) Total Mass of Helium and Air vs Time at Initial Differential Pressure of 800 Pa and 1000 Pa