Analysis to Effects on Conceptual Parameters of Stratospheric Airship with Specified Factors

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***Abstract*—Stratospheric airship is capable of station-keeping at high altitude in precondition of the balance of buoyancy and weight, thrust and drag. Based on specific computation process, when some hypotheses are given, the length of airship can be calculated and it is emphasized to analyze the impacts on payload capability performance and conceptual parameters (such as length, surface area and volume) with altitude, latitude of station-keeping and pressure difference, temperature difference, helium purity. It is shown from the analyses that pressure difference, temperature difference and helium purity have fewer effects on payload capability and length of airship, and in contrast, altitude and latitude of station-keeping have the larger effects. On the other hand, effects on payload capability and length with each technology guideline are also discussed when specified operation parameters keep constant, such as altitude and design wind of station-keeping. It is concluded that the benefit to length and payload capability is the largest with improvement of envelope mass/area ratio but the least with improvement of propeller system efficiency.**

***Index Terms*—stratosphere, airship, conceptual parameters**

I. INTRODUCTION

Airships, unlike aircraft, generate lift from buoyancy instead of through aerodynamics. Consequently, airships do not need to stay in motion to remain aloft. Therefore, they can loiter over a specific location for a long time as well as move to a new location. In addition, airships can carry large-volume, heavy payloads. So it is suitable that they may function as a military intelligence, reconnaissance and communications relay platforms [1].

However, the main issue in high altitude flight is generating lift in the low density atmosphere which results in size of airship being gigantic [2]. The operational environment and mission requirements have significant influences on an airship's capabilities. Factors such as altitude and latitude will affect the buoyancy lift and the available solar power respectively. On the other hand, the wind speed that the airship must overcome to maintain its position is also dependent on the time of year, latitude and longitude. The wind has a significant effect on its drag and therefore power consumption.

It is well known that the three phase of engineering design are conceptual, preliminary and detailed design. And the conceptual design has a direct bearing and influence on the effort and investment in the phases. One of the most important activities in the conceptual design phase is design studies that lead to the identification of the baseline requirements of the final product. Therefore, analyzes and identifies the leverage of various design variables and technologies guidelines on the performance and operational parameters are an essential part of stratosphere airship.

Several methodologies and procedures for obtaining baseline specifications of airship were available. Pant had presented a methodology for arriving at the baseline specification of a non-rigid airship of conventional configuration, given the performance and operational requirements, but in this paper it is only analyzed that design variables (such as pressure altitude, helium purity and temperature difference) have effects on payload capability [3]. J.A. Krausman analyzed that environment parameters had effects on the performance of tethered airship, such as temperature, pressure and wind and pointed out the numerous parameters which must be considered in sizing include such items as weight, material effects, temperature, pressure, and mission altitude and duration [4]. Marcus A. Lobbia and Richard H. Gong presented a modular sizing model which has been proved useful in implementing a variety of sub-models, and identified that rigid airship configuration has more difficulties in capability of reaching high altitude using traditional approaches[5]. Jason E. Jenkins, etc

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applied genetic algorithms to optimal design the HARVe power generation system, subject to constraints on vehicle buoyancy and energy balance [6].

However, these papers mentioned above focus on payload capability or energy balance, and pay little attention to factors which have influences on length and payload capability on condition that buoyancy lift equals to weight of airship and available thrust equals to drag. The paper is to emphasize to analyze the impacts on payload capability performance and conceptual parameters (such as length, surface area and volume) with altitude, latitude, pressure difference, temperature difference and helium purity, and effects on payload capability and length with each technology guideline are also discussed when some operational parameters are determined, such as altitude and design wind speed of station-keeping.

II. COMPUTATION PROCESS

A. Basic Hypotheses

It is known that in order to station-keeping at high altitude for airship, it is necessary to accord with the following [7].

- The balance of buoyancy and weight of airship.
- The balance of thrust and drag of airship.

The size of airship required can be calculated if basic hypotheses are given as follows.

- The NPL low drag airship body shape shown in Fig.1 [8].
- Bare hull (gondola and tail group etc. being not taken into account).
- Payload and power for mission-devices on board being not considered.
- Power provided by Photovoltaic array + Lithium-ion battery storage system and cruise by screw propellers suitable for high altitude environment.
- Horizontal cruise in north to south direction, in other words, pitching and azimuth angle of airship being zero.
- Volumetric drag coefficient being 0.08.
- In winter solstice.
- At altitude of 20km.
- At the locations of Taipei and Beijing.
- Fitness of airship being 0.25.
- Area of photovoltaic array being 50% ratio of top surface of airship.

Winter solstice is taken for date of station-keeping based on the reasons that solar irradiance time is shortest and local wind is a maximum. If the airship can be station-keeping in winter solstice, it is capable of flight at high altitude in all year. Based on statistical wind data in the years of 1971-2000 from Weather Bureau in China, and it is described in Fig.2 that the mean wind varies with the altitude at two locations of Taipei and Beijing. It is pointed out that the date of wind speed at high altitude of 18-30 km was modeled with Weibull distributions by Jason A. Roney [9], and based on the conclusion the characteristics of wind at altitude of 20 km are shown in Table I.

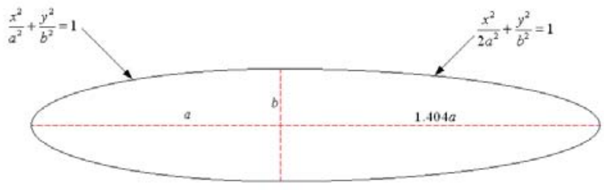


Figure 1. The NPL low drag airship body shape

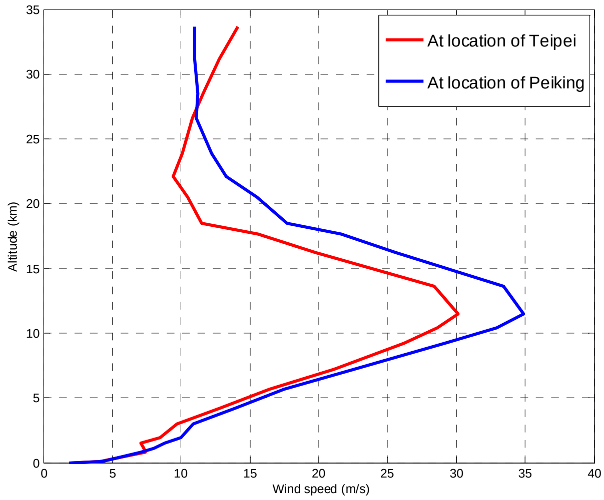


Figure 2. Wind vary with altitude at locations of Taipei and Beijing

TABLE I. CHARACTERISTICS OF WIND AT TWO LOCATIONS

Location	V_{Mean}	STD.	$V_{50\%}$	$V_{95\%}$	$V_{99\%}$
Taipei	10.5 m/s	4 m/s	10.4 m/s	17.3 m/s	20.1 m/s
Beijing	15.5 m/s	4.5 m/s	15.6 m/s	22.8 m/s	25.5 m/s

Note: V_{Mean} – Yearly mean wind; STD. – Standard deviation;

B. Conceputal parameter estimation model

Conceptual parameters estimation model based on two balances for stratospheric airship is shown in Fig.3. When baseline of technologies guidelines in model is given, as described in Table Ⅱ, design wind at altitude of station-keeping calculated at location of Taipei is 15.5 m/s. As can be seen from Fig.4 that length of airship is 171 m if two balances are attained and mass breakdown is shown in Fig.5. On the other hand, the description of the equations in the model is given below.

- Wet surface area and volume of airship

$$S=\frac{2}{3}\pi\left(2a_1b+2b^2+2a_2b\right) \tag{1}$$

$$V_{airship}=\frac{2}{3}\cdot\pi\left(a_1b^2+a_2b^2\right) \tag{2}$$

- Drag and buoyancy lift

$$D=1/2\cdot\rho_{air}V^2V_{airship}^{2/3}C_{DV} \tag{3}$$

$$B=\left(\rho_{air}-\rho_{He}\right)V_{airship} \tag{4}$$

Where, "C_{DV}" is volumetric drag coefficient and "V" is local wind.

- Weight of solar array

$$W_{sc}=S\cdot R_{sc}\cdot Den_{sc} \tag{5}$$

Where, "R_{sc}" is the ratio of solar array area in top surface area of airship and "Den_{sc}" is the solar array mass/area ratio.

- Weight of envelope or hull

$$W_{hull} = Den_{hull} \cdot S \tag{6}$$

Where, "Den_{hull}" is the envelope mass/area ratio.

- Weight of lithium-ion batteries

$$W_{Li.} = E_{Li.} / (\eta_{Li.} \cdot Den_{Li.}) \tag{7}$$

Where, "Den_{Li}" is storage system energy/mass ratio; "$\eta_{Li.}$" is storage system efficiency; "$E_{storage}$" is partial energy outputs from solar array for night.

- Weight and thrust of propeller system

$$W_{Prop.} = P_{Prop.} / Den_{Prop.} \tag{8}$$

$$T = P_{Prop.} / V \tag{9}$$

Where, "$P_{Prop.}$" is power outputs for propeller system; "$Den_{Prop.}$" is propeller system power/mass ratio.

In addition, energy outputs from solar array in a day (E_{sc}) can be calculated in the following equations:

$$P_{sc} = SI \cdot \sin(B_{inc.}) \cdot S_{Proj.sc} \cdot \eta_{sc} \tag{10}$$

$$E_{sc} = \int_{h_{sr}}^{h_{ss}} P_{sc} dh \tag{11}$$

Where, "SI" is the solar intensity at altitude of 20 km, 1262 W/m^2; "η_{sc}" is the solar array efficiency; "$S_{Proj.sc}$" is the horizontal projection of solar array surface area; "$B_{inc.}$" is the angle of solar incidence; "h_{sr}, h_{ss}" is sunrise and sunset respectively.

The balance of energy in a day can be described as:

$$\int_0^{h_3} (P_{mean} - P_{sc}) dh + \int_{h_4}^{24} (P_{mean} - P_{sc}) dh = \eta_{storage} \int_{h_3}^{h_4} (P_{sc} - P_{mean}) dh \tag{12}$$

The sketch map for balance of energy is shown in Fig.6 on condition that some hypotheses are given.

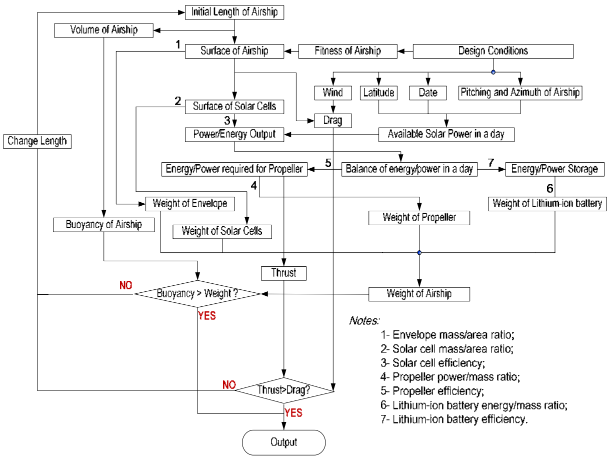


Figure 3. Computation process for conceptual parameters

TABLE II. BASELINE OF TECHNOLOGY GUIDELINES

Technology guidelines	Baseline
Envelope mass/area ratio (g/m^2)	400
Solar cells mass/area ratio (g/m^2)	250
Solar cells efficiency	8%
Lithium-ion battery energy/mass ratio (Wh/kg)	160
Lithium-ion battery efficiency	95%
Propeller power/mass ratio (W/kg)	75
Propeller efficiency	75%

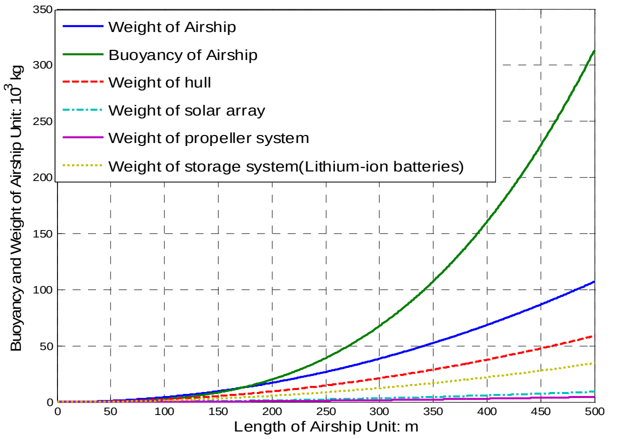


Figure 4. Size of airship and components mass

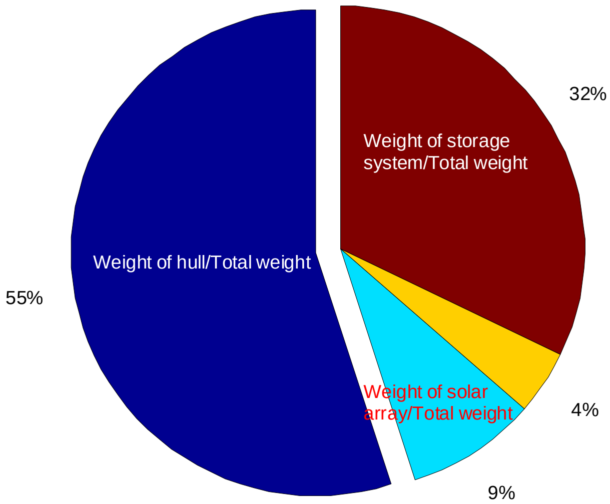


Figure 5. Mass breakdown

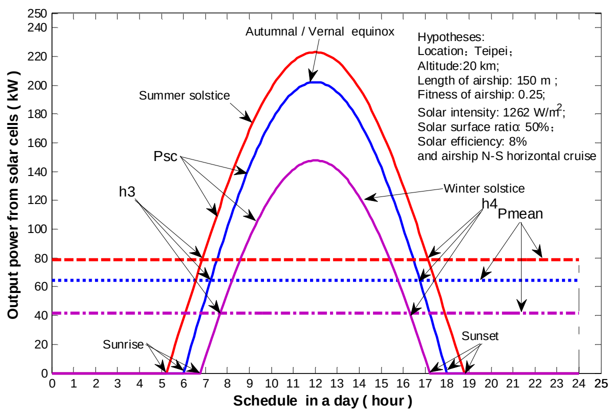


Figure 6. Sketch map for balance of energy in a day

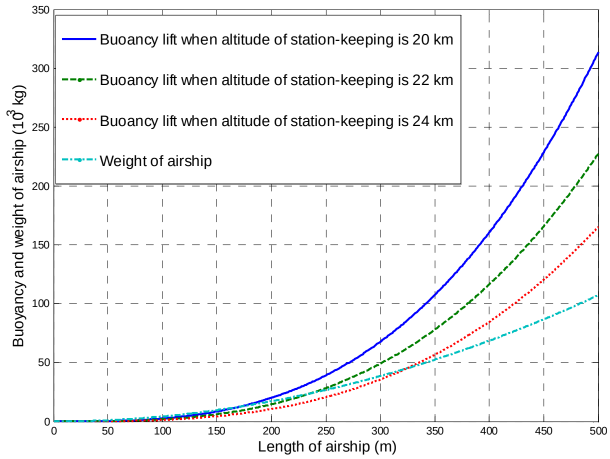
III. CONCEPTUAL PARAMETERS SENSITIVITY ANALYSIS

According to the computation process, as shown in Fig.3, and the baseline of technology guidelines mentioned previously, the impacts on payload capability performance and conceptual parameters (such as length, surface area and volume) with altitude, latitude, pressure difference, temperature difference and helium purity are analyzed as follows. On the other hand, it is also analyzed to length of airship varying with typical dates.

A. *Altitude of station-keeping*

It is well known that with the increase of altitude, the atmosphere density decreases, which results in decrease of buoyancy lift when size of airship keeps constant. On the other hand, if design wind and solar array area ratio keep constant, the available thrust is larger than drag.

It can be seen from Fig.7 that when altitude varies from 20 to 24 km, the length of airship required increases from 171 to 324.1 m accordingly. On the other hand, in case that airship size keeps constant, the payload capability would decrease obviously, as shown in Fig.8. Supposing that design wind speed keeps constant, with the atmospheric density decreases, the drag decreases accordingly, and the relationship between drag and thrust is shown in Fig.9.



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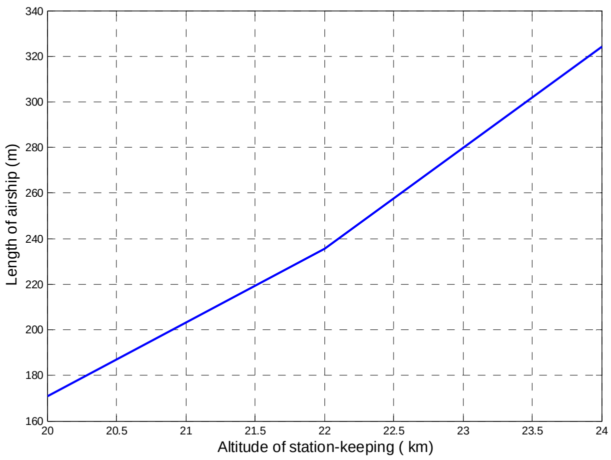

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Figure 7. Size of airship varies with altitude of station-keeping

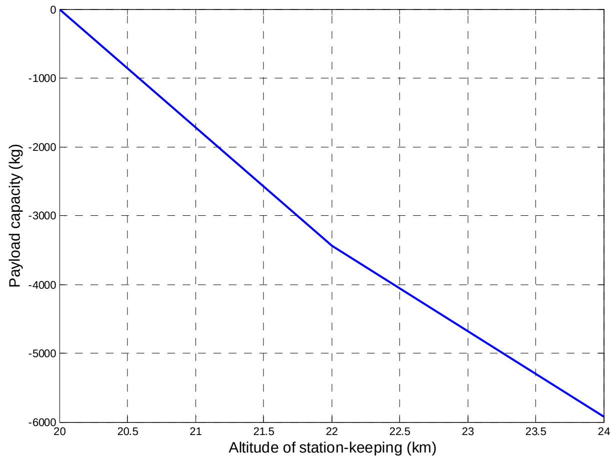


Figure 8. Payload capability varies with altitude of station-keeping

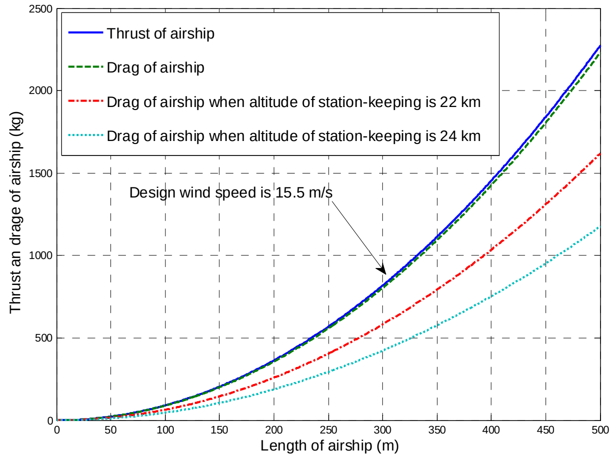
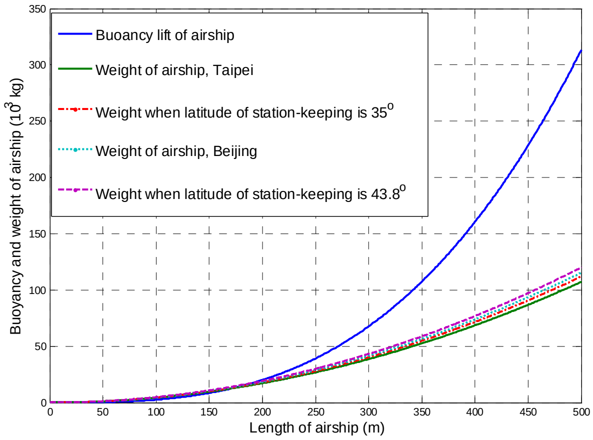


Figure 9. Relationship between drag and thrust varies with altitude

B. *Latitude of station-keeping*

Latitude of station-keeping has large impact on sunlight length. With lower latitude in same hemi-sphere of earth, sunlight time is longer, which results in increase of available energy in a day. If constant wind speed is supposed, the solar array area ratio decreases, resulting in decrease of weight and length, as shown in Fig.10. On the other hand, in case that airship size keeps constant, with the increase of latitude from 25 to 43.8 degree, the payload capability decreases from 0 to -1500 kg, as shown in Fig.11.



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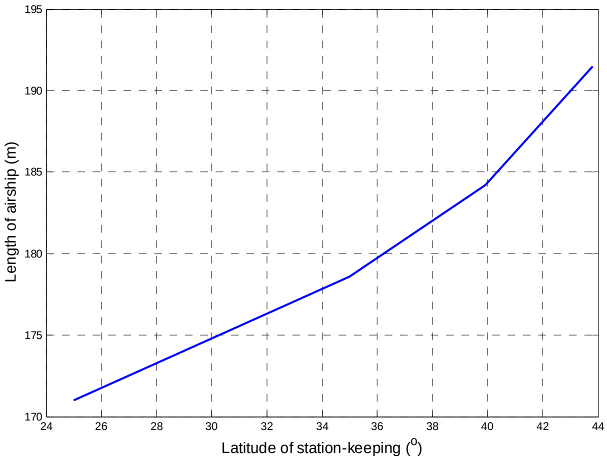

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Figure 10. Size of airship varies with latitude of station-keeping

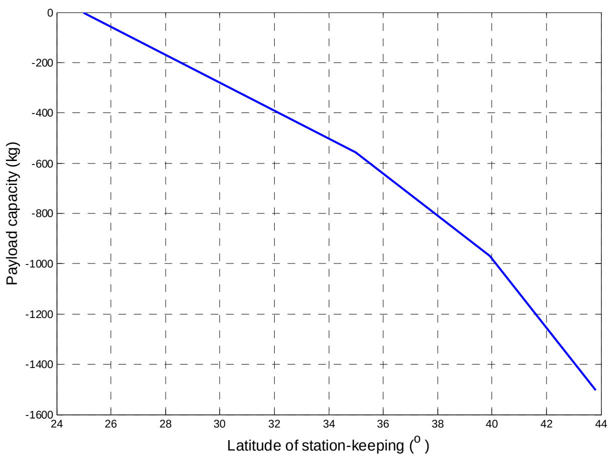


Figure 11. Payload capability varies with latitude of station-keeping

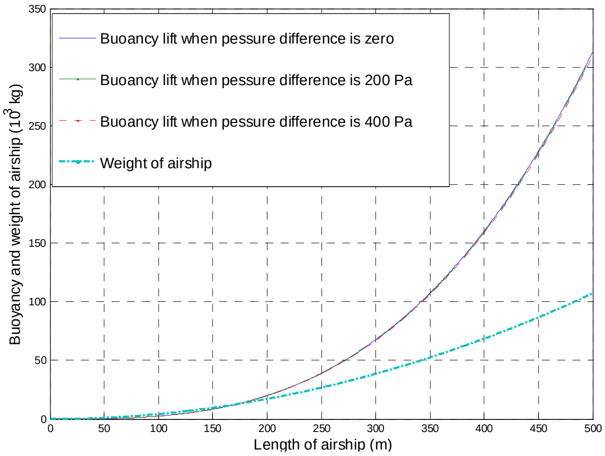
C. Pressure difference

If pressure difference between inner and outer of envelope is considered, the airship unit buoyancy lift can be described as:

$$\rho_n = \frac{25P_a - 4\Delta P}{29P_a}\rho_a \tag{13}$$

Where, " ΔP "is the pressure difference; " ρ_a " and " P_a " are atmospheric density and pressure at altitude of station-keeping respectively.

It is apparent that unit buoyancy lift decreases from $\frac{25}{29}\rho_a$ to $\frac{25P_a - 4\Delta P}{29P_a}\rho_a$ with pressure difference, resulting in increase of airship's size slightly. As can be seen from Fig.12 with the increase of pressure difference from 0 to 400 Pa, the length of airship increases linearly from 171 to 173 m, and payload capability decreases linearly from 0 to – 147 kg in case of length of airship keeps constant.



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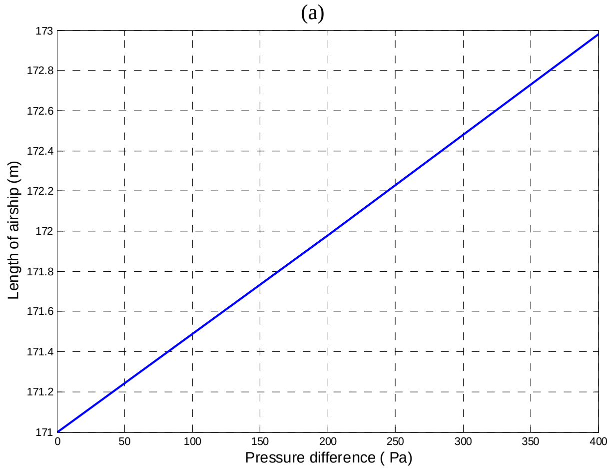

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Figure 12. Size of airship varies with pressure difference

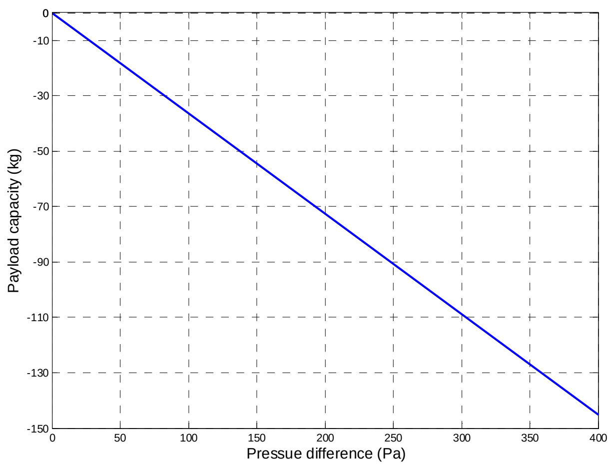


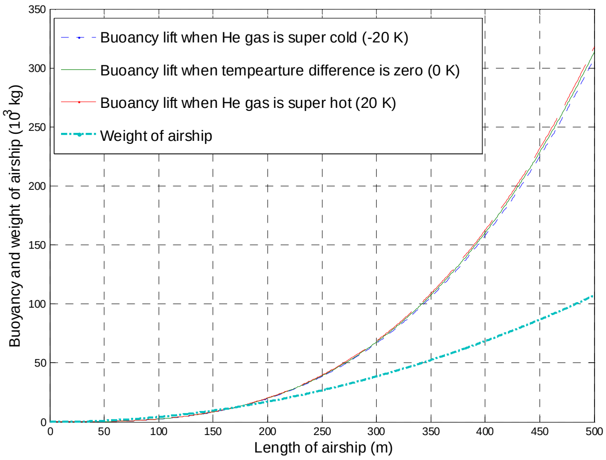
Figure 13. Payload capability varies with pressure difference

D. Temperature difference

Supposing that the phenomenon that helium is super-hot or super-cold occurs practically, the helium density can be calculated as follows:

$$\rho_{He} = \frac{4}{29} \cdot \frac{T_a}{T_a + \Delta t}\rho_a \tag{14}$$

Where, "T_a" is ambient temperature and " Δt " is temperature difference. It is obvious that when temperature difference is larger than zero, the helium density decreases, which results in increase of unit buoyancy lift from $\frac{25}{29}\rho_a$ to $\left(1-\frac{4}{29}\cdot\frac{T_a}{T_a+\Delta t}\right)\rho_a$ accordingly. It can be seen from Fig.14 that when helium is super-cold, in other words, with the temperature difference varying from 0 to -20 K, the length of airship increases from 171 to 173.8 m and when helium is super-hot, in other words, with the increase of temperature difference from 0 to 20 K, the length of airship decreases from 171 to 168.7 m. In a word, length of airship linearly varies with temperature difference almost. On the other hand, in case that airship size keeps constant, from the Fig.15, it can be seen that payload capability also almost linearly varies with temperature difference. With the increase of temperature difference from -20 to 20 K, the payload capability increases from -203 to 170 kg.



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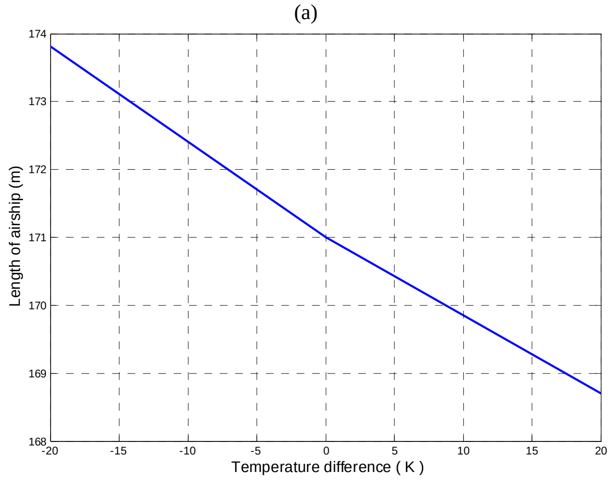

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Figure 14. Size of airship varies with temperature difference

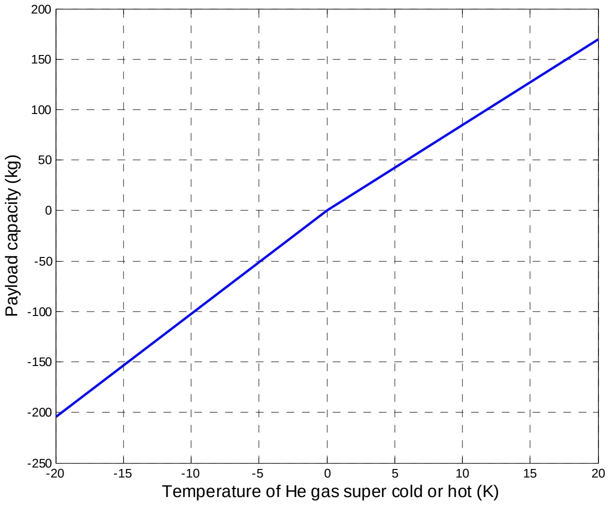


Figure 15. Payload capability varies with temperature difference

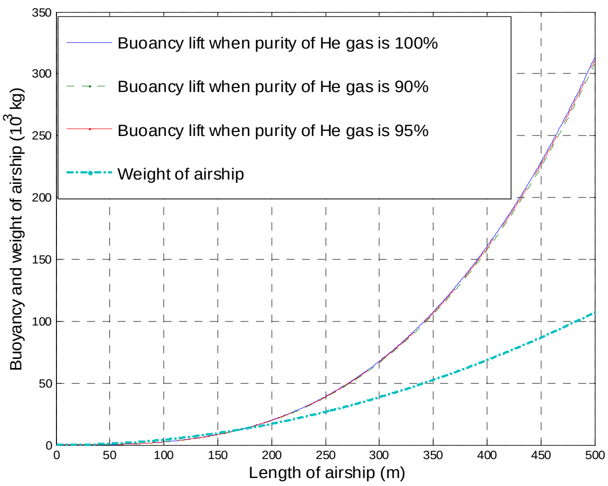
E. Helium purity

Because atmosphere may enter the helium chamber through small holes in the envelope, helium purity would decrease with increase of time of station-keeping.

When helium purity is considered, the unit net buoyancy lift calculated can be described as:

$$\rho_n=\left(1-\frac{4}{29k}\right)\rho_{air} \tag{15}$$

Where, "k" is the helium purity, less than 1.0; It is apparent that unit net buoyancy lift decreases from $\frac{25}{29}\rho_a$ to $\left(1-\frac{4}{29k}\right)\rho_{air}$. As can be seen from Fig.16 the length of airship linearly varies with helium purity and with the decreases of helium purity, the buoyancy decreases accordingly. On the other hand, if airship size keeps constant, from the Fig.17, it can be seen that payload capability also almost linearly varies with helium purity. With the increase of purity from 90% to 100%, the payload capability increases from -220 to 0 kg.



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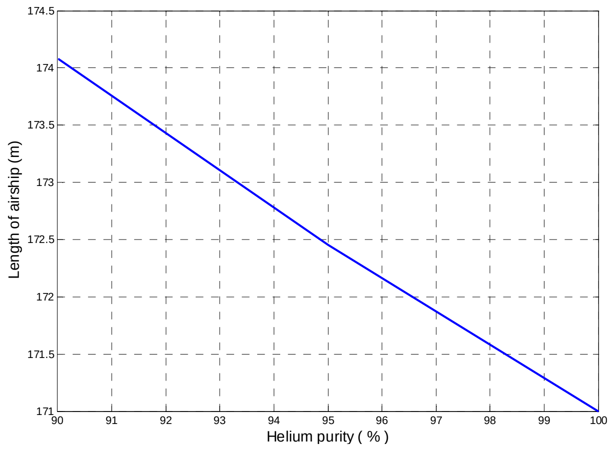

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Figure 16. Size of airship varies with Helium purity

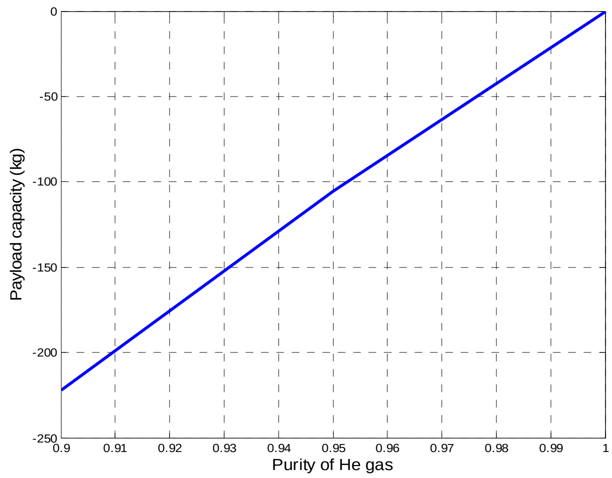

Figure 17. Payload capability varies with Helium purity

F. Different date (typcial dates taken for example)

Four typical dates are taken for example. It is well known that energy outputs are the largest in summer solstice and the least in winter solstice because of sunlight time difference. In summer solstice, the solar array ratio can be decreased, which results in weight of airship being decreased and shorter length of airship. On the other hand, in vernal equinox and autumn equinox, the length and weight of airship varying are same.

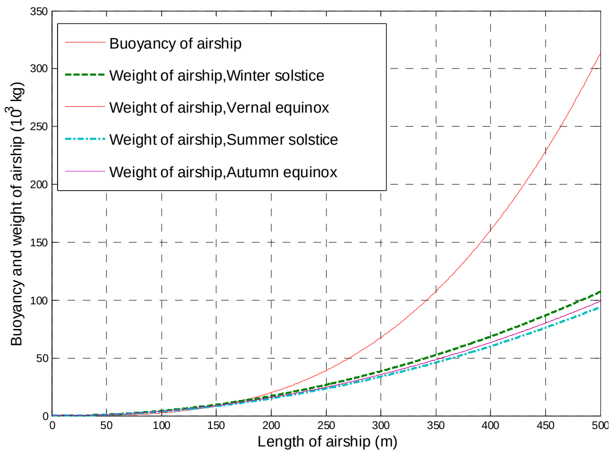

Figure 18. Size of airship varies with four typical dates

IV. EFFECTS ON CONCEPTUAL PARAMETERS WITH EACH TECHNOLOGY GUIDELINE

If specified operation parameters keep constant, such as altitude and design wind of station-keeping, effects on payload capability and conceptual parameters(such as length, surface area and volume of airship) with each technology guideline are discussed.

The trends concerning each technology guideline improvement in airship in the future which are summarize in Table Ⅲ. The new length of airship is to be obtained when each technology guideline varies separately. On the other hand, supposing that the length of airship keeps constant with each technology guideline improvement respectively, it is apparent that the payload capability increases accordingly. The effects on size of airship and payload capability with each technology guideline are shown in Table Ⅳ and Table Ⅴ respectively. It can be seen that the benefit to length and payload capability is the largest with improvement of envelope mass/area ratio but the least with improvement of propeller system efficiency.

TABLE III. IMPROVEMENT OF TECHNOLOGIES GUIDELINES

Each technology	Guidelines improvements
Envelope mass/area ratio (g/m^2)	200
Solar cells mass/area ratio (g/m^2)	150
Solar cells efficiency	12%
Lithium-ion battery energy/mass ratio (Wh/kg)	200
Lithium-ion battery efficiency	98%
Propeller power/mass ratio (W/kg)	125
Propeller efficiency	85%

TABLE IV. EFFECTS ON SIZE OF AIRSHIP

Technology guidelines	Envelope mass/area ratio	Solar array mass/area ratio	Solar array efficiency	Storage system energy/mass ratio	Storage system efficiency	Propeller power/mass ratio	Propeller efficiency
Improvement	400→200 50% ↑	250→150 40% ↑	8→12% 50% ↑	160→200 25% ↑	95→98% 3.16% ↑	75→125 66.7% ↑	0.75→0.85 1.33% ↑
Length (%)	26.9 ↓	3.5 ↓	18.1 ↓	5.85 ↓	0.88 ↓	2.34 ↓	0.47 ↓
Unitary (%)	53.8	8.77	36.26	23.39	27.76	2.63	35.18

TABLE V. EFFECTS ON PAYLOAD CAPABILITY OF AIRSHIP

Technology guidelines	Envelope mass/area ratio	Solar array mass/area ratio	Solar array efficiency	Storage system energy/mass ratio	Storage system efficiency	Propeller power/mass ratio	Propeller efficiency
Improvement	400→200 50% ↑	250→150 40% ↑	8→12% 50% ↑	160→200 25% ↑	95→98% 3.16% ↑	75→125 66.7% ↑	0.75→0.85 1.33% ↑
Payload (%)	27.47 ↑	3.43 ↑	18.23 ↑	6.43 ↑	0.98 ↑	1.72 ↑	0.57 ↑
Unitary (%)	54.94	8.58	36.46	25.72	31.01	2.58	42.86

V. CONCLUSIONS

It is concluded from conceptual parameters sensitivity analyses above that altitude and latitude of station-keeping have large impacts on payload capability and size of airship. With the increase of altitude or latitude, the size of airship increases rapidly. On the other hand, if pressure difference, temperature difference and helium purity are considered, there are several conclusions as follows:

- These factors have fewer effects on payload capability and size of airship.
- With the decrease of pressure difference and increase of helium purity, temperature difference from less than zero to larger than zero, the size of airship decreases or payload capability increases.

When specified operation parameters keep constant, such as altitude and design wind of station-keeping, effects on payload capability and length with each technology guideline are also discussed, there are several conclusions as follows:

- Improvement of envelope mass/area ratio has the largest unitary effect on payload and size of airship.
- It can be seen that the benefit to length and payload capability is the largest with improvement of envelope mass/area ratio but the least with improvement of propeller system efficiency.

So, conceptual parameters such as payload capability and size of airship depend on where (latitude, altitude) and when (time of year) the airship is to be flown, and can be varied with various design variables and technologies guidelines.

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