Air Drag on a Stratospheric Balloon in Tropical Regions

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Stratospheric balloons are popular for scientific applications as they can carry heavy payloads to perform observations for a long duration. However, for practical applications, a major challenge is the control of the trajectories of the balloons as well as station keeping for a period of time due to severe weather condition such as strong wing at the stratosphere. In order to have a better control of the movement of a stratospheric balloon, we need to have a better understanding of the air flow drag acting on a typical stratospheric balloon. In this paper, numerical simulation studies using the Star CCM+, a computational fluid dynamics software, are carried out to investigate the air drag coefficients of a balloon in the stratosphere in tropical region. By analyzing the weather data provided by the local Meteorological Service for the past three years and considering the balloon size according to the payload capacity, the characteristic Reynolds numbers and flow regime are identified. Thereafter, numerical investigations are performed to study the air drag acting on a pumpkin-shaped stratospheric balloon under typical stratospheric weather conditions in tropical regions, which is justified by referring to the drag force acting on a sphere when a flow past it under those Reynolds numbers that is obtained by using the respective empirical and semi-empirical solutions obtained from experiments.

Nomenclature

A	=	area of cross section of the balloon
a	=	equatorial radius of the balloon
b	=	polar radius of the balloon
C_d	=	drag coefficient
c	=	speed of sound
D	=	equatorial diameter of the balloon
F_d	=	drag force
H	=	height of the balloon
T	=	temperature
v	=	wind speed
μ	=	viscosity
ρ	=	density

I. Introduction

SCIENTIFIC stratospheric balloon belongs to a Lighter Than Air (LTA) vehicles floating at stratosphere above 20 km high amplitude. Relative to the traditional high amplitude observation systems, such as, aircraft, rocket and satellite systems, the stratospheric balloon system is superior as it can carry heavy payloads, it can work for a long duration, and it is also simpler and cheaper in assembling, launching and operating. In order to maximize the operational performance of the scientific stratospheric balloon system in some particular region, for instance, the tropical region that we are interested in, the long duration station keeping of the balloon system is expected. However, for practical applications, a major challenge is the control of the trajectories of the balloons as well as station keeping for a period of time due to severe weather condition such as strong wing at the stratosphere. This

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problem is aggravated by lack of active control methods in the balloon systems due to weight and energy constraints. In order to have a better control of the movement of a stratospheric balloon, we need to have a better understanding of the air flow drag acting on a typical stratospheric balloon. In this paper, based on the actual weather data provided by the local Meteorological Agency, numerical simulation studies using the Star CCM+, computational fluid dynamics software, are carried out to investigate the air drag coefficients of a balloon in the stratosphere in the tropical region. The weather data obtained from the local Meteorological Service for the past three years is analyzed. Thereafter, considering the balloon size according to the payload capacity and the operational altitude, the characterized Reynolds numbers and flow regimes are identified. The numerical investigations are thereafter performed to study the air drag acting on a pumpkin-shaped super-pressure stratospheric balloon under typical stratospheric weather conditions in tropical regions.

II. Local Weather Data in a Tropical Region

In order to investigate the operational conditions for the stratospheric balloon system, the weather data and the atmospheric information have been obtained from the local Meteorological Service. To measure the weather data at different altitudes, a freely rising meteorological balloon is released by the local Meteorological Agency twice a day, usually at 00 Coordinated Universal Time (UTC) (morning at the local time zone) and at 12 UTC (evening at the local time zone), respectively, which carries the observation equipment. The meteorological balloon system

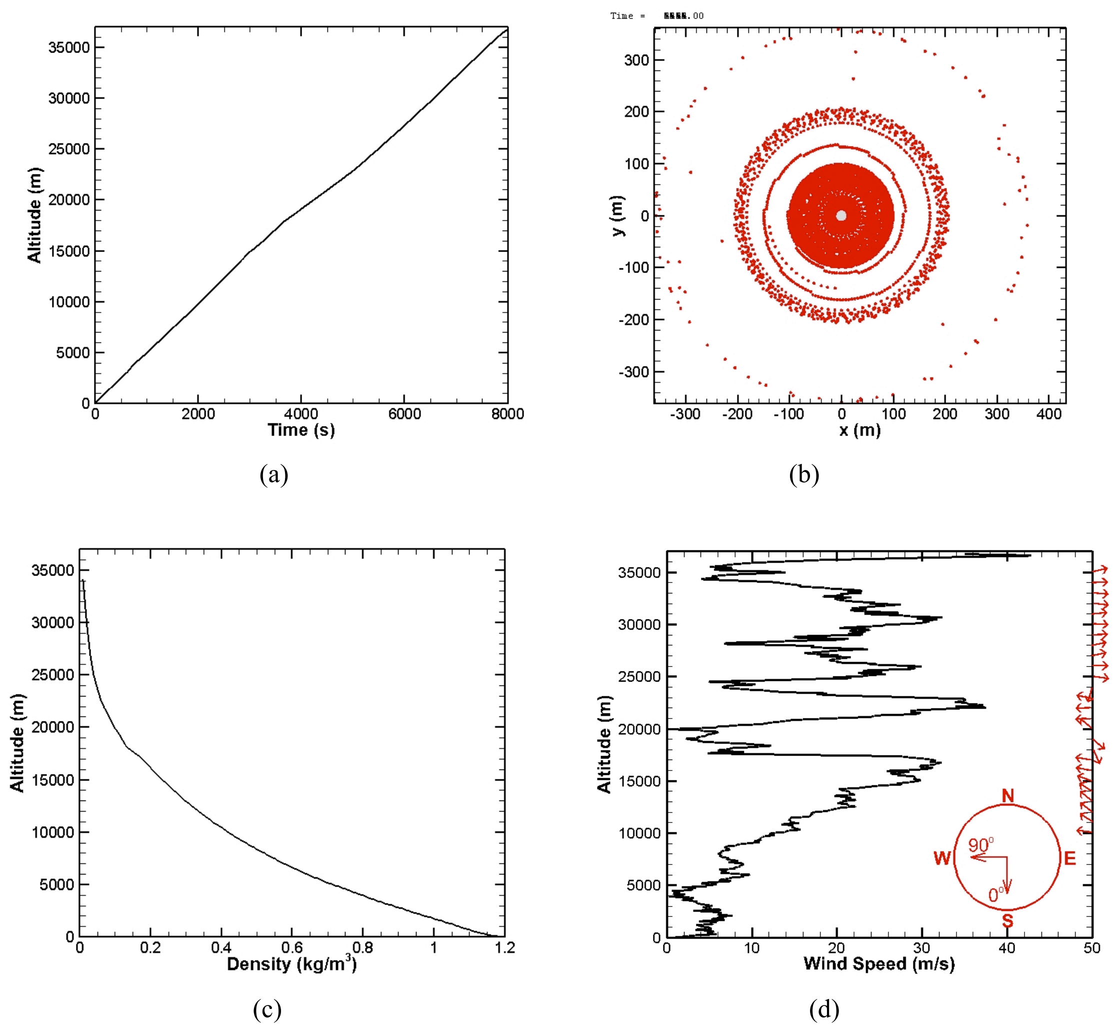
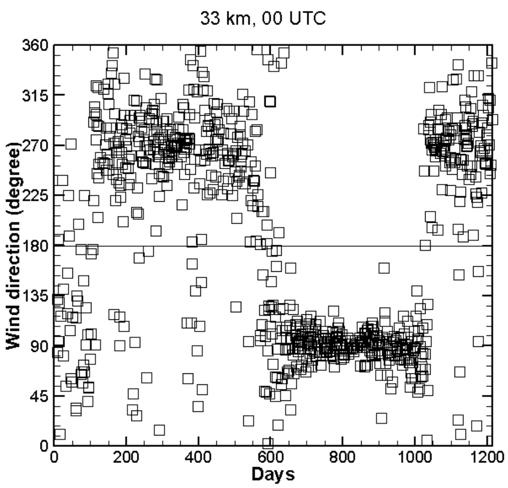


Figure 1. A sample set of weather data obtained at 00 UTC on 02-Jan-2013, including (a) the altitude of the meteorological balloon along time; (b) the relative position of the meteorological balloon to the observatory station, (c) air density, and (d) wind speed & direction along the altitude.

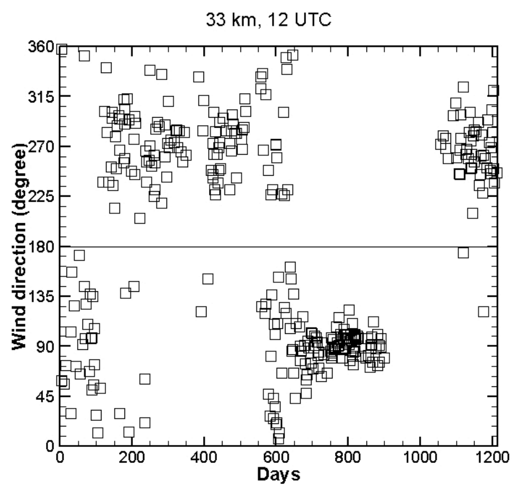
communicates with and transfers the measured data back to the observatory station every second. The observations made by the meteorological balloon system mainly include the rising speed, the altitude and the relative position of the balloon system to the observatory station, the air pressure, temperature and density, the wind speed and direction, as well as the Dew point of the air. The information closely related to study the air drags acting on the stratospheric balloon is the wind speed and direction together with the air density, temperature and pressure.

A sample set of weather data were presented in Figs. (1) which were collected by the meteorological balloon system released by the local Meteorological Service at 00 UTC on 02-Jan-2013. The meteorological balloon reached the highest altitude of 36.8 km in 7997 s, as shown in Fig. 1(a). The maximum radius of the trajectory of the meteorological balloon relative to the observatory station at different altitude levels (horizontal radius) was less than approximated 350 m, as presented in Fig. 1(b). In Fig. 1(c), we find that the air density goes down in an approximately exponential manner along the altitude. The variation of wind at different altitude levels is displayed in Fig. 1(d). It is clear to note that there was an obvious change of the wind direction between altitudes from 10 km to 24 km and altitudes from 25 km to 36 km. Accordingly, if we would like to use the passive control method for the balloon system, such as the StratoSail,[1,2] we can locate the StratoSail and the balloon at these two altitude levels, respectively.

Until now, we have obtained the weather data from the local Meteorological Service for the period from January 2012 to April 2015. Ideally, there would be 2432 sets of weather data. However, due to the weather conditions and the air traffic control, the meteorological balloon cannot rise in some occasions, and thereafter there are in total only



(a)



(b)

Figure 2. Variation of wind direction at 33 km in our tropical region during the period from January 2012 to April 2015.

2225 sets of data, in which 1205 sets of data were measured at 00 UTC and 1020 sets of data were measured at 12 UTC. Also, since the meteorological balloon reaches to a random height every time due to its free rising, there are 1006 sets of data that are suitable for us to study the air drag acting on the stratospheric balloon in which the atmospheric properties and wind information are available for the altitude up to or above 33.5 km. In those 1006 sets of data, 706 sets were obtained at 00 UTC, while the rest 300 sets were obtained at 12 UTC. One of the key reasons as to why is that there are much fewer useful data obtained at 12 UTC is that the meteorological conditions in the evening (12 UTC) at our local tropical region is not as good as that in the morning (00 UTC).

In the initial design of our stratospheric balloon system, we set up the operational altitude of the balloon at altitude of 33 km. The air drag on the stratospheric balloon is due to the wind. From the weather data, we obtain the wind speed, direction, air density, temperature, and pressure at 33 km in our tropical region through interpolation.[3] The wind direction variation during the period of January 2012 to April 2015 is shown in Fig. 2, in which the well-known quasi-biennial oscillation (QBO)[4] phenomenon around the equator (tropical regions) is presented. The wind speed distribution is displayed in Fig. 3 by using the basic statistical analysis. The average wind speed at 33 km is 17 m/s, but with a high derivation as 9 to10 m/s, which indicates that the wind speed at high altitude varies significantly. Another two atmospheric properties closely related to calculate the air drag are air density and air

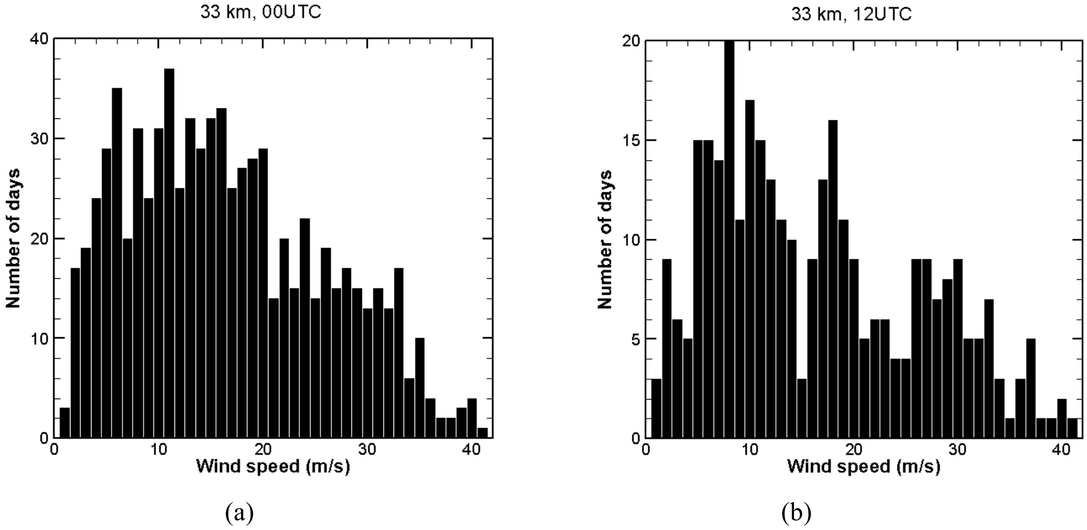


Figure 3. Distribution of wind speed at 33 km in our tropical region during the period from January 2012 to April 2015.

temperature. Air density is needed to estimate the size of the balloon and is used to calculate the drag force directly, while air temperature can be used to obtain air viscosity and speed of sound. At 33 km in our tropical region, the average air density is 0.01 kg/m^3 with standard derivation of 6×10^{-4} kg/m^3, and air temperature is -39 ^{o}C with standard derivation of. Also, the atmospheric pressure at 33 km is 765 pa with standard derivation of 14 pa.

III. Air Drag Acting on a Stratospheric Balloon

A. The Size of the Stratospheric Balloon

In our project, the super-pressure balloon is chosen given its better capability to maintain the operation altitude for a long duration compared to the zero pressure balloons.[5] Zero pressure balloons are more popular choices for modern scientific observations at high altitude for the past half century, because it is easy to construct a large size zero pressure balloon from thin lightweight films due to the minimized pressure on the balloon film. However, because of the big temperature drop after the sunset at high altitude, the volume of a zero pressure balloon is reduced correspondingly to maintain the low pressure on the film which consequently causes the reduction of the buoyant force of balloon system. In order to maintaining the nighttime operation altitude, the ballast has to be dropped from the zero pressure balloon system. Due to the ballast, the ratio of the payload carried by the zero pressure balloon system is decreased. Also, using ballast to control the flying altitude prevents the zero pressure balloon system from a long time operation since, when the ballast is completely used, the left operating hours of the zero pressure balloon system is very limited. On the contrary, a super pressure balloon is unaffected by the sunset and is stable in altitude as it is fully inflated due to the higher pressure inside the balloon relative to the surrounding air. Since there is no need to drop ballast to maintain altitude, it is possible for a super pressure balloon system to operate for a long duration.

Having decided that the stratospheric balloon will be operated at the altitude of 33 km, and obtained the air properties at that height, we can estimate the size of the balloon based on the payload. Our target payload is 200 kg. According to the mass of payloads and the total mass of super pressure balloon systems given in the previous literatures,[6-9] also see Table 1, we estimate that the total mass of the super pressure balloon system is 700 kg to carry 200 kg payload through interpolation.[3] The shape of modern super pressure balloons is almost an oblate spheroid, also known as the pumpkin shaped balloons and/or natural shape balloons,[5,10] which has been inspired from the partially inflated balloon section during launching[11] as well as the shape of parachutes[12]. The shape of an oblate spheroid is described as

$$\frac{x^2+y^2}{a^2}+\frac{z^2}{b^2}=0\,, \tag{1}$$

Table 1 Comparison of mass of payloads and total mass super pressure balloon systems.

Balloon name	PB60[6]	586NT[7]	PB300[6]	616NT[8]	631NT[9]
Payload [kg]	100	295	490	1815	2270
Total [kg]	430	900	1150	3900	4500

where a is the length of the equatorial radius of the oblate spheroid balloon and b is the polar radius. The volume of that balloon is $3\pi a^2 b/4$. Letting the ratio of the height H=2b and the diameter D=2a of the balloon equal to 0.6,[10] and using the air density at 33 km altitude as ρ=0.01kg/m^3, through balancing the buoyant force due to the volume of the balloon and the total weight of the balloon system with mass of 700 kg, we find that D is approximated 60 m and H is 36 m. So that, the volume of the super pressure balloon is 67858.4 m^3, which is a quite reasonable estimation compared to the relation graph of the total mass of super pressure balloon system and the volume of the balloon given in Fig. 2.2 of Ref. 5.

B. Numerical Simulation Studies on Air Drag Acting on the Stratospheric Balloon

In aerodynamics, the drag coefficient is mainly a function of Reynolds number, Re,

$$\mathrm{Re} = \frac{\rho D v}{\mu}, \tag{2}$$

in which, v is the wind speed. The only missing information in Eq. (2) is the dynamic viscosity of air μ, which can be calculated through the Sutherland's law using the air temperature T. The Sutherland's law[13] is

$$\mu = 1.512 \times 10^{-6} \frac{(T + 273.15)^{1.5}}{T + 273.15 + 120.0}. \tag{3}$$

At the altitude of 33 km in our tropic region, the viscosity of air is 1.53×10^{-5} pa·s. So that the range of the Reynolds number for the air flow past the balloon is among 1×10^5 to 1.6×10^6, which obviously belongs to the turbulent flow regime. Also, as the stratospheric air is dry, the speed of sound c can also be found based on the air temperature by using the following relationship[14]:

$$c = 331.45\sqrt{1 + \frac{T}{273.15}}. \tag{4}$$

As such, the speed of sound at the altitude of 33 km is 306.88 m/s. As the maximum wind speed at that altitude is less than 41 m/s, so that we can regard the air flow past the balloon at 33 km as the incompressible flow since the Mach is less than 0.3.

Having all the information about the air flow on hand, the air drag acting the balloon has then been calculated by the commercial Computational Fluid Dynamics (CFD) software, STAR CCM+. The simulation geometry model of flow domain was constructed as follows. The center of the balloon was located at the origin with its equator on the xy-plane, and then a numerical rectangular wind tunnel was created to enclose the balloon. The wind blows along the x axis. The upstream of the flow was set as 10D long and the downstream was extended to 30D. Along both the y and z directions, the wind tunnel size was from -8D to 8D. The inlet condition of the flow was given by the uniform wind speed normal to the boundary, and the outlet condition of the flow was set as the pressure outlet. On the rest four walls of the wind tunnel, the free slip boundary condition has been applied to reduce the wall effects on the flow domain. The balloon surface was set as no-slip, and prism layers were generated from the balloon surface and then inflated to the flow domain. After that, the flow domain was discretized by the unstructured polyhedral elements.

In our calculations, the k-ω SST flow model with high-Reynolds-number wall treatment has been chosen to deal with the turbulent flow. Though the Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) models are the scientific trend to study turbulent flows which are claimed to be able to capture many flow details of turbulence, these two models require very large computational powers and they are very time-consuming. Since our purpose to study the air drag acting on the balloon is to obtain the necessary information for the design of the balloon system with better station keeping ability, the current engineering standard k-ω SST flow model is a very reasonable choice for us to start with. One key factor in simulating turbulent flows by CFD is to approximate the boundary layer behavior accurately. This highly depends on the prism layers generation on the balloon surface when meshing. In our simulations, the thickness of the first layer of the prism (wall distance) has been initially estimated by the formulation for a uniform flow past a smooth plate[15] with the desired *y*+ as around 200. Then with a few numerical tests, the wall distance was tuned to make sure that the *y*+ values are within 12 to 250 in all of our calculations. We then let the prism layers grow with a constant stretch factor, which is less than 1.15, to digest the estimated total thickness of the boundary layer. However, we do not stop at that prism layer, but keep inflating another 5 prism layers, which should be able to guarantee us a good approximation on the boundary layer behavior.

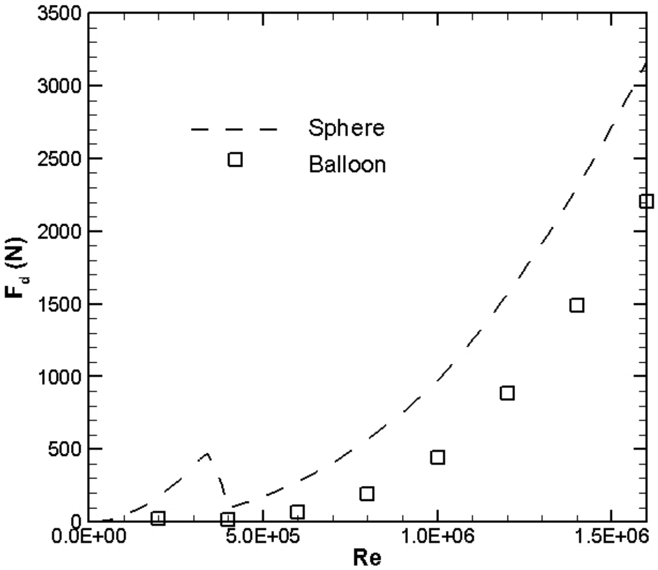


Figure 4. Drag force acting on the balloon under different Reynolds number.

The drag force F_d acting on the balloon under different Reynolds numbers is shown in Fig. 4. In Fig. 4, we also presented the drag force acting on a sphere (dashed line) when a flow past it under the same Reynolds numbers. The diameter of the sphere is the same as that of the balloon, and for simplicity, we call that sphere as the sphere associated to the balloon. The drag coefficient $C_d=2F_d/(\rho v^2 A)$ for that sphere under different Reynolds numbers, where A is the area of the cross section of the sphere, can be found by the respective empirical and semi-empirical solutions obtained from experiments[16]. Corresponding, the drag forces on that sphere are obtained. Referring to the drag forces acting on the sphere associated to the balloon, we can see from Fig. 4 that the drag force acting on the balloon obtained by the CFD software Star CCM+ are reasonable since the balloon is less blunter compared to the associated sphere, though progresses are still needed to improve the accuracy. Nevertheless, the information of the air drag acting on the balloon that we found is still very useful for the initial design of the station keeping of the balloon system.

IV. Conclusion

In this paper, the air drag acting on a super pressure balloon floating in a tropical region has been investigated. Through the basic study and analysis on the weather data obtained from the local Meteorological Service, the air flow conditions around the balloon at the operational altitude (33 km) have been gotten. According to the target payload and flight altitude of the balloon, the total mass of the balloon system and the size of the balloon have been estimated. Then, the Reynolds numbers of the air flow past the balloon were obtained and numerical simulations have been carried out to calculate air drag acting on the balloon, which supplies us useful information for the station keeping of the balloon system.

In the future, more elaborate statistical analysis on the weather data will be carried out to improve the accuracy of the parameters to represent the practical operation environment of the balloon system. Also, as the control equipment will be used for the purpose of the station keeping of the balloon system, such as StratoSail, the size of the balloon will be re-calculated according to the additional mass of the control equipment. Consequently, new calculations on the air drag acting on the balloon will be performed using the new size of the balloon together with the effects of the external force acting on the balloon due to the control equipment. The control equipment will be adjusted accordingly based on the updated air drag force. An iteration loop will be built to search for the desired balloon size and control ability to satisfy the station keeping goal of the whole balloon system.

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