Mühendislik Bilimleri ve Tasarım Dergisi
8(1), 252 – 261, 2020
e-ISSN: 1308-6693

Journal of Engineering Sciences and Design
DOI: 10.21923/jesd.397265

Araştırma Makalesi — Research Article

STATION KEEPING OF WIND DRIVEN STRATOSPHERIC BALLOON VIA PROPULSION UNIT

Öznur KAYHAN*

Gebze Technical University, Engineering Faculty, Department of Chemical Engineering, Kocaeli, Turkey

Keywords

Stratospheric Balloon, Station Keeping, Propulsion Power, Wind Velocity, Horizontal Control.

Abstract

One of the most difficult problems in stratospheric balloon's design is to keep the balloon's geographic coordinates. Stratospheric wind speeds vary significantly both daily and throughout the year. Wind drag acting on the balloon should be manipulated to control the horizontal coordinates (longitude and latitude degree) of the stratospheric balloons. In this paper, propulsion unit is applied to a wind driven stratospheric balloon to keep balloon's coordinate over flight area. The simulation was applied to a zero-pressure high altitude balloon using actual wind profile for the first time to control the horizontal movement of the balloon. In addition, required thrust power and some parameters effects on it have been investigated. The results indicate that propulsion unit would be helpful to manipulate the horizontal motion of the balloon and to achieve keeping the balloon's geographic location.

RÜZGAR SÜRÜKLEMELİ STRATOSFERİK BALONUN İTME ÜNİTESİ İLE İSTASYON KORUMASI

Anahtar Kelimeler

Stratosferik Balon, İstasyon Koruması, İtme Gücü, Rüzgar Hızı, Yatay Kontrol.

Öz

Stratosferik balon tasarımında en zorlu problemlerden birisi de balonun coğrafik koordinatlarının korunmasıdır. Stratosferik rüzgar hızları hem günlük hem de yıl boyunca önemli ölçüde değişir. Balon üzerinde etkisi olan rüzgar sürüklemesi stratosferik balonların yatay koordinatlarını (enlem ve boylam derecesi) kontrol etmek için manipüle edilmelidir. Bu makalede, itme ünitesi rüzgar sürüklemeli stratosferik balona balonun uçuş alanı üzerinde koordinatlarının korunması için uygulanmıştır. Simülasyon, rüzgar sürüklemeli sıfır basınçlı yüksek irtifalı balona balonun yatay hareketini kontrol etmek için gerçek rüzgar profili kullanılarak ilk kez uygulanmıştır. Buna ek olarak, gerekli itici güç ve bunun üzerindeki bazı parametrelerin etkileri araştırılmıştır. Elde edilen sonuçlar, uygulanan itme ünitesinin balonun yatay hareketini engelleyerek balonun coğrafik konumunun korunmasına yardımcı olabileceğini göstermiştir.

Alıntı / Cite

Kayhan, Ö., (2020). Station Keeping of Wind Driven Stratospheric Balloon via Propulsion Unit, Journal of Engineering Sciences and Design, 8(1), 252-261.

Yazar Kimliği / Author ID (ORCID Number)	Makale Süreci / Article Process	
Ö. Kayhan, 0000-0002-1447-2952	**Başvuru Tarihi / Submission Date**	21.02.2018
	Revizyon Tarihi / Revision Date	16.09.2019
	Kabul Tarihi / Accepted Date	30.10.2019
	Yayım Tarihi / Published Date	20.03.2020

1. Introduction

Air vehicles can be divided into static lift air vehicles, and dynamic lift aircrafts. High altitude balloons and airships are examples of static lift air vehicles and airplanes and missiles are examples of dynamic lift aircrafts. Static lift air vehicles have the advantage due to their low speed and high altitude operation. Therefore, they are recommended as stratospheric platforms floating at a high altitude (18. 000 m to 36.500 m) of the atmosphere named stratosphere and atmospheric density is very low in this layer (Chen et al., 2014).

* İlgili yazar / Corresponding author: okayhan@gtu.edu.tr, +90-262-605-2116

High altitude balloons are lighter than air (LTA) controllable flight vehicles flying at stratosphere, where wind speed is less intense and wind direction is relatively stable. Balloon systems have ability to observe wide-area coverage for extended durations that satellites and aircrafts cannot have. High altitude platforms positioned in the stratosphere due to propose image quality for observation compared to space-based platforms have been attractive interest for many years. High altitude self –propelled stratospheric balloons capable of keeping station over a desired geographic location would be a low-cost alternative platform to achieve variety of space missions such as scientific experiments, observation, surveillance and tele communication purposes (Yang and Liu, 2017; Fesen and Brown, 2015; Fesen, 2006).

Stratospheric wind speeds around 20, 000 m can vary significantly both daily and throughout the year (Fesen and Brown, 2015). Wind drag acting on the balloon causes to migrate the balloon in stratospheric layer of the atmosphere horizontally and this migration should be manipulated to control the high-altitude balloon geographic horizontal coordinates and to hold the balloon's station within the selected region. Integration of propulsion unit into balloon system can be a method to keep the balloon's horizontal coordinates. Propulsion power is one of the significant problems of balloon's design to keep the balloon at desired altitude for extended durations.

Many research projects have been conducted on high altitude balloons, but most of these researches investigated the balloon material to go higher altitude, thermal analysis of the lift gas or geometric design of the balloon and flight trajectory. Some of them have proposed methods to control position of high altitude airship and super pressure balloon. Chen et al. (2014) designed control system of a multi vectored thrust for stratospheric airship. Fesen and Brown (2015) described general framework of station keeping of airship. Wynsberghe and Turak (2016) proposed an electric propulsion system for super pressure balloon. There has been no study to control the high altitude zero pressure balloon's position in real region that includes real wind profile up until now. Author's previous study (Kayhan and Hastaoğlu, 2014) implies modeling of stratospheric balloon using transport phenomena and gas compress - release system to place balloon at its orbit without using ballast, to control the vertical movement and extend the flight time. Also, author studied simulation and control of serviceable stratospheric balloon traversing a region via transport phenomena and PID (proportional-integral-derivative) control (Kayhan et al., 2016) to place the balloon at target altitude and ensure balloon's horizontal flights over desired coordinates and interfere with the balloon system whenever technical service is needed. These two studies were proposed for the first time.

The purpose of this study is to integrate propulsion unit into wind driven zero pressure balloon system to manipulate the horizontal movement of the stratospheric balloon and to hold it over the launch location. The balloon system in this study includes not only altitude control but also longitude and latitude coordinate control that have not been studied in the same study before. Results could be useful to control the balloon's flight within the desired coordinates and design of the propulsion unit and power system.

2. Theory

For the stratospheric balloons, a model was developed based on balloon dynamics, heat and mass transfer aspects in previous study (Kayhan and Hastaoğlu, 2014). Three of the major equations are reproduced below from the previous work:

Balloon velocity in vertical direction is:

$$\frac{dv_z}{dt} = -\frac{v}{\|v\|} c_d \frac{1}{2M} \rho_{air} {v_z}^2 A_p + \frac{\rho_b - \rho_{air}}{\rho_b} g \qquad (1)$$

Lift gas leak:

$$N_A = k_{ci}(C_{ib} - C_1) = D_{ABre} \frac{(C_1 - C_2)}{\Delta x} = k_{co}(C_2 - C_{out}) \qquad (2)$$

Temperature of the lift gas:

$$q_T = h_{ci}(T_1 - T_{ib}) + q_{i,\infty} = \frac{k_f}{\Delta x}(T_2 - T_1) = h_{co} (T_a - T_2) + \alpha q_{rad} + q_{e,\infty} \qquad (3)$$

where M, ρ_{air}, ρ_b, A_p, g are total weight of the balloon and auxiliary equipment (kg), density of air and balloon system (kg/m^3), projected area of the balloon (m^2), gravitational acceleration (m/s^2); N_A, k_{ci}, k_{co}, C_{ib},C_1, C_2, C_{out}, D_{ABre}, Δx

are lift gas flux through balloon (kmol/m^{2}s), convective mass transfer coefficients at the inside of the balloon and outside balloon surfaces (m/s), lift gas concentrations at inside, inside balloon and outside balloon surfaces, and outside of the balloon (kmol/m^3), real effective diffusion coefficient (m/s^2), balloon wall thickness (m); q_T, h_{ci}, h_{co}, T_1,T_2, T_{ib}, T_a, k_f, α, q_i,q_e,q_{rad} are total heat flux for the lift gas (W/m^2), convective heat transfer coefficients inside and outside surfaces of the balloon (W/m^{2}K), temperature of the lift gas at the inside and outside surfaces of the balloon , bulk temperature of the lift gas and atmospheric temperature (K), thermal conductivity of the balloon wall (W/mK), solar absorptivity of the balloon film, internal and external infrared radiation density and solar radiation flux (W/m^2), respectively.

In order to determine aerodynamic forces and heat and mass transfer coefficients one needs to know the relative wind velocity and its components with respect to the balloon's motion. When wind drag over the balloon is not manipulated wind drifts the balloon from the floating coordinate. Dynamic forces in the presence of the wind over the balloon were determined author's previous study (Kayhan et al., 2016) and were calculated by using following equations below (Farley, 2005):

$$\begin{aligned} v_{rx} &= v_{wx} - v_x \\ v_{ry} &= v_{wy} - v_y \\ v_{rz} &= v_{wz} - v_z \end{aligned} \tag{4}$$

where v_x, v_y, v_z (m/s) are the balloon's velocity components v_{wx}, v_{wy}, v_{wz} (m/s) are the wind velocity components, then the relative velocity components of the balloon, v_{rx}, v_{ry}, v_{rz} (m/s) in x,y,z direction of the balloon coordinate, respectively. The relative velocity of the balloon (v_r) is obtained from:

$$v_r = \left(v_{rx}^2 + v_{ry}^2 + v_{rz}^2\right)^{1/2} \tag{5}$$

Drag force magnitude is:

$$Drag = -\frac{1}{2}\rho_{air} {v_r}^2 C_d A_p \tag{6}$$

where C_d is the drag coefficient and A_p (m^2) is the projected area of the balloon. When the drag is written into its vector components:

$$\begin{aligned} Drag_x &= Drag\ v_{rx}/v_r \\ Drag_y &= Drag\ v_{ry}/v_r \\ Drag_z &= Drag\ v_{rz}/v_r \end{aligned} \tag{7}$$

Balloon vertical velocity (v_z) can be calculated as follow:

$$\frac{dv_z}{dt} = \frac{Drag_z}{M} + \frac{\rho_b - \rho_{air}}{\rho_b} g \tag{8}$$

If buoyancy forces are ignored in horizontal directions due to density variations, horizontal velocities can be obtained from:

$$\frac{dv_x}{dt} = \frac{\mathrm{Drag}_x}{M} \quad \frac{dv_y}{dt} = \frac{Drag_y}{M} \tag{9}$$

In x, y, z directions, velocities and displacement components of the balloon can be calculated through integration of the Equations (8,9).

Figure 1 shows thrust configuration of balloon system and balloon's coordinate system. These thrusters as seen in Figure 1 can be applied to balloon to counter the prevailing stratospheric winds.

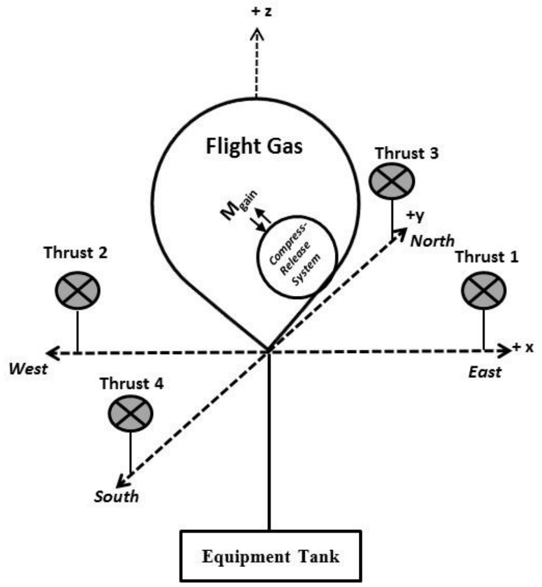

Figure 1. Thrust configuration of balloon system

Thrust power required (P_{thrust}) for the balloon system and total drag force can be calculated from

$$P_{thrust} = D_{total}(\frac{v_r}{\eta_p \eta_g}) \tag{10}$$

$$D_{total} = \sqrt{(Drag_x{}^2 + Drag_y{}^2)} \tag{11}$$

Thrust force is applied only to horizontal directions (x, y) of the balloon to manipulate the wind effect. The wind velocity at 'z' direction is zero in float region of the balloon and neglected. In the Equation (10) η_p, is the propulsive efficiency, η_g is the gear box transition efficiency determined equal to 85, 80 % (Sultana et al., 2015) respectively.

3. Numerical Method

In this study integration of propulsion unit to balloon main system is shown schematically in Figure 1 and balloon program including thrust unit codes were written in Fortran. The program flow chart is shown in Figure 2. As shown in Figure 2, balloon main program consists of subroutines which are atmospheric model, heat and mass transfer model of lifting gas, dynamic and control model of the balloon.

The balloon system consists of helium inside as flight gas and Gas-Compress-Release control system. Before the launch, on the ground, a certain amount of helium was pumped into the balloon until it started to rise from the ground. Balloon was controlled to reach the target altitude (H) and steadied at its orbit. When the balloon ascends over the target altitude, the lift gas inside the balloon (helium initially) is evacuated in a controlled manner (M_{gain}) by pumping it to the Lift-Gas-Storage. Thus, the volume of the balloon decreases preventing its rise further. At altitudes higher than the target value, pumping is continued until the balloon starts to descend below the target altitude. However, at altitudes lower than the target value, Lift-Gas is released into the balloon from the helium storage tank. The Compress-Release cycle is continued until all available storage gas is consumed due to escape through the balloon wall. Naturally, then the descent starts, and a certain amount of lift gas is to be kept accommodating a soft landing.

Control model includes vertical and horizontal movement control of the balloon. Gas-compress release system controls the altitude and vertical velocity of the balloon, propulsion unit controls the horizontal velocity and movement of the balloon. Control systems ensure to reach the balloon to desired altitude (H) and keep it at constant longitude, latitude coordinates for required time. Subroutines that form the balloon main program work systematically each other well. It is important to note that system was solved via numerical techniques using iterative scheme.

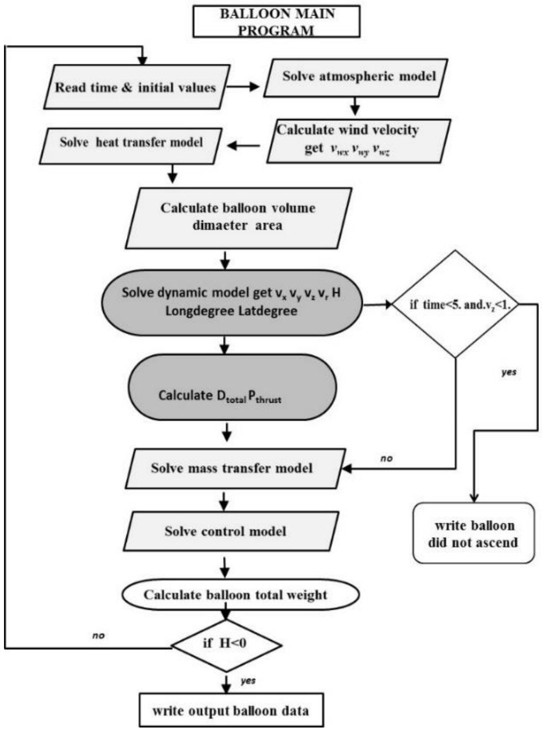

Figure 2. Balloon main program including propulsion unit

4. Wind Profile of the Flight Region

The wind characteristic plays an important role in obtaining horizontal motion of the balloon. Wind profile to a large degree, depends on the location, time of the year and altitude (Colozza, 2003). Wind velocity consists of longitude and latitude components, and the angle to the south (Liu et al., 2014).

To simulate the balloon system Erzurum, one of the cities of Turkey, was chosen as launch station. A sample of wind profile is shown in Figure 3 and 4 which covered an altitude of 0 to 16.785 km. Because of available wind profile simulation, floating was limited to this altitude.

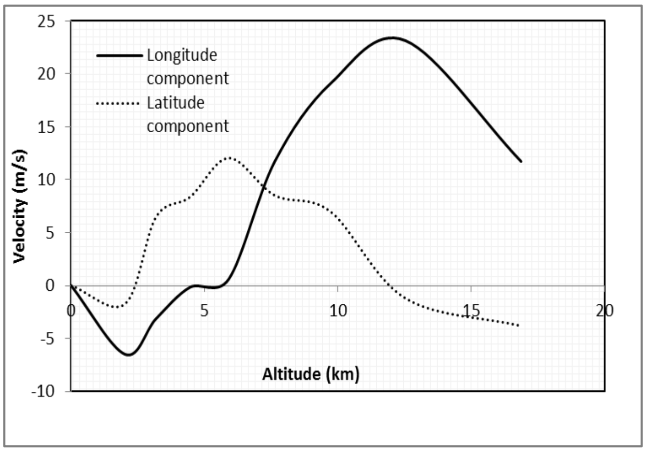

Figure 3. The measured variation of wind velocity with altitude for launch station, 15 August 2014 at 12:00 noon (Courtesy of the General Directorate of Meteorology of Turkey)

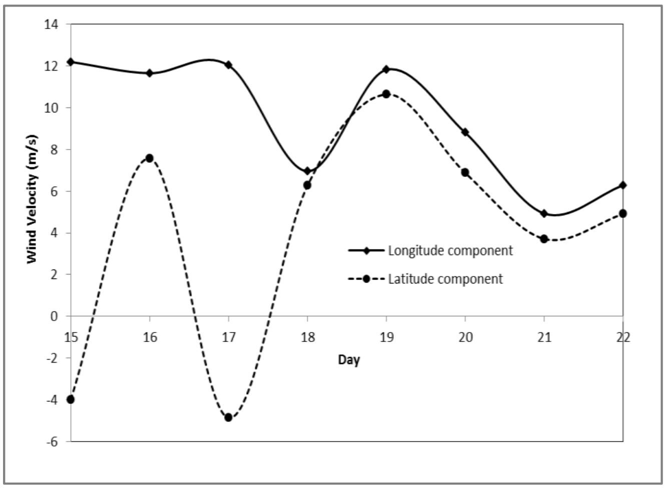

Figure 4. The measured variation of wind velocity at 16,785 m altitude for launch station in 15-22 August 2014 (Courtesy of the General Directorate of Meteorology of Turkey)

5. Numerical Results

The stratospheric balloon model based on transport phenomena (momentum, mass and heat transfer), Gas-Compress-Release system and wind driven balloon dynamic performance used in this work were validated in author's previous studies (Kayhan et al., 2016; Kayhan and Hastaoğlu, 2014).

For the station keeping performance simulation of balloon over Turkey, parameters are chosen as seen in Table 1. The balloon was assumed to launch at 08:00 am on August 15, 2014 from Erzurum (39.53°N, 41.16°E, 0 m). Because of the available wind data, balloon was controlled to reach design altitude of 16,785 m. Figure 5 shows 3-D trajectories of the balloon wind driven flight and station keeping flight. The balloon in wind driven flight moved from launch station to a land station (36.24 °N, 32.64 °E, 0 m). The balloon drifted with the wind in horizontal direction and 16,785 m altitude. Note that there is no control mechanism for horizontal movement of the wind driven balloon flight. It can be seen from the Figure 5 that when horizontal movement control is applied to the balloon via propulsion unit, the balloon does not drift away by the wind and keep longitude and latitude coordinates (39.53°N, 41.16°E) and only flies at vertical (z) direction.

Table 1. Design parameters of the balloon

Parameter	Value
Maximum volume, m^3	29,878
Floating altitude, m	16,785
Helium weight, kg	700
Store weight, kg	500
Equipment weight, kg	1000

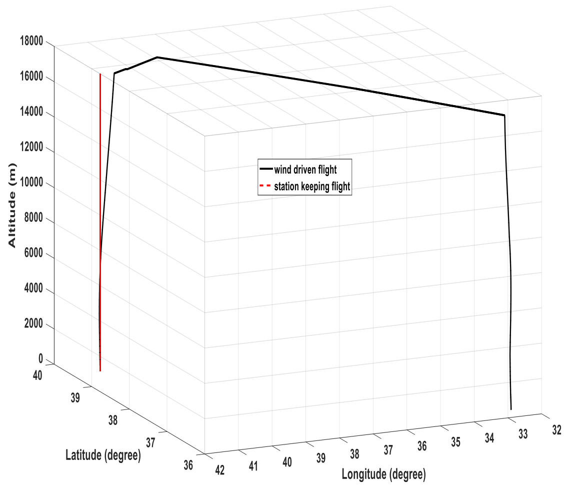

Figure 5. 3-D trajectory of the wind driven balloon's flight and station keeping flight

Figure 6 shows the variation of the flight time with the altitude for the station keeping flight as seen in Figure 5 and velocity and relative velocity components of the balloon for station keeping flight are depicted in the Figure 7.

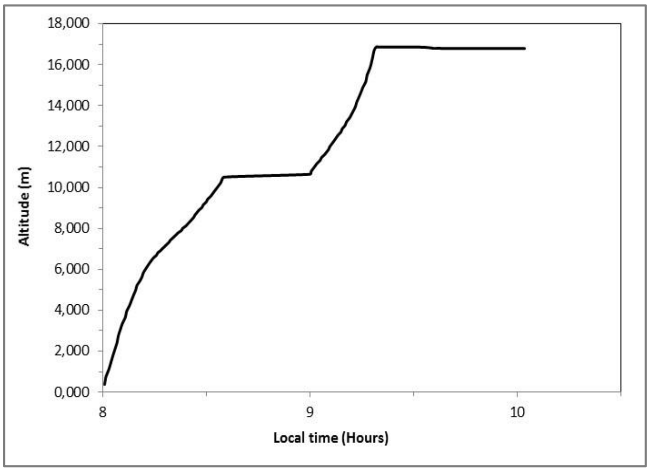

Figure 6. Variation of the flight time with the altitude for ascending stage of station keeping flight

Velocities of the horizontal directions (V_x, V_y) were obtained as zero and accomplished by propulsion unit throughout the flight to target altitude.

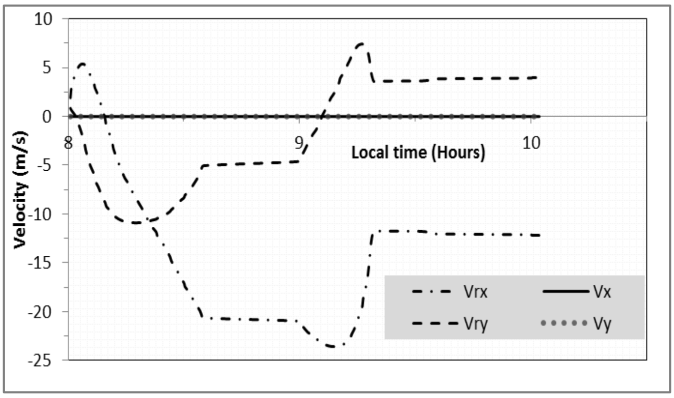

Figure 7. Variation of the flight time with horizontal velocities of the balloon for ascending stage of station keeping flight

Balloon diameter varies with altitude at ascending stage as seen in Figure 8 due to decrease in atmospheric pressure and density. The maximum diameter has been calculated as 43 m. When balloon reaches over the target altitude gas-compress altitude- velocity control mechanism works and dimeter descends to keep the altitude at 16,785 m. Besides, relative velocity of the balloon increases with altitude until altitude is 12,500 m and then decreases to target altitude as seen in Figure 9. Because, the wind velocity variation with altitude affects the balloon horizontal movement as seen in Figure 3.

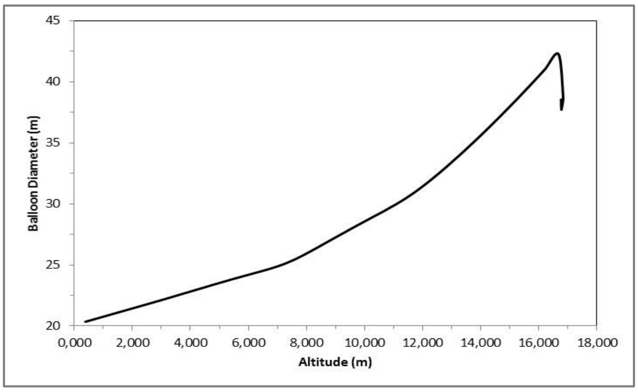

Figure 8. Variation of balloon diameter with altitude for ascending stage of the station keeping flight

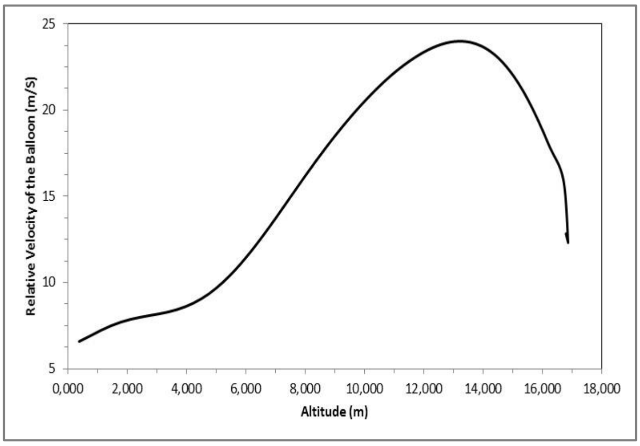

Figure 9. Balloon relative velocity-altitude variation for ascending stage of the station keeping flight

The drag is proportional to the square of relative velocity. Power is drag times velocity. Therefore, propulsion power is proportional to cube of relative velocity. As seen in Figure 10, when relative velocity is 25 m/s, required thrust power obtained over 1000 kW. This amount of power can be supplied for a balloon using photovoltaic panel (Kayhan, 2018; Wang et al., 2007) and lightweight electric motors (Kongl et al., 2012).

It was found in previous study (Kayhan and Hastaoğlu, 2014) that when mass transfer coefficient decreases, flight time increases. To observe the thrust power for the extended flight, effective mass transfer coefficient was decreased, and it was possible to keep the balloon at 16,785 m for four days as seen in the Figure 11(a) and relative velocity variation of balloon in the Figure 11 (b).

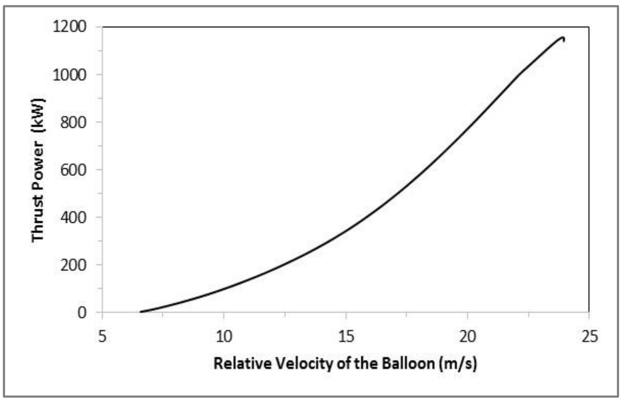

Figure 10. Balloon relative velocity-thrust power variation for ascending stage of the station keeping flight

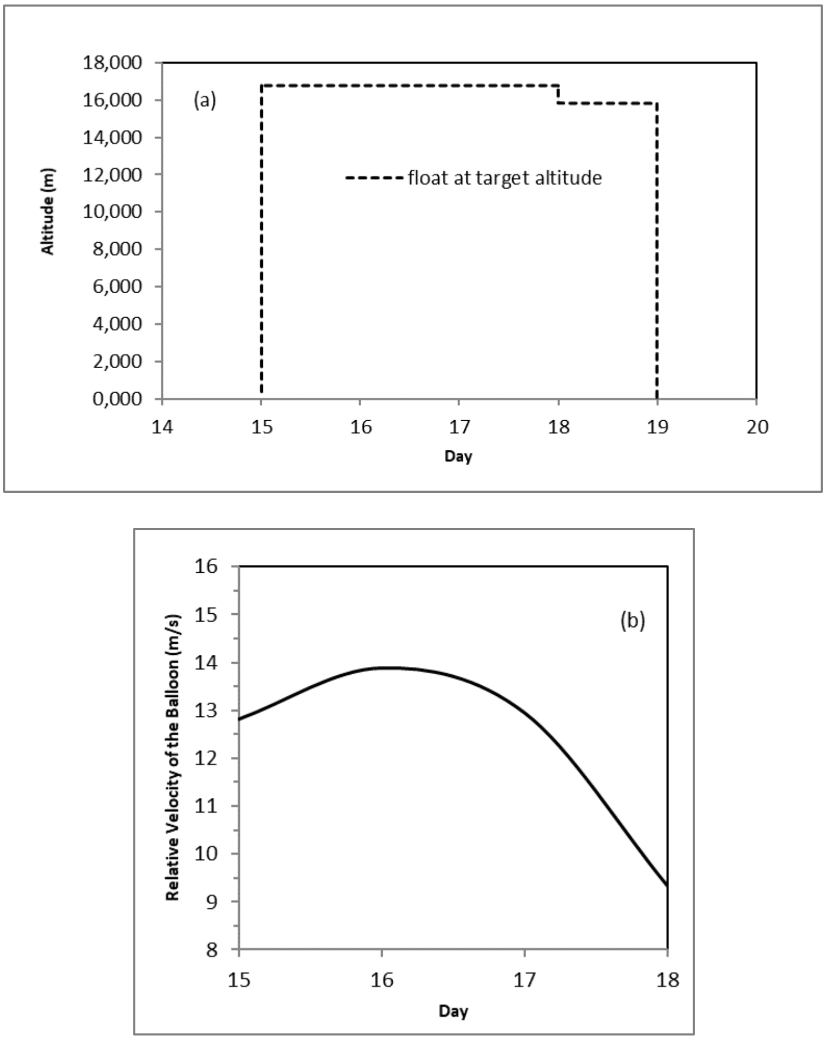

Figure 11. Station keeping balloon flight (a) flight day-altitude variation in August (b) flight day-relative velocity of the balloon variation in August

For three days flight of the balloon over station at float altitude as seen in Figure 13, it was found that required thrust power is between 40-155 kW. This power is smaller than the required power of ascending stage of the balloon when consider with Figure 10. This result shows that in order to keep the horizontal coordinates of the balloon at floating stage needs less power than at ascending stage.

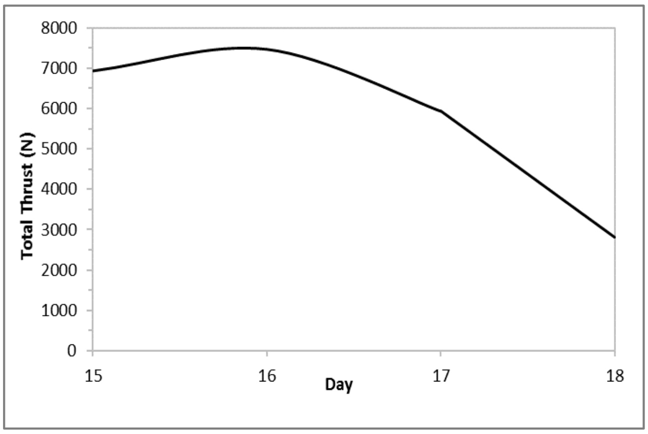

Figure 12. Total thrust variation with flight days of station keeping flight in August

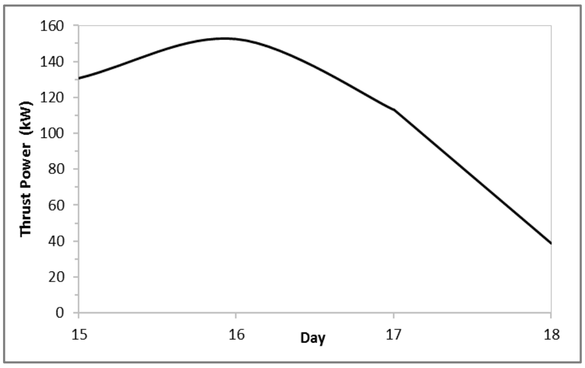

Figure 13. Thrust power variation with flight days of station keeping flight in August

6. Result and Discussion

Wind driven balloon system via propulsion unit has been simulated to manipulate the wind drag over stratospheric balloon to keep the balloon at desired geographic coordinates. For the ascending and the floating stage of the station keeping flight, required thrust and power have been numerically investigated. The simulation was run for stratospheric balloon that have 29,878 m^3 maximum volume launches from the selected launch station. The vertical velocity control unit of gas compress release helps the balloon reach the target altitude, keep it there for desired period. The horizontal velocity control of propulsion unit helps manipulate the wind drag and keep the balloon at desired horizontal longitude and latitude coordinates. Therefore, it is possible to control the horizontal movement of the wind driven balloon over a country or region by propulsion unit. In keeping the balloon at target coordinates required power for ascending and floating is obtained maximum 1156 kW, 153 kW, respectively. It is concluded that propulsion unit needs less energy for floating than ascending stage of the station keeping flight of the balloon. Future work involves developing alternative method for power management of ascending stage of the balloon.

Acknowledgments

The support of Professor M. Alaittin Hastaoğlu (Author's PhD supervisor-retired) is gratefully acknowledged. The General Directorate of Meteorology of Turkey is gratefully acknowledged for supplying the wind data.

Conflict of Interest

No conflict of interest was declared by the author.

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