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Multidisciplinary Design Optimization of Scientific Balloon Integrating Thermal and Dynamic Models

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ABSTRACT

The budget as well as temporal constraints makes it indispensable for a balloon designer to simultaneously take account of thermal and dynamic performance of scientific balloon when designing its shape. This paper presents a detailed design procedure of zero pressure scientific balloon considering its thermal and dynamic characteristics in ascending and floating conditions. Weather data during the ascent of the balloon was attained from Global Forecast System(GFS) provided by National Weather Service in National Oceanic and Atmospheric Administration, and was processed with kwgrib2 program, which was provided by Korea Meteorological Administration. A separate numerical program using Matlab/Simulink was developed to predict dynamic motion and thermal properties of the scientific balloon and to design its shape. The prediction code was verified with the earlier balloon analysis code: ACHAB. The modules to predict dynamic and thermal properties of the scientific balloon were seamlessly integrated on the Isight program. Suspended load on the balloon, free helium ratio, density of polyethylene, thickness of the film and time to start descending were chosen to be optimization parameters, and the distance between the landing point and launching point, free helium ratio and the volume of the balloon were chosen to be the objective functions to be minimized in order to minimize the cost to make the balloon and retrieve the landed balloon. Adaptive Simulated Annealing (ASA) was used for optimization technique and a kriging model was built to reduce time taken for the optimization.

NOMENCLATURE

r = radius of balloon
z = altitude of balloon apex
z_b = altitude of balloon base
w_e= actual mass per unit area of balloon film
s = length of balloon film from base
l_s = maximum length of balloon film
R = maximum radius of balloon
m_{gas} = mass of lifting gas, kg
T_{gas} = temperature of lifting gas, K

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P_{gas} = pressure of lifting gas, Pa
R_{gas} = specific gas constant of the lifting gas (2078.5 J/kgK for helium)
c_v = specific heat at constant volume of the lifting gas (3121.5 J/kgK for helium)
c_f = specific heat of the film material (2092 J/kgK for polyethylene)
ρ_g = gas density, kg/m^3
ρ_a = ambient air density, kg/m^3
T_{air} = ambient air temperature, K
P_{air} = ambient air pressure, Pa
P_0 = surface air pressure, Pa
g = acceleration of gravity, 9.8 m/s^2
V_{design} = design maximum volume of the gas envelope, m^3
T_{film} = balloon skin temperature, K
σ = Stephan-Boltzmann constant, 5.67E-8 W/m^{2}K^4
α = bulk averaged balloon skin absorptivity for visible sunlight
α_{IR} = bulk averaged balloon skin absorptivity for IR
ε = bulk averaged balloon skin IR emissivity
τ = bulk averaged balloon skin transmissivity for visible sunlight
τ_{IR} = bulk averaged balloon skin transmissivity for IR
r = bulk averaged balloon skin reflectivity
q_{sun} = direct solar flux, W/m^2
q_{Albedo} = diffuse planetary albedo flux, W/m^2
$q_{IRplanet}$ = diffuse up-welling planetary infrared flux, W/m^2
k_{gas} = conductivity of helium gas
k_{air} = conductivity of air
$HC_{internal}$ = convection heat transfer coefficient inside a balloon
$HC_{external}$ = convection heat transfer coefficient for the external skin
TA = true anomaly
I_{sun} = solar irradiance flux at the top of the atmosphere

1. INTRODUCTION

Scientific balloon is the cost-efficient platform to carry out space-environmental experiments, compared to rockets and ground-test facilities. Generally, it consists of three parts: balloon, parachute and payload. Usual balloons consist of exhaust valve, tear panel, separating mechanism, load tapes and radar reflective tape. The payload system has gadgets for telecommunication with ground center and pressure sensor, temperature sensor and GPS receiver to track the position of balloon and to check its status. All these components are to be considered carefully to launch and manage the scientific balloon successfully.

Among the components to take account of when to make a scientific balloon, designing the balloon shape is important since it decides the overall cost to develop a system of scientific balloon. The bigger its volume and gross area are, the more the costs to get prepared of helium gas and film of the balloon are, respectively. Once suspended load, target altitude, thickness of film and density of polyethylene are decided, the shape of balloon in full inflation is decided by solving a system of ODEs.

Baginski applied parallel shooting method to determine the shape of the balloon during ascent state (Baginski 1998). He found that the ordinary shooting method could be used in determining the shape of the balloon at float altitude but it was ineffective for computing ascending shapes.

Before flying the balloon, flight simulation should be made to check whether the balloon can accomplish its mission. There have been several works trying to predict the performance of scientific balloon. Dai, Liu and Morani integrated thermal and dynamic model to predict the trajectory of balloon and succeeded to validate their works by comparing their results with experimental data (Liu 2014). They also successfully optimized the trajectory of stratospheric balloon, made a reliable selection of the best day to fly balloon and defined balloon parameters that influenced the trajectory. Palumbo and Farley developed a 3-D Simulation Code that integrated the balloon designing code and trajectory prediction code, named ACHAB and BalloonAscent respectively (Palumbo 2007, Farley 2005).

In this paper, a zero-pressure balloon is assumed to fly at Korean Aero Center located in Goheung-gun, Jeollanam-do, Korea. Design optimization of the balloon is executed varying 5 parameters: suspended load on the balloon, free helium ratio, thickness of film of balloon, density of polyethylene and time to start descend. The purpose of optimization is to minimize the cost to make and manage balloon by reducing the volume of balloon, free helium ratio and the distance between the starting point and the landing point of base design.

2. BALLOON SHAPING AND PREDICTING ITS TRAJECTORY

2.1. Designing the shape of balloon at float state

When designing the shape of zero-pressure balloon, buoyant force at target altitude should be equal to the weight of the total system of balloon. For natural shape balloons without load tapes, the shape of balloon is decided by solving a system of ODEs derived from balancing equations of tension, weight and buoyant force for the z direction and the r direction. Defining the dimensionless length λ as (Yajima 2004)

$$\lambda = \left(\frac{\mathrm{F}_1 + F_2}{b_g}\right)^{\frac{1}{3}}, \tag{1}$$

the following dimensionless parameters can also be defined.

$$\tilde{r} = \frac{r}{\lambda}, \tilde{z} = \frac{z}{\lambda}, \tilde{z}_b = \frac{z_b}{\lambda}, \tilde{s} = \frac{s}{\lambda}, \tilde{l}_s = \frac{l_s}{\lambda}, \tilde{R} = \frac{R}{\lambda}, \tag{2}$$

$$\tilde{T}_\theta = \frac{T_\theta}{b_g \lambda^2}, \tag{3}$$

$$\tilde{S} = \frac{S}{\lambda^2}, \qquad \tilde{V} = \frac{\mathrm{V}}{\lambda^3}. \tag{4}$$

ODEs derived from the relationship among tension, weight and buoyant can be written as follows:

$$\tilde{r}\tilde{T}_\theta \frac{d\theta}{d\tilde{s}} = -k\Sigma_e \tilde{r} \frac{d\tilde{r}}{d\tilde{s}} - (\tilde{z} - \tilde{z}_b)\tilde{r}, \tag{5}$$

$$\frac{\mathrm{d}\left(\tilde{r}\tilde{T}_\theta\right)}{d\tilde{s}} = k\Sigma_e \tilde{r} \frac{d\tilde{z}}{d\tilde{s}}, \tag{6}$$

where

$$\mathrm{k} = (2\pi)^{-\frac{1}{3}}. \tag{7}$$

In addition, following equations should also be solved at the same time to get the shape of the balloon:

$$\frac{\mathrm{d}\tilde{r}}{d\tilde{s}} = \sin\theta, \quad \frac{d\tilde{z}}{d\tilde{s}} = \cos\theta, \tag{8}$$

$$\frac{\mathrm{d}\tilde{S}}{d\tilde{s}} = 2\pi\tilde{r}, \quad \frac{d\tilde{V}}{d\tilde{s}} = \pi\tilde{r}^2 \frac{d\tilde{z}}{d\tilde{s}}. \tag{9}$$

where Σ_e is the dimensionless film weight defined by

$$\Sigma_\mathrm{e} = \frac{w_e g}{k b_g \lambda}, \tag{10}$$

where $\mathrm{b_g}$ represents the effective buoyant force per unit volume, which is

$$\mathrm{b_g} = \left(\rho_a - \rho_g\right)g. \tag{11}$$

T_θ stands for tension per unit length acting on a section of film of balloon over surfaces of constant φ, which stands for the angle in a plane perpendicular to the rotational axis z. F_1 and F_2 represents the force in the z-direction acting at the base(P_1) and apex(P_2) of the balloon respectively, as shown in Fig. 1. The balloon we design here is assumed not to have the force acting at the apex and only suspended load on the balloon makes downward force from the bottom of the balloon. Balloon shape can be achieved with the following initial conditions:

$$\tilde{\mathrm{r}}=\tilde{\mathrm{z}}=\tilde{\mathrm{S}}=\tilde{\mathrm{V}}=0, \tilde{\mathrm{r}}\tilde{\mathrm{T}}_\theta=\frac{1}{2\pi\cos\theta_0} \tag{12}$$

where the length of film l_s and initial angle θ_0 are decided by shooting method.

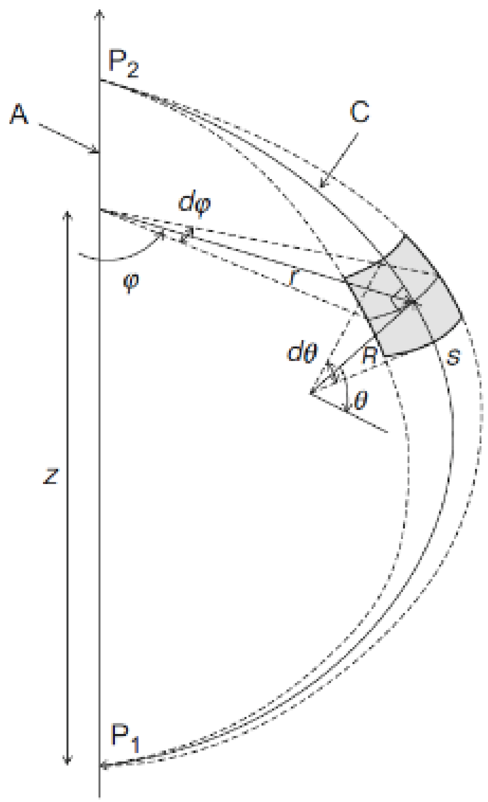


Fig. 1 Surface elements on balloon shape formed by rotating curve C around axis A (Yajima 2004)

2.2. Weather information during the ascent

To predict the motion of the scientific balloon in horizontal direction, weather data, such as the direction and magnitude of wind velocity and temperature and density of air, along the altitude of the balloon should be known, since the balloon depends on the drag force to move horizontally. In this study, temperature and density of air are given by 1976 U.S. Standard Atmosphere. Though it might be different from the environment of Korea, earlier codes (Palumbo 2007, Farley 2005) used the model to predict the trajectory of scientific balloon and got meaningful results. To compare our code to them for verification, we determined to use U.S. Atmosphere model.

In case of wind velocity, there is no standard data up to the altitude of 30km in Korea. Some earlier codes used monthly average velocity data to predict the trajectory but we could not get the average velocity data of Korea in the stratosphere. We found Global Forecast System(GFS), a weather forecast model produced by National Centers for Environmental Prediction(NCEP), provides climate data and forecast data.

Climate data of a.m. 6:00 30th of June, 2015 was used in this study over the area of 125.5 to 132 degrees in longitude and 33 to 37.5 degrees in latitude as shown in Fig. 2. Since climate data up to altitude of 30km and around the selected area is enormous, the data is given in compressed form, grib2 file. To extract the file, Kwgrib2 program was used. It is provided by Korea Meteorological Administration and requires Linux environment. Using Kwrgrib2 program, we could get horizontal direction velocity and geopotential height data over the level of 10 to 1000mb in the form of .csv file.

Fig. 2 Target area to attain climate data (Lon. 125.5~132, Lat. 33~37.5)

2.3. Thermal model of the scientific balloon

To predict the trajectory of balloon, the temperature of lift gas in the balloon should be predicted accurately since it greatly affects the motion of balloon. Motion in horizontal direction is mainly related to wind velocity but the volume of balloon is determined by the temperature of lift gas, which causes the drag force to differ. Thermal property of lift gas has crucial effect on the motion in vertical direction since the change in volume directly affects the buoyant force, which is the main force for the balloon to lift.

In this study, we assume that the lift gas interacts only with the film of balloon. Thus, we get following equation for the change in temperature of lift gas:

$$\frac{\mathrm{dT_{gas}}}{dt} = \frac{Q_{convInt}}{c_v \cdot m_{gas}} + (\gamma - 1) \cdot \frac{T_{gas}}{\rho_{gas}} \cdot \frac{d\rho_{gas}}{dt} \quad (13)$$

Here, subscript *convInt* refers to internal convection which occurs inside the balloon film.

When we assume there exists no interaction between the lift gas and the film, eq. (13) depicts the adiabatic temperature change of the lift gas.

When it comes to the temperature of the film of a scientific balloon, more heat flux terms including the convection term are added.

$$\frac{\mathrm{dT_{film}}}{\mathrm{dt}} = \frac{Q_{sun} + Q_{albedo} + Q_{IRplanet} + Q_{IRfilm} + Q_{convExt} - Q_{ConvInt} - Q_{IRout}}{c_f \cdot m_{balloon}} \tag{14}$$

where Q_{sun} refers to absorbed direct solar heat flux, Q_{albedo} refers to absorbed albedo heat flux, $Q_{IRplanet}$ refers to absorbed planetary IR heat flux, $Q_{convExt}$ refers to convection heat flux between the film and atmosphere, $Q_{convInt}$ refers to convection heat flux between the film and the lift gas and Q_{IRout} refers to emitted IR energy from the balloon skin. The followings are equations to be used for calculation of eq. (13) and (14).

$$\mathrm{Q_{sun}} = \alpha \cdot A \cdot q_{sun} \cdot \left[1 + \tau \cdot \left(1 + r_{effective}\right)\right] \tag{15}$$

$$\mathrm{Q_{Albedo}} = \alpha \cdot A \cdot q_{albedo} \cdot ViewFactor \cdot [1 + \tau \cdot \left(1 + r_{effective}\right)] \tag{16}$$

$$\mathrm{Q_{IRplanet}} = \alpha_{IR} \cdot A \cdot q_{IRplanet} \cdot ViewFactor \cdot \left[1 + \tau_{IR} \cdot \left(1 + r_{effective}\right)\right] \tag{17}$$

$$\mathrm{Q_{IRfilm}} = \sigma \cdot \varepsilon \cdot \alpha_{IR} \cdot A \cdot T_{film}^4 \cdot \left(1 + r_{effective}\right) \tag{18}$$

$$\mathrm{Q_{IRout}} = \sigma \cdot \varepsilon \cdot 2 \cdot A \cdot T_{film}^4 \tag{19}$$

$$\mathrm{Q_{convExt}} = HC_{external} \cdot A \cdot \left(T_{air} - T_{film}\right) \tag{20}$$

$$\mathrm{Q_{convInt}} = HC_{internal} \cdot A \cdot \left(T_{film} - T_{gas}\right) \tag{21}$$

$$\mathrm{HalfCone_{angle}} = \mathrm{asin}\left[\frac{R_{planet}}{R_{planet} + Z}\right] \tag{22}$$

$$\mathrm{ViewFactor} = \frac{\left(1 - \cos\left(HalfCone_{angle}\right)\right)}{2} \tag{23}$$

$$\mathrm{HC_{external}} = \frac{k_{air}}{Diameter} \cdot (2 + 0.41 \cdot Re^{0.55}) \tag{24}$$

$$\mathrm{HC_{internal}} = 0.13 \cdot k_{gas} \cdot \left(\frac{\rho_{gas}^2 \cdot g \cdot \left|T_{film} - T_{gas}\right| \cdot \mathrm{Pr}_{gas}}{T_{gas} \cdot \mu_{air}^2}\right)^{\frac{1}{3}} \tag{25}$$

$$\mathrm{Pr_{gas}} = 0.729 - 1.6 \cdot 10^{-4} \cdot T_{gas} \tag{26}$$

$$\mu_{\mathrm{air}} = \frac{1.458 \cdot 10^{-6} \cdot T_{air}^{1.5}}{T_{air} + 110.4} \tag{27}$$

$$\mathrm{k_{gas}} = 0.144 \cdot \left(\frac{T_{gas}}{273.15}\right)^{0.7} \tag{28}$$

$$\mathrm{q_{sun}} = I_{sun} \tag{29}$$

$$\mathrm{q_{albedo}} = Albedo \cdot I_{sun} \tag{30}$$

$$\mathrm{q_{IRplanet}} = \varepsilon_{ground} \cdot \sigma \cdot T_{ground}^{4} \tag{31}$$

$$\mathrm{I_{sun}} = 1358 \cdot \left[\frac{1 + 0.016708 \cdot \cos(TA)}{1 - 0.016708^2}\right] \tag{32}$$

Eq. (15)~(32) assumes that the film material is polyethylene, the planet is the Earth, the lifting gas is helium and the shape of the envelope is sphere. ViewFactor refers to the balloon surface area diffuse-radiant view factor of the planet, which is the ratio of balloon surface area that sees the planet surface divided by the total exposed balloon surface area (Farley 2005). R_{planet} is the radius of the planet in meters which is equal to 6,371,000 for Earth. Considering that the film of balloon is influenced by its inner heat environment with multiple reflections, we use the effective reflectivity $r_{effective}=r+r^2+r^3+r^4+r^5+\ldots$, instead of reflectivity $r=1-\alpha-\tau$.

2.4. Dynamic model of the scientific balloon

Dynamic model of the scientific balloon is quite simple. We take account only of drag force on the balloon when predicting its horizontal move. If U_x, U_y, U_z and u_{wind}, v_{wind}, w_{wind} are the absolute velocity components of the balloon and the wind, we can calculate the relative velocity components and the magnitude of relative velocity as following:

$$\mathrm{V_{relx}} = u_{wind} - U_x \tag{33}$$

$$\mathrm{V_{rely}} = v_{wind} - U_y \tag{34}$$

$$\mathrm{V_{relz}} = w_{wind} - U_z \tag{35}$$

$$\mathrm{V_{rel}} = \left(V_{relx}^2 + V_{rely}^2 + V_{relz}^2\right)^{\frac{1}{2}} \tag{36}$$

The magnitude of the drag force and its components can be calculated as following:

$$\mathrm{Drag} = \frac{1}{2} \cdot \rho_{air} \cdot V_{rel}^2 \cdot C_d \cdot A \tag{37}$$

$$\mathrm{Drag_x} = Drag \cdot \frac{V_{relx}}{Vrel} \tag{38}$$

$$\mathrm{Drag_y} = Drag \cdot \frac{V_{rely}}{Vrel} \tag{39}$$

$$\mathrm{Drag_z} = \mathrm{Drag} \cdot \frac{\mathrm{V_{relz}}}{\mathrm{Vrel}} \tag{40}$$

We use drag coefficient C_D for a sphere, for calculating C_D of the natural shape balloon takes too much time since it changes every time.

Using eq. (11), the buoyant force of balloon can be calculated as

$$\mathrm{F_{buoyant}} = b \cdot Volume \tag{41}$$

and the equations of motion can be attained now.

$$\frac{\mathrm{dU_z}}{dt} = \frac{F_{buoyant} + Drag_z - m_{gross} \cdot g}{m_{virtual}} \tag{42}$$

$$\frac{\mathrm{dU_x}}{dt} = \frac{Drag_x}{m_{virtual}} \tag{43}$$

$$\frac{\mathrm{dU_y}}{\mathrm{dt}} = \frac{Drag_y}{m_{virtual}} \tag{44}$$

m_{gross} is the overall mass of the balloon which consists of suspended payload mass and the mass of balloon envelope. $m_{virtual}$ is calculated with an assumed virtual mass coefficient $C_{virtual}$=0.37 to consider the mass of air that is dragged along with the balloon mass as shown in eq. (45).

$$m_{\mathrm{virtual}} = m_{gross} + m_{gas} + C_{virtual} \cdot (\rho_{air} \cdot Volume) \tag{45}$$

2.5. Code verification

The easiest way to validate the code would be to compare the simulation results to real flight data but it is not simple to use the actual flight data. To use the actual flight data to validate the prediction code, 1) the input parameters to predict the flight trajectory of scientific balloon should be well specified and 2) atmospheric data measured during the flight should be well logged. Most flight data, however, doesn't usually meet the two conditions.

To verify the thermal and dynamic model of our program, we compared our results of trajectory prediction and Palumbo's work (Palumbo 2007). The exact input data used for the comparison could be found from Palumbo's work (Palumbo 2008), as presented in table. 1 and table. 2.

Table. 1 Envelop thermo-optical data

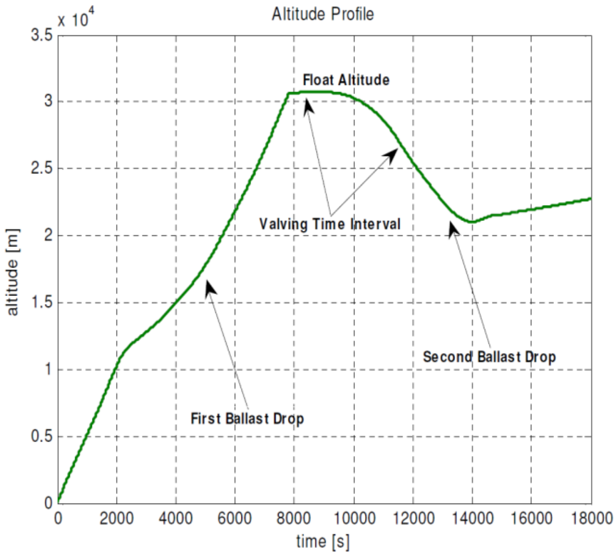
Envelop Thermo-Optical Data		
α=0.024	α_{IR}=0.1	c_e=2092 [J/kgK]
τ=0.916	τ_{IR}=0.86	

Table. 2 Balloon input data

Mass Budget [kg]		Balloon & Flight Settings	
m_{gross}	4487	Volume	334705 [m^3]
$m_{envelope}$	1433	Altitude	~31000 [m]
m_{gas}	798.63	Free Lift Percentage	11 [%]
m_{tot}	5920	$C_{virtual}$	0.37
Ballasting Data		**Initial Settings**	
t_1=5000s	150 [kg]	x_0, y_0, z_0	0
t_2=13000s	350 [kg]	Vx_0, Vy_0, Vz_0	0
Ballast Rate	13.1 [kg/min]	Date of Launch	16-01-2006

Fig. 3~5 show the prediction results of ACHAB, the code of Palumbo, on the left side and the results of our code on the right side. In the first 2000 seconds, our code predicted the ascending rate faster than ACHAB. It was found that the faster ascending rate came from the underestimated drag force. Except the first 2000 seconds, however, rate of climb profiles of both codes had similar magnitude and overall altitude profiles of both codes were in the similar shapes which meant that the earlier incorrect drag force estimation had little influence on the overall altitude profile.

At the float altitude, the oscillation of ascent rate of our code had larger magnitude. In our code, the venting rate of helium gas isn't determined; the excess gas is vented according to the time step of the ode solver. When the specific design of venting duct is made, the oscillation magnitude of vertical velocity at the float altitude would be fixed.



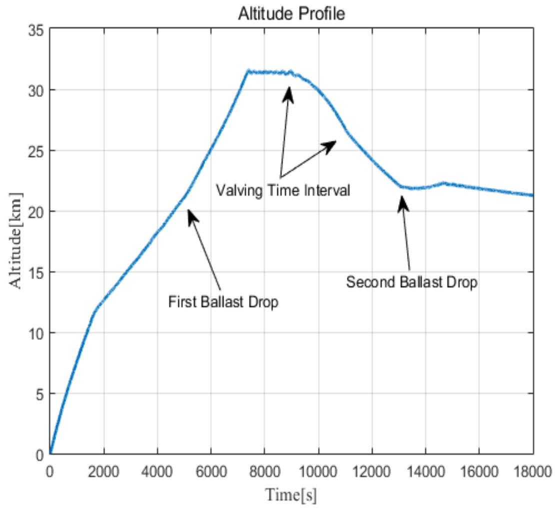
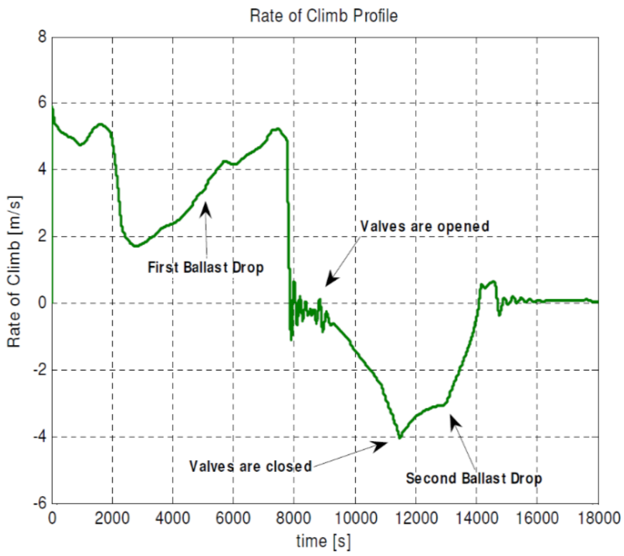


Fig. 3 Altitude vs time data of ACRHAB (left) and our code (right)



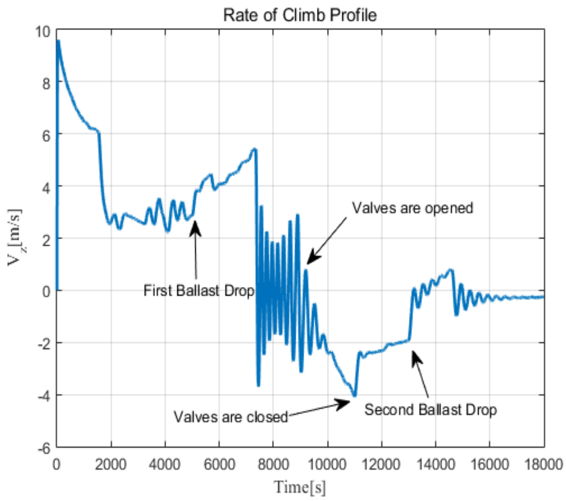


Fig. 4 Ascent rate vs time data of ACHAB (left) and our code (right)

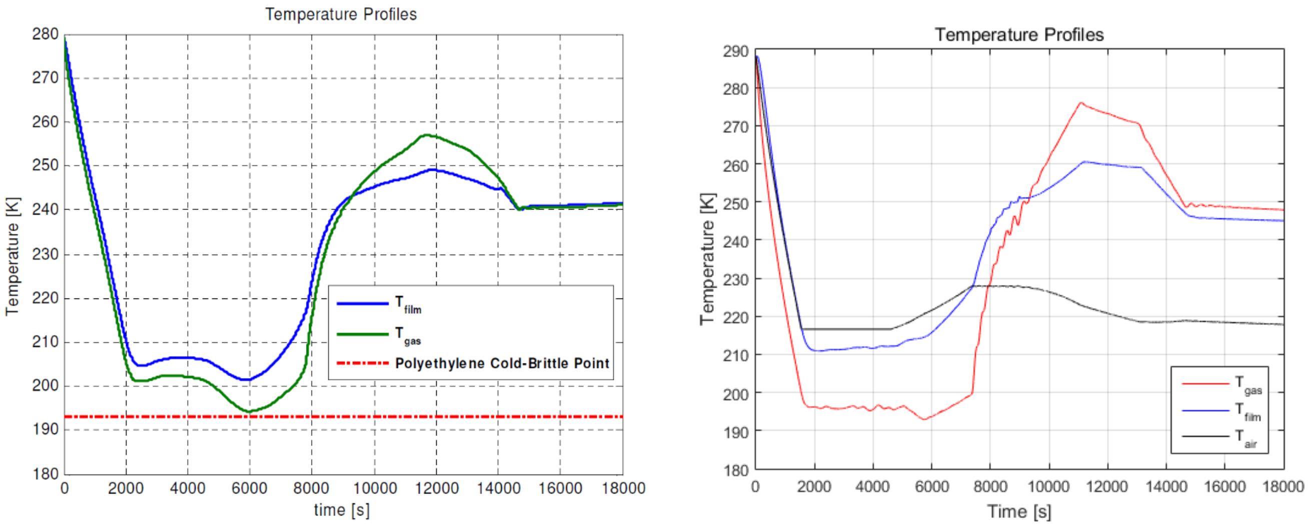


Fig. 5 Temperature vs time data of ACHAB (left) and our code (right)

In Fig. 5, our code predicted the temperature profiles of gas and film to be higher than those of ACHAB. Since the temperature of gas and the ascend velocity are in a close relation, the overestimated gas temperature is thought to be another reason of difference in the profile of rate of climb after the valves are opened. Since there wasn't specific design of venting valves, we had to find out the amount of exhaust gas to get the ascent velocity to be -4m/s. After second ballast drop, the velocity was below zero, which meant that the exhaust gas was vented more than that of ACHAB. Though the predicted temperature of gas and ascending velocity were a bit different from those of ACHAB, overall altitude profile was not far different and we decided to use this code for multidisciplinary optimization of the scientific balloon.

3. MULTIDISCIPLINARY OPTIMIZATION OF SCIENTIFIC BALLOON

Multidisciplinary optimization of scientific balloon was proceeded with Isight program. The process of optimization is depicted in fig. 6. Optimizer contained in Isight provides input parameters to multidisciplinary analysis module. The input parameters consist of total weight of payload (suspended mass), termination time, thickness of the film, density of film and free helium ratio. Total weight of payload, thickness of film and density of PE are used to determine the balloon shape at the float altitude. Then atmospheric data at a.m. 6:00 on 30th of June, 2015 is loaded. Using the loaded weather data and our thermal model, the trajectory of scientific balloon is predicted with the input value of termination time and the ratio of surplus helium. Trajectory prediction module outputs the landing point and its distance from launching point. Finally, the optimizer finds the value of input parameters where distance between landing point and launching point, the maximum volume of scientific balloon and the surplus helium ratio are minimized.

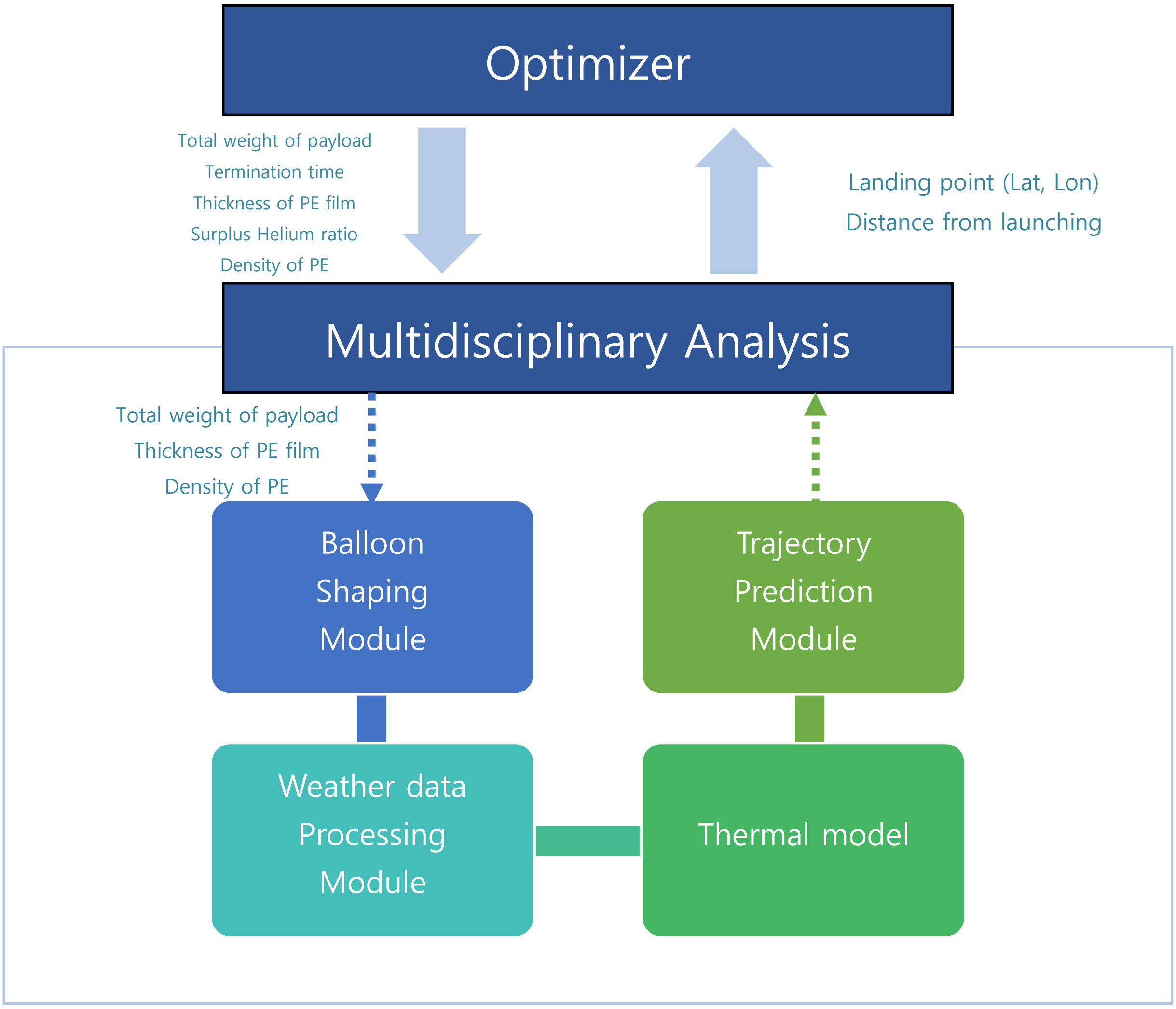


Fig. 6 Process of multidisciplinary optimization of scientific balloon

Value of each input parameters of base design is described in table. 3. We assumed payload to be 50kg and the sum of mass of other objects including suspending rope and telecommunication devices to be 10kg. The launching point was set to be 34.623593, 127.185930 degrees in latitude and longitude, which is Korean Aero Center located in Goheung-gun, Jeollanam-do, Korea. Design altitude was 30km. Each input parameter was varied so that lower case and upper case had the value of 90 and 110 percent of the value of the base design. Design of experiments was conducted using latin hypercube method and 100 points were selected. Using these selected points, a kriging model was built to shorten the time for optimization. Then the optimization was conducted using adaptive simulated annealing technique and about 10,000 data points were calculated to find the optimized point. Values of input parameters are shown in table. 4.

Table. 3 Value of input parameters of base design

Value of input parameters of base design		
Suspended load : 60kg	Density of PE : 940kg/m^3	Thickness of film : 20μm
Termnination time : 5 hours after launching	Ratio of surplus helium gas : 13%	

Table. 4 Value of input parameters of optimized point

Value of input parameters of base design		
Suspended load : 58.85kg	Density of PE : 931.46kg/m^3	Thickness of film : 19.37μm
Termnination time : 4.57 hours after launching	Ratio of surplus helium gas : 2.84%	

We set the scale factor of three objective functions (maximum volume, free helium gas ratio, distance between launching and landing point) to be equal. The shape of the natural balloon and prediction of its trajectory in the case of base design and optimized design are shown in fig. 7 ~ 10. The volume of scientific balloon was calculated to be 5682.5 m^3 and 4783.7 m^3 for base design and optimized design. The distance between launching and landing point of scientific balloon was predicted to be 200.5145 km and 120.7109 km for base and optimized design.

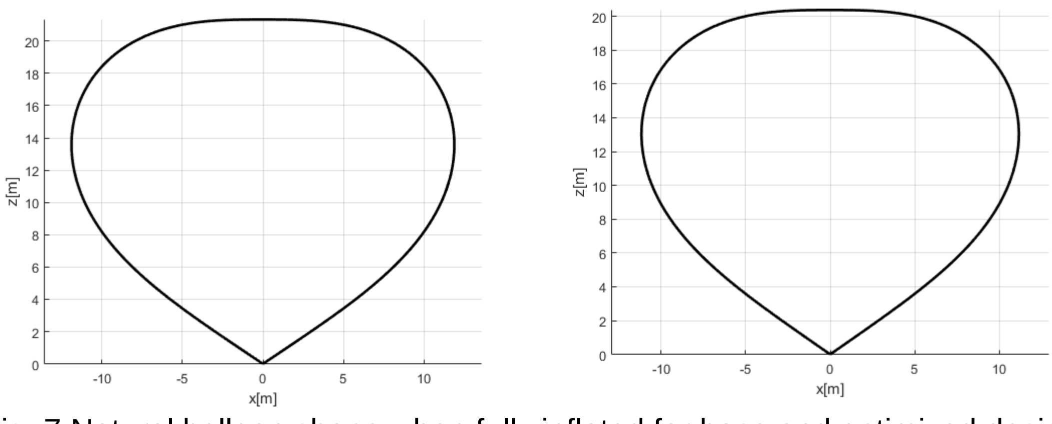


Fig. 7 Natural balloon shape when fully inflated for base and optimized design

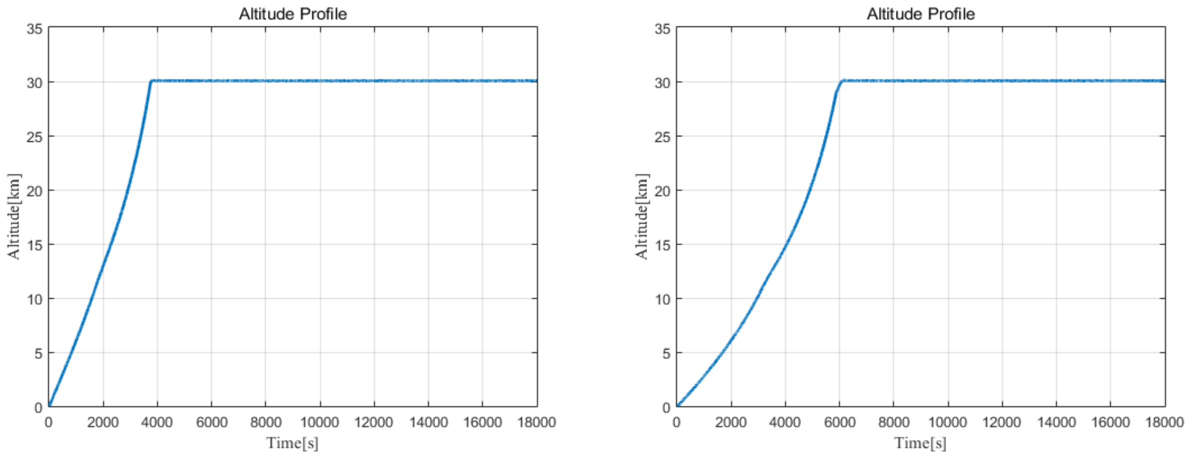


Fig. 8 Altitude profile for base and optimized design

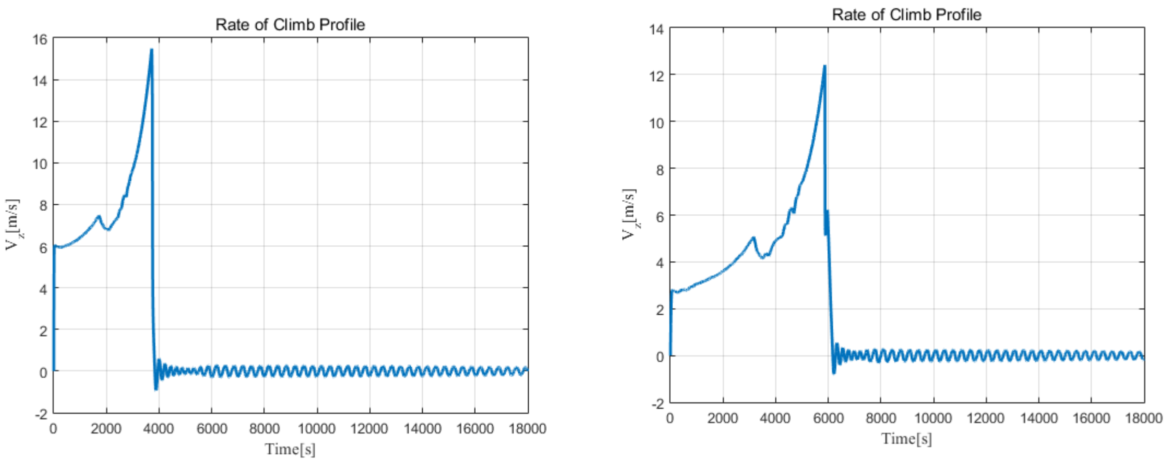


Fig. 9 Rate of climb profile for base and optimized design

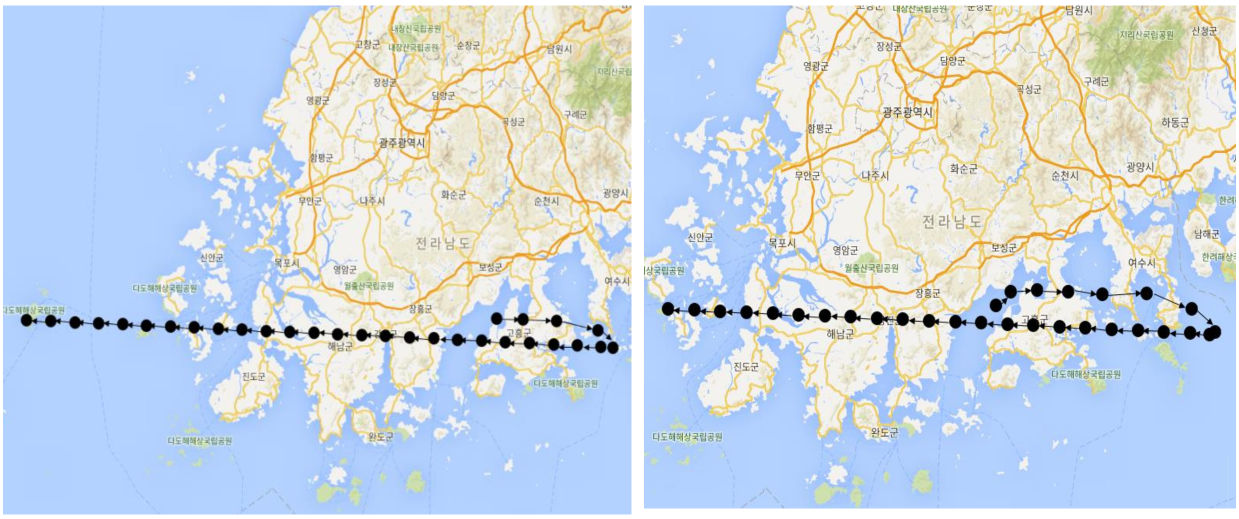


Fig. 10 Trajectory profile for base and optimized design (Time interval : 10 min)

4. CONCLUSION

Multidisciplinary design optimization of scientific balloon was conducted integrating the dynamic and thermal model of the balloon. The objective functions were the maximum volume of balloon, free helium ratio and the distance between launching and landing point. They were all successfully minimized with equal scale factors. The input parameters of optimized design were determined but when to develop a system of scientific balloon, the optimized values would not be satisfied exactly. Nevertheless, the optimization results would help a balloon designer to estimate for making a balloon so it’s worthy to try optimization.

Acknowledgements

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