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Thermal Performance of Stratospheric Airships During Ascent and Descent

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On the basis of some assumptions and simplifications, a thermal model is developed to describe the heat transfer behavior of stratospheric airships. The Runge–Kutta method is adopted to solve the governing equations. Considering the airship flight state, control style, and working environment, some of its basic characteristics and thermal performances are investigated. The variations in the temperatures of the film, internal helium, and internal air of the airship with altitude during its ascent and descent are obtained. The results reveal that among the influencing factors, the airship velocity, air filling, and air venting seriously affect its thermal performance. When the airship ascends in the adiabatic situation or the venting velocity reaches a specific value above 11 km, the temperature of the film could drop to its damage point, which would seriously influence the airship operation.

Nomenclature

A	=	effective area of absorbing radiation, m^2
B	=	net lift, N
C_{DV}	=	drag coefficient
C_p	=	specific heat, $J/(kg \cdot K)$
C_{pa}	=	specific heat for internal air, $J/(kg \cdot K)$
C_{pf}	=	specific heat for film, $J/(kg \cdot K)$
C_{ph}	=	specific heat for helium, $J/(kg \cdot K)$
D	=	day of a year (1 January is 1, 31 December is 365)
d_m	=	correction of sun–Earth distance
Gr	=	Grashof number
g	=	acceleration of gravity, $kg/(s \cdot m^2)$
h	=	heat transfer coefficient
I	=	solar radiation flux, J/m^2
m	=	mass, kg
m_{add}	=	added mass, kg
m_s	=	net mass of the airship structure, kg
Nu	=	Nusselt number
n	=	relative atmosphere mass
P	=	pressure, Pa
Pr	=	Prandtl number
p_t	=	atmospheric transmittance
R	=	gas constant, $J/(kg \cdot K)$
r_e	=	reflectivity
Q	=	heat, J
S	=	area, m^2
S_{ref}	=	characteristic area, m^2
T	=	temperature, K
T_{bb}	=	blackball temperature, K
t	=	time, s or h
U	=	velocity, m/s
V	=	volume, m^3
X	=	day angle of the sun, rad
z	=	altitude, m
α	=	effective absorptivity
γ	=	ratio of specific heats, C_p/C_v
Δ	=	difference used as prefix
δ	=	declination of the sun, rad
δ	=	thickness, m
ε	=	effective emissivity
θ	=	solar zenith angle, rad
λ	=	thermal conductivity, $W/(m \cdot K)$
ρ	=	density, kg/m^3
σ	=	Stefan–Boltzmann constant
φ	=	latitude, rad
ω	=	hour angle of the sun, rad

Subscripts

$a-f$	=	internal air and film
$a-h$	=	internal air and helium
air	=	internal air
ao	=	ambient air
$ao-f$	=	ambient air and film
f	=	film
he	=	helium
$h-f$	=	helium and film
0	=	initial state

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I. Introduction

With the development of aerospace science and technology, the use of special space and solar energy resources has attracted scientists' attention [1,2]. As a high-altitude platform, stratospheric airships have wide application, especially in communication, broadcasting, remote sensing, scientific research, etc. The performance of the stratospheric airship during its ascent and descent is affected by its structure, control system, and ambient parameters. In flight, the helium and air inside the airship will expand or be compressed, corresponding to the variation in ambient pressure. Meanwhile, the ambient temperature, airship velocity, and solar radiation mainly influence the heat transfer of the airship. As a result, they will affect the net lift of the airship and therefore the controlling performance. The thermal design is of primary importance for achieving a better performance for a high-altitude airship. In the past decades, some research has been published on the high-altitude platform, but most has focused on the geometry design and power system of the airship and its surroundings [3–6]. Carlson and Horn [7] made a thermal model and predicted the trajectory of a high-altitude balloon. Lee et al. [8] carried out research on gas adiabatic expansion and its influence on airship temperatures. Cathey [9] studied the radiative properties of a balloon. Spencer and Clark [10] developed a radiation model for a balloon. Harada et al. [11] conducted two experiments on thermal characteristics of a 25-m-long airship and a 35-m-long photovoltaic-equipped airship, which flew steadily at a low altitude. The airship is more complicated than a balloon in structure because of its multiballonets, or gas bags. Up to now, there has been no successful experiment in model verification for large high-altitude airships or a complete or mature theory in its thermal evaluation [12–14]. On the basis of some assumptions and simplifications, we have developed a physical model to investigate the thermal performance of the airship during its ascent and descent.

II. Control Mode of the Airship

The stratospheric airship (see Fig. 1) consists of a helium bag and air ballonet. The helium bag normally has no mass transfer with the external environment (but heat transfer occurs with the air ballonet, ship film, and external environment) and transports the pressure to the air ballonet and the film. The internal air pressure is presumed to be the same as the helium pressure. The mass transfer between the ballonet and external air is conducted through valves or by air blowers. The sketch of the airship is presented in Fig. 1.

During ascent, the ambient pressure and temperature decrease and the helium expands. Meanwhile, the air ballonet is compressed and the air is vented outside. The air ballonet can be totally or partially filled with air, depending on the working state. The valve under the air ballonet is used to vent or fill with the air. The air might be completely vented when the airship reaches its operational ceiling, at which the volume of the air ballonet is approaching zero. Then the helium valve is opened automatically, venting part of the helium gas for transforming to floating flight. The function of the air ballonet is mainly to control the airship net lift.

During descent, the external air is pumped into the air ballonet through the valve by the air blower to keep the airship pressure at a constant value that is somewhat higher than ambient pressure so that the airship can descend gradually and its gasbag will not be flattened. The head is better toward the airstream, and keeping its shape and rigidity is especially important for the airship.

From the point of view of a theoretical analysis, the pressure altitude is determined from the volume of the ballonet of the airship. When the internal air is completely thrust out, the airship ascends to its operational ceiling. Therefore, it is believed that the bigger the mass of the airship, the more helium gas needs to be put in, and the lower the volume of the air ballonet. In general, at ground level, the helium bag is compressed to a volume of about 1/16 of that at floating altitude [15].

III. Basic Characteristics of the Stratospheric Airship

A. Helium Mass Filled in the Airship

The net lift of the airship is

$$B = \rho_{ao} V g - (m_{air} + m_{he} + m_s) g \tag{1}$$

where helium mass m_{he} and internal air mass m_{air} can be expressed, respectively, as

$$m_{he} = \rho_{he} V_{he}, \qquad m_{air} = \rho_{air} V_{air} \tag{2}$$

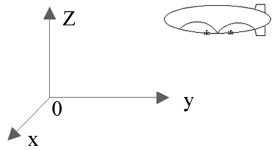

Fig. 1 Sketch of the airship in ground coordinates.

and

$$V_{air} + V_{he} = V \tag{3}$$

From Eqs. (1–3), we can get

$$\frac{B}{g} = (\rho_{ao} - \rho_{air}) V + \left(\frac{\rho_{air}}{\rho_{he}} - 1\right) m_{he} - m_s \tag{4}$$

The helium gas and air can be treated as ideal gases. The pressures of internal air and helium are presumed to be the same with a value somewhat higher than the ambient air pressure: that is,

$$p_{he} = p_{air} = p_{ao} + \Delta P \tag{5}$$

Considering an ideal condition, if the velocity of the airship was so slow that the airship reached a thermal balance with ambient environment (i.e., $T_{air} = T_{ao} = T_{he}$), and if the pressure difference between the internal air and ambient air was ignored (i.e., $p_{air} = p_{ao}$), then $\rho_{air} = \rho_{ao}$ and

$$\frac{\rho_{air}}{\rho_{he}} = \frac{R_{he}}{R_{air}}$$

would be obtained. Substituting these into Eq. (4), then

$$B/g = 6.24 m_{he} - m_s \tag{6}$$

This means that the helium mass m_{he} should be equal to at least $m_s/6.24$. In the actual situation, the airship will be affected by the aerodynamic drag, and the airship might be ultracold or superhot under the influences of solar radiation and gas expansion. Therefore, the helium mass filled in the airship may be larger than the preceding value so that it can provide enough lift to raise the airship to its ceiling altitude at a steady speed.

B. Ceiling Altitude of the Airship

When the air inside the airship is almost vented, the airship will reach its ceiling altitude. Based on the preceding assumptions and equations, we can obtain

$$m_{he} = \rho_{he}(V - V_{air}) = \rho_{ao} \frac{R_{ao}}{R_{he}} (V - V_{air}) \tag{7}$$

$$\rho_{ao} = \frac{m_s + B/g}{(1 - (R_{ao}/R_{he}))(V - V_{air})} \tag{8}$$

If the net load of the airship m_s, net lift B, and the volume ratio V_{air}/V are given, the ambient air density can be obtained. Therefore, the airship ceiling altitude can be predicted.

C. Velocity of Gas Venting

Deriving the items in Eq. (3) with respect to t, then

$$\begin{aligned}\frac{dV}{dt} &= \frac{dV_{he}}{dt} + \frac{dV_{air}}{dt} = U\left(\frac{dV_{he}}{dz} + \frac{dV_{air}}{dz}\right)\\ &= U\left\{V_{he}\left(\frac{1}{T_{he}}\frac{dT_{he}}{dz} - \frac{1}{P_{he}}\frac{dP_{he}}{dz}\right)\right.\\ &\quad \left.+ V_{air}\left(\frac{1}{T_{air}}\frac{dT_{air}}{dz} - \frac{1}{P_{air}}\frac{dP_{air}}{dz}\right)\right\}\end{aligned} \tag{9}$$

Let $T_{air} = T_{ao} = T_{he}$ and $p_{he} = p_{air} = p_{ao}$, then

$$\frac{dV}{dt} = UV\left(\frac{1}{T_{he}}\frac{dT_{he}}{dz} - \frac{1}{P_{he}}\frac{dP_{he}}{dz}\right) \tag{10}$$

This approximation may lack some accuracy, but it is reasonable and can help us to obtain some valuable characteristics. Vented/pumped gas has direct influences on the temperatures of the film and internal gases. It is thus necessary to know the characteristic of the gas-venting/pumping velocity, especially in the airship design phase.

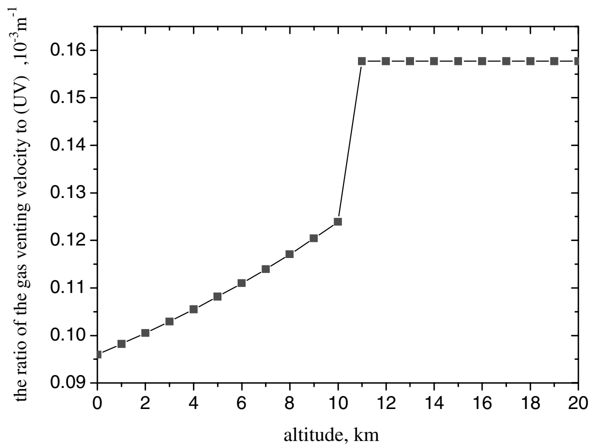

Fig. 2 Variation of the ratio of gas-venting velocity to (*UV*) with altitude.

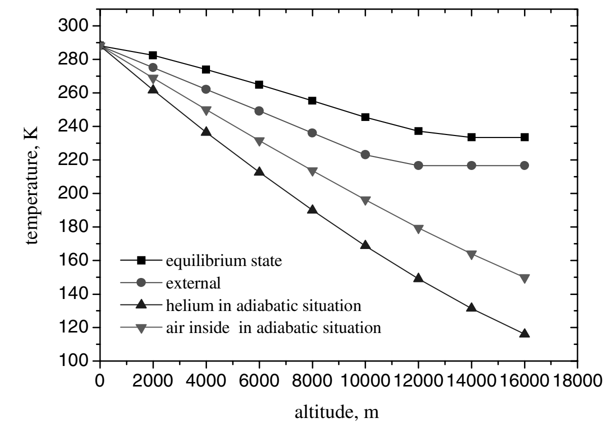

Fig. 3 Variations in the internal gas temperatures with altitude for adiabatic and thermal equilibrium situations.

Using Eq. (10), the variation in the gas-venting velocity with altitude can be evaluated and is plotted in Fig. 2.

Figure 2 shows that the ratio of gas-venting velocity to UV increases almost linearly with increasing altitude below 11 km and keeps constant with a much higher value than that above 11 km. This is because above 11 km, atmospheric temperature keeps constant, and the second term on the right-hand side of Eq. (10) is a constant from 11 to 20 km. The discontinuity of the curve between 10 to 11 km is attributed to a discontinuity in the derivation of the environment temperature with respect to z.

D. Effect of Ascent Velocity on Heat Transfer

The energy-conservation equation of the internal air according to the first law of thermodynamics can be expressed as

$$\rho V C_p dT = dQ + V dP \tag{11}$$

Deriving the items in Eq. (11) with respect to altitude z, then

$$\frac{dT}{dz} = \frac{1}{\rho V C_p U}\frac{dQ}{dt} + \frac{1}{\rho C_p}\frac{dP}{dz} \tag{12}$$

During ascent and descent, if the velocity is sufficiently high so that the internal gas can be treated as if it were in the adiabatic situation, then

$$\frac{dT}{dz} = \frac{1}{\rho C_p}\frac{dP}{dz} \tag{13}$$

$$T = T_0\left(\frac{P}{P_0}\right)^{\frac{\gamma-1}{\gamma}} \tag{14}$$

If the velocity is sufficiently low that the heat exchange between the internal gas and the film is efficiently conducted, the temperature of the gas would approach the film temperature (i.e., $T = T_f$), which is called a thermal equilibrium situation. The film temperature is affected by solar radiation, convection, and infrared radiation. Figure 3 shows the variations in the internal gas temperatures with altitude for adiabatic and thermal equilibrium situations.

Figure 3 shows that in a condition of thermal equilibrium, the temperatures of the internal gases are the same as the film temperature, which is higher than the ambient air temperature. Under adiabatic conditions, the temperatures of the internal gases decrease dramatically with increase in altitude, and the expansion of helium gas makes this trend more severe.

IV. Thermal Model Development of the Airship

A. Governing Equations

The thermal environment for the airship includes the external and internal environments. Heat transfer between the airship and its environment mainly comprises radiation, convection between the film, internal gases, and external environment [16–20]. Considering the semitransparent property of the film, thermal radiation between the film, external environment, and internal gases includes direct solar irradiation, reflected and scattered solar radiation, and infrared radiation. Because the film is so thin, the heat conduction of the film is neglected for the purpose of simplification. The sketch of heat transfer or energy balance for the airship is presented in Fig. 4.

The energy equations for the airship film, internal helium, and internal air can be, respectively,

$$C_{\mathrm{pf}} m_f \frac{dT_f}{dt} = Q_f \tag{15}$$

$$C_{\mathrm{ph}} m_{\mathrm{he}} \frac{dT_{\mathrm{he}}}{dt} = Q_{\mathrm{he}} + V_{\mathrm{he}}\frac{dp_{\mathrm{he}}}{dt} \tag{16}$$

$$C_{\mathrm{pa}} m_{\mathrm{air}} \frac{dT_{\mathrm{air}}}{dt} = Q_{\mathrm{air}} + V_{\mathrm{air}}\frac{dp_{\mathrm{air}}}{dt} \tag{17}$$

$$C_{\mathrm{pa}} m_{\mathrm{air}} \frac{dT_{\mathrm{air}}}{dt} = Q_{\mathrm{air}} + V_{\mathrm{air}}\frac{dp_{\mathrm{air}}}{dt} + C_{\mathrm{pa}}(T_{\mathrm{ao}} - T_{\mathrm{air}})\frac{dm_{\mathrm{air}}}{dt} \tag{18}$$

Although both Eqs. (17) and (18) are the energy equations for internal air, Eq. (17) is for when ascending and Eq. (18) is for when descending, which considers the added heat from the pumped external air. From Fig. 4, the heat Q_f, Q_{air}, and Q_{he} can be expressed as

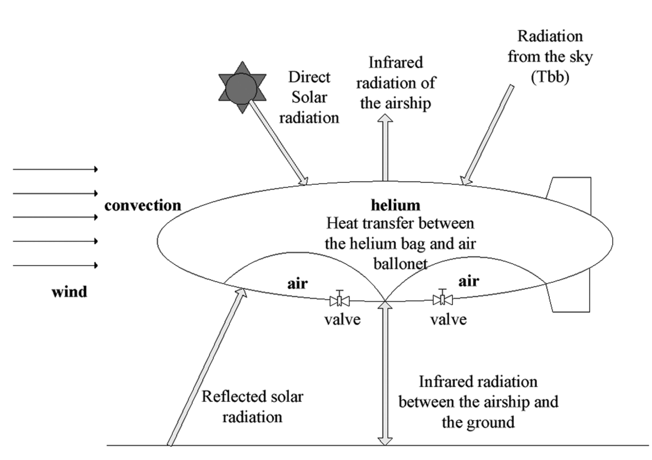

Fig. 4 Sketch of heat transfer or energy balance for the airship.

$$Q_f = I\alpha_f A_f + \varepsilon_{h-f}\sigma(T_{\rm he}^4 - T_f^4)S_{h-f} + \varepsilon_{a-f}\sigma(T_{\rm air}^4 - T_f^4)S_{a-f} + h_{a-f}(T_{\rm air} - T_f)S_{a-f} + h_{h-f}(T_{\rm he} - T_f)S_{h-f} + h_{{\rm ao}-f}(T_{\rm ao} - T_f)S + \varepsilon_f\sigma(T_{\rm bb}^4 - T_f^4)S \quad (19)$$

$$Q_{\rm air} = I\alpha_{\rm air}A_{\rm air} + h_{a-f}(T_f - T_{\rm air})S_{a-f} + \varepsilon_{a-f}\sigma(T_f^4 - T_{\rm air}^4)S_{a-f} + \varepsilon_{\rm air}\sigma(T_{\rm bb}^4 - T_{\rm air}^4)S_{\rm air} - Q_{a-h} \quad (20)$$

$$Q_{\rm he} = I\alpha_{\rm he}A_{\rm he} + \varepsilon_{h-f}\sigma(T_f^4 - T_{\rm he}^4)S_{h-f} + h_{h-f}(T_f - T_{\rm he})S_{h-f} + \varepsilon_{\rm he}\sigma(T_{\rm bb}^4 - T_{\rm he}^4)S_{\rm he} + Q_{a-h} \quad (21)$$

where the heat transferred from internal air to helium is

$$Q_{a-h} = \left(\varepsilon_{a-h}\sigma(T_{\rm air}^4 - T_{\rm he}^4) + \left[(T_{\rm air} - T_{\rm he})\Big/\left(\frac{1}{h_{a-f}} + \frac{1}{h_{h-f}} + \frac{\delta_f}{\lambda_f}\right)\right]\right)S_{a-h} \quad (22)$$

The momentum equation of the airship in the vertical direction is

$$\frac{d((m + m_{\rm add})(dz/dt))}{dt} = g(\rho_{\rm ao}V - m) - \frac{1}{2}\rho_{\rm ao}C_{\rm DV}\frac{dz}{dt}\left|\frac{dz}{dt}\right|S_{\rm ref} \quad (23)$$

where $S_{\rm ref}$ can be expressed as

$$S_{\rm ref} = V^{2/3} \quad (24)$$

The boundary conditions are the environmental parameters and the initial conditions are

$$U = 0, \qquad T_{\rm ao} = T_{\rm air} = T_f = T_{\rm he} = 285 \text{ K} \quad \text{at } z = 0 \text{ km}$$

$$U = 0, \qquad T_{\rm ao} = T_{\rm air} = T_f = T_{\rm he} = 218 \text{ K} \quad \text{at } z = 20 \text{ km}$$

The governing equations were solved with the Runge–Kutta method.

B. Black-Ball Model

To calculate the heat transferred between the surroundings and the airship by infrared radiation, we can assume that the sky is like a black ball at a certain altitude with a certain temperature. Therefore, the radiation heat transferred between the surroundings and some unit of the airship can be expressed as

$$Q = \varepsilon S\sigma(T_{\rm bb}^4 - T^4) \quad (25)$$

The sky or black-ball temperature can be simply expressed as [21]

$$T_{\rm bb} = 0.052T_{\rm ao}^{1.5} \quad (26)$$

C. Convective Heat Transfer

To evaluate the convective heat transfer coefficient h, the Nusselt number needs to be determined. For the airship, heat convection between the film and ambient air can be forced or natural. However, between the internal gas and the film or its bag shell, the convection is commonly natural. The Nusselt numbers are adopted in the present study as follows [7]:

For natural convection between the film and ambient air,

$$Nu = 2 + 0.6(GrPr)^{1/4} \quad \text{for } GrPr < 10^9 \quad (27)$$

For forced convection between the film and ambient air,

$$Nu = 0.37Re^{0.6} \quad \text{for } 10 < Re < 10^5 \quad (28)$$

For natural convection between the internal gas and the film or its bag shell,

$$Nu = 2.5(2 + 0.6(GrPr)^{1/4}) \quad \text{for } GrPr < 1.5 \times 10^8 \quad (29)$$

and

$$Nu = 0.325(GrPr)^{1/3} \quad \text{for } GrPr > 1.5 \times 10^8 \quad (30)$$

D. Solar Radiation

The solar direct radiation I_D irradiated on the plane at the normal direction can be expressed as

$$I_D = I_0 d_m^2 p_t^n \quad (31)$$

In Eq. (31), the correction of sun–Earth distance and the extinction of the solar radiation through the aerosphere are considered. The solar constant $I_0 = 1367 \text{ W/m}^2$, the value of 0.6 to 0.7 is adopted for atmospheric transmittance p_t, and d_m and n can be expressed as [22,23]

$$d_m = 1.000109 + 0.033494\cos X + 0.001472\sin X + 0.000768\cos(2X) + 0.000079\sin(2X) \quad (32)$$

$$n = \frac{1}{\cos\theta + 0.1500(93.885 - \theta)^{-1.253}}\frac{p_{\rm ao}}{101325} \quad (33)$$

where

$$\cos\theta = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \quad (34)$$

$$\delta = 0.006894 - 0.399512\cos X + 0.072075\sin X - 0.006799\cos(2X) + 0.000896\sin(2X) - 0.002689\cos(3X) + 0.001516\sin(3X) \quad (35)$$

$$\omega = \frac{\pi}{12}(t - 12) \quad (36)$$

$$X = 2\pi\frac{D - 1}{365} \quad (37)$$

Scattered radiation I_S can be evaluated with

$$I_S = I_0 p_t^n(1 - p_t^n)/[2(1 - 1.4\ln p_t)] \quad (38)$$

Typically, the plane gets the scattered radiation of 98 W/m^2 on the ground and only 8.9 W/m^2 at the altitude of 20 km.

The reflected radiation I_R also increases the radiation flux, which can be expressed as

$$I_R = r_e I_D \quad (39)$$

The reflectivity r_e can be approximately adopted as 0.18 for clear sky and 0.57 for overcast sky.

Summarizing Eqs. (31), (38), and (39), the total solar radiation can be expressed as

$$I = I_D + I_S + I_R \quad (40)$$

V. Airship Thermal Performance During Its Ascent and Descent

To investigate the thermal performance of stratospheric airships with the developed model, the design index of the airship listed in Table 1 was chosen.

The variations in the airship temperature with altitude during ascent are shown in Fig. 5. During the ascending process, the temperature of the helium is lower than that of the atmosphere, which

Table 1 Design index of the airship

Parameter	Value
Length, m	220
Diameter, m	54
Area, m^2	33,000
Volume, m^3	380,000
Ceiling altitude ,km	20

should be attributed to its doing work through expansion. The temperatures of the film and internal air are higher than those of the atmosphere below 11 km, which can be attributed to their absorption of solar radiation and/or the work done by helium's expansion. However, the temperature of the internal air decreases dramatically above 11 km, due to the higher ratio between the amount vented and that remaining. From Figs. 3 and 5, it can be seen that the velocity has a strong effect on the temperature of the internal gas. Therefore, in the design phase, two factors should be considered: one is that the ascent velocity of the airship should be limited (otherwise, the temperature of the film might drop to its damage value) and another is that the internal air should not be vented too fast (otherwise, the internal gas temperatures could decrease very dramatically).

The variations in the airship temperature with altitude during descent are plotted in Fig. 6. During the descending process, the temperatures of internal gases are higher than those of the atmosphere and the film, and their temperature trends are the same, which can be attributed to the remaining moisture in the gas bags absorbing solar radiation. The temperature of the helium is the highest, which can be attributed to its absorption of solar radiation and the work done by the pumped air. The internal air temperature is lower than the helium temperature and higher than the film temperature, which can be attributed to its doing work and to absorption of solar radiation under the condition of descent. Other reasons can be found in the explanation for Fig. 5.

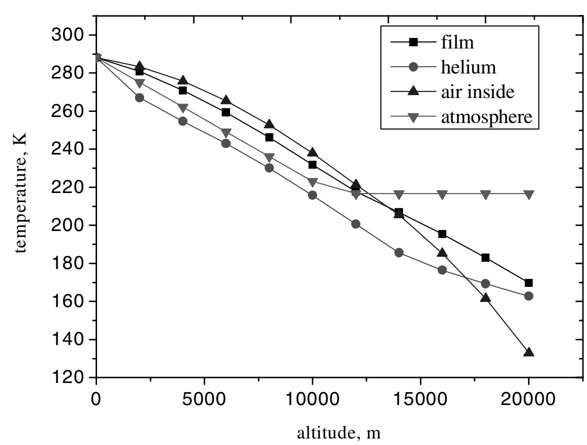

Fig. 5 Variations in the airship temperature with altitude during ascent.

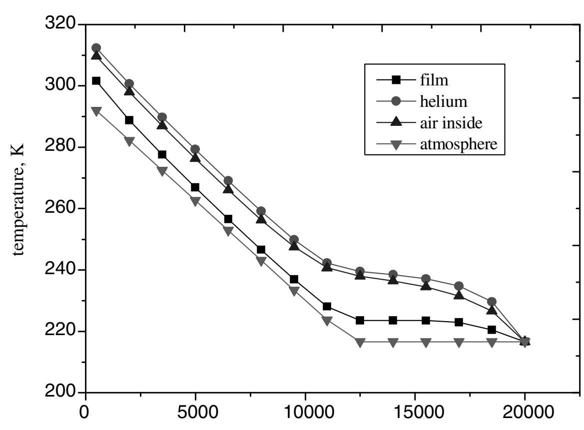

Fig. 6 Variations in the airship temperature with altitude during descent.

VI. Conclusions

A thermal model has been developed to estimate the thermal performance of stratospheric airships in the present work. The temperature variations of a stratospheric airship during its ascent and descent have been obtained. From the results, the following conclusions can be drawn:

1) The ascent velocity of the airship plays an important role in its thermal performance. If the velocity is too fast, the temperature of the film could drop to its damage value, which would create difficulties for the airship's operation. The process of internal gas adiabatic expansion is the limiting situation, in which the temperatures of the internal gases and the film are much lower than those present at the stage of thermal equilibrium.

2) The temperatures trends in the film and internal gases are the same as those for the ambient air during ascent and descent, especially under an altitude of 11 km. The differences mainly depend on the airship velocity, solar radiation, gas expansion or compression, and gas-venting velocity.

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