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Centrifugal Blower of Stratospheric Airship

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ABSTRACT In order to keep airship shape and realize desired performance during the course of landing safely from 20-km altitude, a specific blower is needed to be designed, and its characteristics should be analyzed. The CFturbo software is used to design the stratospheric blower. The performance of the designed stratospheric blower is calculated by computational fluid dynamics software PumpLinx simulation. Then, the performance of the blower at different altitudes is analyzed by simulation. It is shown that the designed stratospheric blower can basically meet the requirements of the semirigid airship of 160 m in length. The blower can make the airship land safely, and its efficiency can reach about 77% in the stratosphere. As the altitude decreases, the efficiency and volume flow (at different heights) of the blower gradually decrease. In addition, the sensitivity of different geometric parameters to the efficiency is analyzed, which can provide a reference for the optimization design of the stratospheric blower.

INDEX TERMS Stratospheric airship, CFturbo, centrifugal blower, PumpLinx, sensitivity.

I. INTRODUCTION

Compared to other aircraft, aerostats the characteristics of a large load, long-endurance, high safety and low cost [1]. At present, the aerostat has gradually gained the widespread attention and application in some countries in the world. In particular, the stratospheric airship has great potential application in military and civilian fields. Some countries are now carrying out research on key technology and model development. The realization of this platform of going up, staying, and dropping back to the whole process is the key to its actual availability. It is necessary to design a loop control system that can achieve the process of the ascent and descent of the airship. The key components in the loop control system are valves and blowers. The emission of the ballonet gas can be realized through the valve, the blowers are used to drum air into the ballonet [2]–[4]. As to the Stratospheric Centrifugal Blower, there are few people study it in China. Now, the stratospheric airships often use the mature aviation blowers. In other countries, the Google balloon uses a specific stratospheric blower. There are few efficient blowers in the world that can meet the specific needs of the stratospheric airships, and few studies have been conducted on their characteristics and design [5], [6].

The blower used in the stratospheric airship needs to be able to effectively achieve the purpose of blowing air into the ballonet of an airship during the airship descending from the height of 20 km to the ground. Compared with the conventional blower, it has a large variation in the properties of the fluid medium (Atmospheric ambient temperature of 20000 m is generally 216.6K which is lower than ground. The air density is 0.08891 kg/m^3, which is 1 / 13.8 of the ground air density) Small differential pressure needs to be overcome by a stratospheric blower, and the input power of the motor used in the blower is constant. As the height decreases, the air density increases gradually, while the rotational speed of the blower decreases gradually. Therefore, the blower applied to the stratospheric airship needs to be specially designed and developed [7]–[9].

In this paper, CFturbo and Pumplinx software are used to design a highly efficient stratospheric blower for an airship [10]. The flow rate reaches 1m^3/s and the differential pressure is about 600Pa. The characteristics of the blower at the high and low altitude are analyzed. At the same time, the influence of the efficiency by structural parameters of the blower is also studied and analyzed.

II. NECESSARY ANALYSIS OF PERFORMANCE OF BLOWER DURING DESCENDING PROCESS OF TYPICAL STRATOSPHERIC AIRSHIP

Airships are usually classified into blimps, semi-rigid airships, and rigid airships according to their structure. The blimp maintains the air-ship shape by filling the envelope with gas with some internal and external differential pressure. Semi-rigid airship through the bottom of the boat keel and

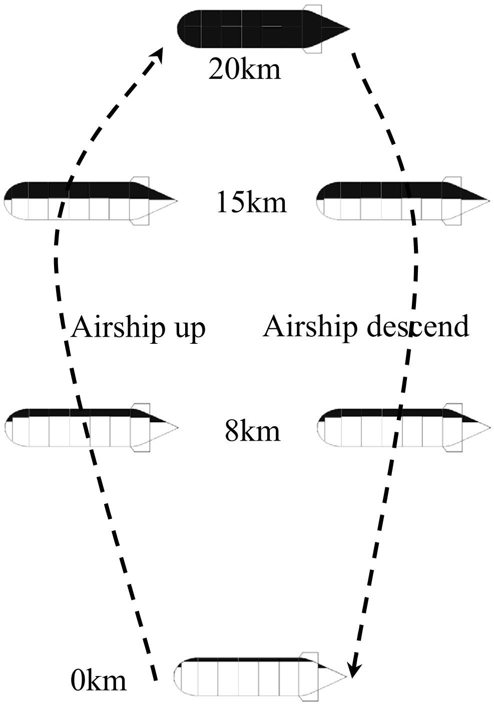

FIGURE 1. The change of Helium and air volume during flight of airship.

skin filled with gas generated by the internal and external pressure to maintain the shape of the external pressure. The rigid airship has a complete frame structure consisting of trusses and cables. The structures of outer cladding form smooth outer skins. The maintaining of the morphology depends on the rigid structure.

During the descent process of the rigid airships, there is no need for blower working. The blimp and semi-rigid airships can be grouped as airships, which need to maintain a certain differential pressure between inside and outside. Therefore, air needs to be pressed into the airbag to overcome a certain pressure through the blower during the process of descending. Generally, the blimp often needs to overcome larger differential pressure than the semi-rigid airship.

Currently, the stratospheric airships mainly use soft or semi-rigid structure. The paper regards semi-rigid airship with a length of 160m and a volume of 304859.9m^3 as the research object. Require of the blower performance during its descending progress is analyzed.

The performance requirements of airship blower are directly related to the velocity of decrease. Figure 2 shows the relationships among descent speed, the height of the airship and blower flow.

As shown in Figure 2, the actually required volume flow (gas volume flow at nonstandard conditions) also decreases as the flight altitude decreases. For example, the airship descends at a speed of 2m/s, the required volume flow at 20km altitude is about 100m^3/s. The volume flow required is reduced to about 7.7m^3/s(only 7.7% of 20km) when the altitude is 5km. It is obvious that there is a wide range of

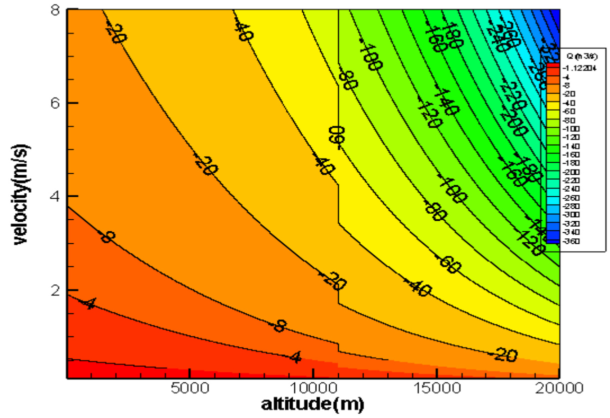

FIGURE 2. The volumetric venting rate of blower under the conditions of different altitude and descend velocity.

changes in the demanded flow. If the blower maintains a constant power, the descending speed at a high altitude is much lower than low altitude.

In addition, external wind conditions vary with altitude, at the same time, the temperature also changes with the altitude changes. But for the stratospheric airship, due to the limitation of its propulsion system capability, it often adopts the strategy of wind-drifting during the descent, so that the airship and the wind field are basically in a state of no relative velocity in the horizontal plane. The velocity of descent speed is also small. The wind speed and direction only affect the direction and distance of the airship drifting, which has less impact on the blower.

During the descending progress, the temperature and the air density will change significantly. For the blower, atmospheric density has an impact on the aerodynamic performance of the impeller. The temperature has an impact on the performance of blower drive motor. This paper focuses on the aerodynamic performance of the impeller.

III. BLOWER PERFORMANCE AND GEOMETRIC PARAMETERS

For the blowers with the same structure, although the blower size, the speed, and the working environment are different, their performances can be described by the dimensionless parameters described below. flow coefficient:

$$\varphi = \frac{Q}{\frac{\pi}{4} D_2^2 u_2} \tag{1}$$

pressure coefficient:

$$\psi = \frac{P}{\frac{1}{2}\rho u_2^2} = f_1(\varphi, Re) \tag{2}$$

power coefficient:

$$\lambda = \frac{PQ}{\eta_i} = f_2(\varphi, Re) \tag{3}$$

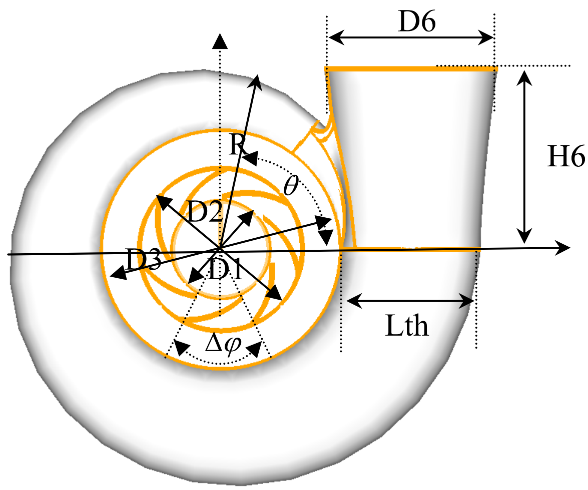

FIGURE 3. The shape parameters of blower.

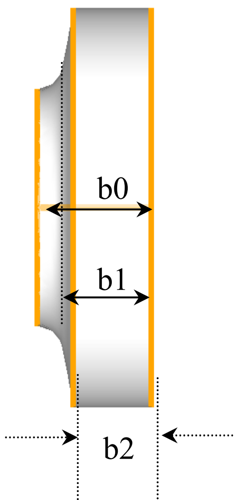

FIGURE 4. The parameters of the blower blade.

specific speed:

$$n_s = 5.54n\frac{Q^{1/2}}{\left(\frac{1.2}{\rho}P\right)^{3/4}} \tag{4}$$

where Q is volume flow, D2 is the impeller diameter, u_2 is the tangential velocity at the outlet of impeller. P is pressure, and n is the motor speed.

In similar working conditions, flow coefficient, pressure coefficient, and internal efficiency are all equal.

The definition of the shape parameters of the blower is shown in Figure 3 and Figure 4.

where b0 is the inlet width of the blower, b1 is the blade inlet width, b2 is the blade outlet width, D1 is the impeller inlet diameter, D2 is the impeller diameter, D3 is the diffuser diameter, L is the diffuser width, t is the thickness of the blade, Z is the number of blades, $\Delta\varphi$ is the blade wrap angle, Lth is the diffuser inlet width, D6 is the diffuser outlet width, and H6 is the diffuser length.

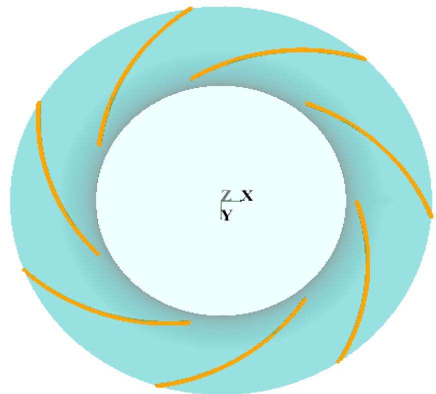

FIGURE 5. The shape of impeller of stratosphere blower.

IV. STRATOSPHERIC CENTRIFUGAL FAN DESIGN

According to the relationship among the descending velocity of airspeed and the blower flow rate mentioned above (Figure 2). It can be assumed that 20 blowers are used, whose internal and external differential pressure is 600pa and volume flow is $1m^3/s$, it can make the airship drops at a speed of 0.5 m/s at an altitude of 20 km (air density 0.0889 kg/m^3), with the decrease at altitude, the speed of airship can be gradually increased. In this way, the airship landing safely can be realized.

Using numerical calculation method, to analyze the characteristics of the stratospheric blower, the characteristics of the stratospheric centrifugal blower at high and low altitude and the influence of the geometric parameters of the blower on its performance are studied. The conclusions of these researches can provide a reference for the design of the stratospheric blower.

A. DESIGN OF STRATOSPHERIC CENTRIFUGAL BLOWER IMPELLER

In this paper, CFturbo software [11] is used in the design of stratospheric blowers. The software is a semi-empirical parametric design of impeller and volute with a large number of rotating machinery performance data. It is widely used in rotating machinery such as pumps, blowers, and turbines design, just set the flow, efficiency and other performance requirements, you can automatically generate impeller and volute shape. Therefore, according to the design parameters determined by the stratospheric blower, the CFturbo software can be used to design the impeller efficiently and quickly. The designed impeller by CFturbo software is shown in Figure 5

B. DESIGN OF THE STRATOSPHERIC CENTRIFUGAL BLOWER VOLUTE

As the volute structure design, in order to guarantee the volute and impeller matching performance, the influence on impeller caused by the gas condition at the outlet should be fully considered. In the CFturbo software, the design parameters of the volute must match the relevant parameters of the

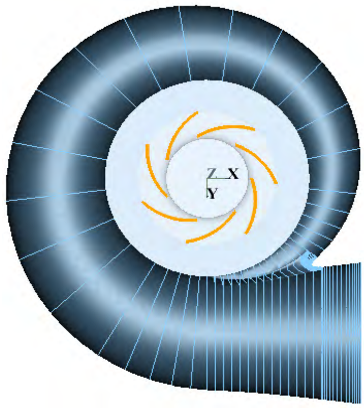

FIGURE 6. The shape of volute of stratosphere blower.

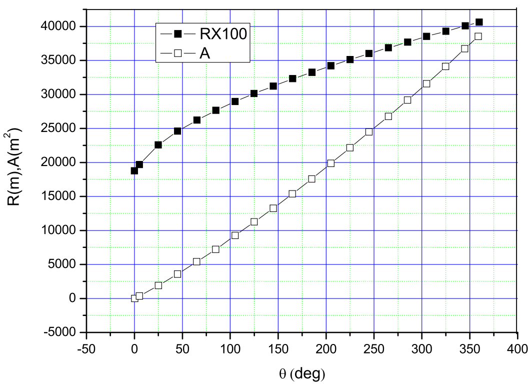

FIGURE 7. The radius and area of stratosphere blower.

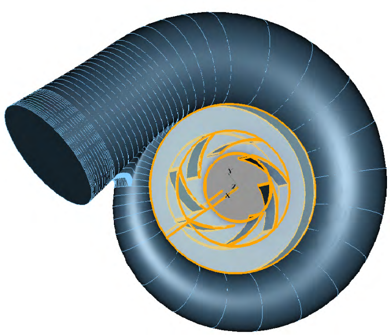

FIGURE 8. The shape of stratosphere blower.

impeller. The volute designed by Cfturbo software is shown in Figure 6. Figure 7 shows the relational between volute area and the volute radius.

The three-dimensional stratospheric blower composed by the impeller, volute and other components provides a model for the performance simulations. The basic geometric parameters of the blower are shown in Table 1.

V. PERFORMANCE ANALYSIS OF STRATOSPHERIC CENTRIFUGAL BLOWER

A. STRATOSPHERIC BLOWER ANALYSIS

A wide range of CFD numerical analysis tools are available for characterization analysis of rotating machinery.

TABLE 1. The shape parameters of stratosphere blower.

Item	*Parameter symbol*	*Parameter value（mm）*
Blower inlet width	*b0*	*88*
Blade inlet width	*b1*	*72*
Blade outlet width	*b2*	*61*
Impeller suction inlet diameter	*D1*	*151*
Diameter of impeller	*D2*	*255*
Diffuser diameter	*D3*	*376.86*
Diffuser width	*L*	*61*
Blade entrance angle	β_{b1}	*18.9°*
Blade exit angle	β_{b2}	*25.6°*
Blade thickness	*t*	*1*
Number of leaves	*Z*	*7*
Leaf wrap angle	$\Delta\varphi$	*56.1°*
Diffuser entrance width	*Lth*	*217.95*
Diffuser outlet width	*D6*	*270.71*
Diffuser length	*H6*	*282.65*

The professional CFD simulation software of rotating machinery –PumpLinx [12] is used in this paper. This software seamlessly connects to blower models built by CFturbo and can quickly generate flow grids. PumpLinx simulation has following steps: pretreatment, meshing, flow field calculation, postprocessing and other steps.

PumpLinx preprocessing includes the import of geometric models, the facet segmentation, and naming of geometric models. The stratospheric blower is divided into three parts: the import section, the impeller rotor part, and the volute.

During the mesh progress, the first step is to select the area that can form a closed area, and then set the grid precision, finally a high-precision Cartesian grid is obtained. If the grids need to be adjusted, just reset the grid parameters. In the analysis of the stratospheric blower, the minimum grid size is 0.001, the maximum grid size is 0.05, then a satisfactory grid is obtained. Generally, the number of the grid is about one million, and a credible calculation results can be obtained. With the number of grids increases, the calculation speed will slow down. In this paper, the number of grid varies from 800,000 to 2.7 million depends on difference shape and size.

The calculation of the blower in a given operating condition requires to set the working medium, the boundary conditions, the turbulence model and its discrete format.

The working medium of the blower is air, and its physical properties are shown in Table 2.

In this paper, the boundary conditions include the blower speed, outlet volume flow, inlet pressure, outlet pressure, input power, medium velocity distribution and pressure distribution.

The Standard K-Epsilon turbulence model is included in PumpLinx. The discrete formats are Upwind, Central and Second Order Upwind. This paper uses Upwind discrete format when calculating.

TABLE 2. The physical parameters of 20km altitude air.

parameter name	Parameter value
Fluid medium	air
Density (kg/m3)	0.0889
Viscosity (N.s/m2)	1.4216e-5
Reference temperature (K)	216.65

TABLE 3. The shape parameters of pump.

Item	Parameter symbol	Parameter value（mm）
Blower inlet width	b0	24.6
Blade inlet width	b1	24.6
Blade outlet width	b2	24.6
Impeller suction inlet diameter	D1	101.6
Diameter of impeller	D2	203.2
Diffuser diameter	D3	216
Diffuser width	L	24.6
Blade entrance angle	β_{b1}	16°
Blade exit angle	β_{b2}	16°
Blade thickness	t	3
Number of leaves	Z	4
Leaf wrap angle	$\Delta\varphi$	141°
Diffuser entrance width	Lth	108
Diffuser outlet width	D6	108
Diffuser length	H6	200

TABLE 4. The calculation conditions of pump in PumpLinx.

Simulation method	Steady state
Rotating speed	1450r/min
Temperature	300K
Fluid medium	Water
Density	998kg/m3
Dynamic viscosity	0.001003
Entrance pressure	101325Pa
Turbulence model	Standard K-Epsilon
Discrete format	Upwind

B. ANALYTICAL METHOD VALIDATION

Baunand and Flack [13] and El-Naggar [14] show the Experimental data of a model pump. The following model is used to verify the accuracy of the modeling and calculation methods used.

When CFD is used to calculate the blower, the meshing mode, density and distribution of flow field will have a certain impact on the calculation results. FOR the experimental pump, the influence on the simulation results caused by the number of flow field grids is analyzed, then the number of grids used in the performance analysis is determined.

TABLE 5. The mesh convergence of pump.

	Different flow（m^3/s）		
Number of grid cells	0.016	0.015	0.013
942056	0.81	0.82	0.81
1977416	0.82	0.82	0.82
4133970	0.82	0.82	0.82
4375587	0.82	0.82	0.82

TABLE 6. The mesh effect of stratosphere blower.

	Different flow（m^3/s）		
Number of grid cells	1.1	1	0.8
833787	0.798	0.793	0.747
2773070	0.775	0.769	0.728
6925034	0.734	0.74	0.711
8069398	0.744	0.741	0.715

$$(C_H = \frac{\Delta p_t}{240000})$$

The difference between the calculation results of the standard pump and the test results is shown in Figure 12 and 13. It should be noticed that the modeling and simulating calculation methods used in this paper can get the tendency of the blower characteristics accurately.

C. PERFORMANCE ANALYSIS OF STRATOSPHERIC CENTRIFUGAL BLOWER

The above mentioned method is used to analyze the characteristics of the designed stratospheric centrifugal blower. First, analyze the impact of flow field grid.

As shown in Table 6 and Figure 14 and 15, different numbers of grid have an impact on blower performance. But different grids can get the tendency of the characteristics curve. For the characteristics of stratospheric centrifugal blower the number of grid is about 2773070 in following simulation.

In addition, according to the performance of the blower, the dimensionless performance curve of the blower can be obtained through the mentioned above performance parameters, which can be used as the basis for blower selection and performance analysis with different sizes and conditions. The blower dimensionless performance curve is shown in Figure 16.

From the figure 17, we can learn that with the increase of the flow coefficient, the specific speed is also increasing.

It can be concluded from the above analysis that the stratospheric centrifugal blower designed according to the requirement, the efficiency can reach about 77% at an

TABLE 7. The calculation conditions in PumpLinx.

Simulation method	Steady state
Fluid medium	Air
Rotating speed	Variety
Air temperature	Variety
Air density	Variety
Entrance pressure	Variety

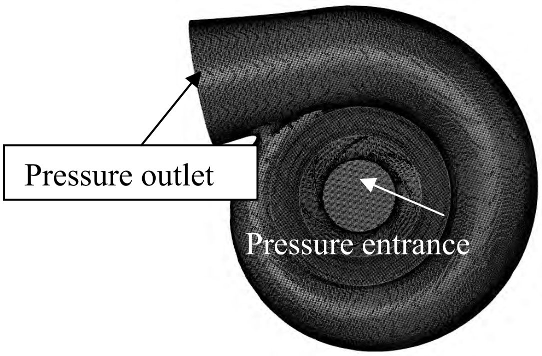

FIGURE 9. The mesh and boundary conditions of stratosphere blower.

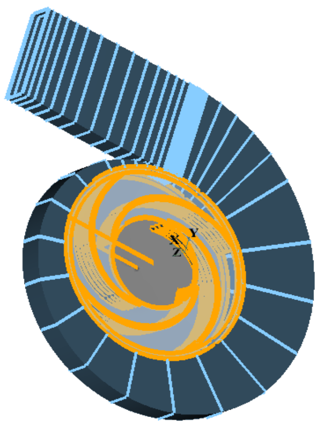

FIGURE 10. The shape of pump.

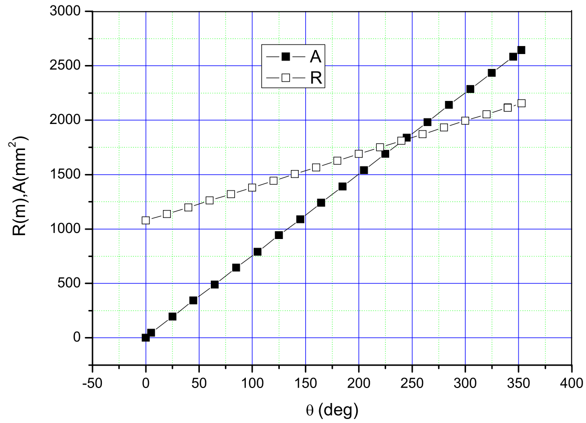

FIGURE 11. The radius and area of pump.

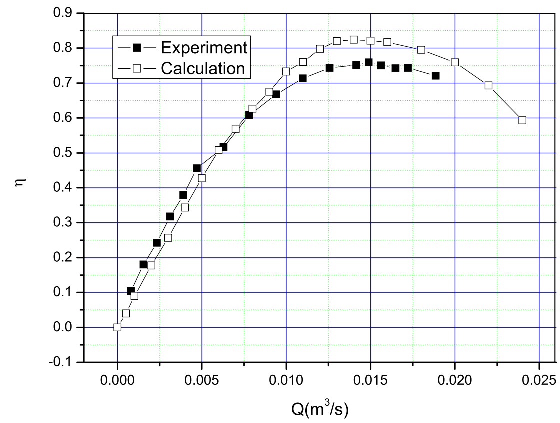

FIGURE 12. The comparison of volumetric venting rate and efficiency of pump.

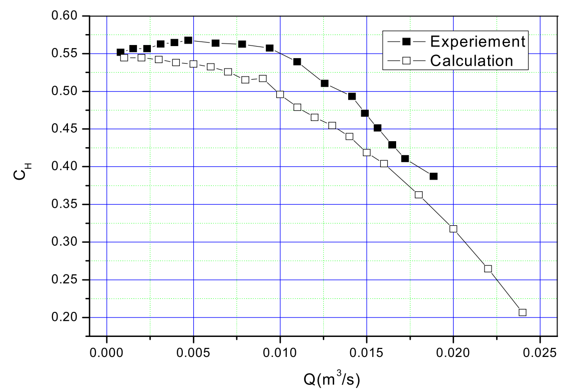

FIGURE 13. The comparison of volumetric venting rate and pressure difference of pump.

altitude of 20 km. The above analysis shows that the performance of a stratospheric airship's loop control system can be improved by the design of the stratospheric blower. At the same time, the performance of the entire airship platform is also improved.

VI. THE CHARACTERISTICS ANALYSIS OF STRATOSPHERIC CENTRIFUGAL BLOWER WITH ALTITUDE DECREASING

The descent of the stratospheric airship can be achieved in two ways. One is by releasing part of the helium, and the other is to blow air by the blower to increase the weight of the airship. Both two methods need to use a blower, to press air into the ballonet to keep the shape of the airship unchanged.

When the airship descends, the ambient air density is changing, at the same time, the input power of the blower is limit-ed. The blower needs to overcome differential pressure with the changing condition.

For the above stratospheric blower, the input power (738W) and the differential pressure (572Pa) are basically constant. The efficiency, flow rate and the number of revolutions are analyzed with altitude changed.

It is shown in Fig.19 that under the constant differential pressures and the constant input power. As the altitude

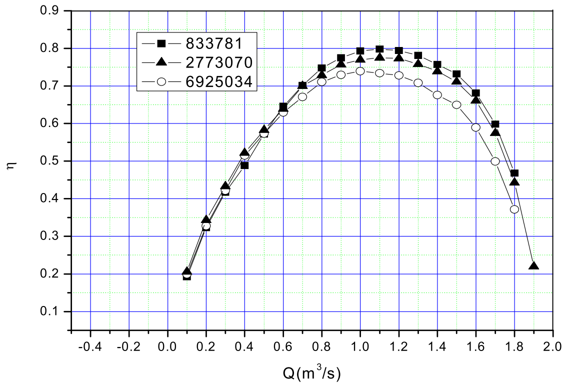

FIGURE 14. The relationship between volume flow and efficiency of the stratosphere blower.

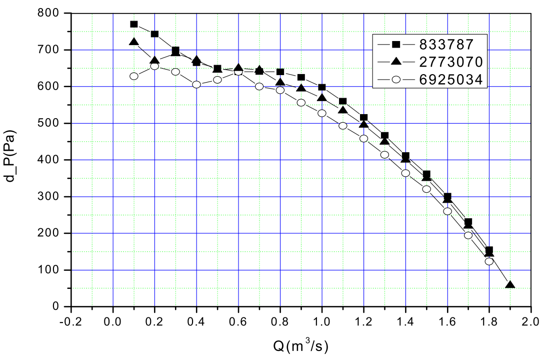

FIGURE 15. The relationship between volume flow and differential pressure of the stratosphere blower.

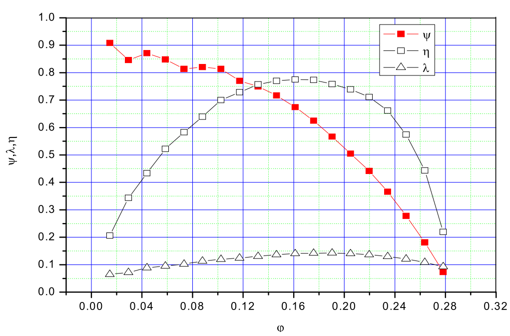

FIGURE 16. The relation of flux coefficient with pressure coefficient, power coefficient and efficiency of stratosphere blower.

decreases, the physical speed of the blower will gradually decreases. During the descent progress, the rotation speed of the blower can be controlled by the fuzzy approach [15]–[17].

It is shown in Fig. 20 that under the constant differential pressures and the constant input power, with the altitude decreases, the efficiency of the blower is also gradually reduced. From 20 kilometers to the ground, the efficiency of the blower is reduced about 19%.

It is shown in Fig.21 that under the constant differential pressures and the constant input power, with the altitude decreases, the actual volume flow of the blower will be reduced, and this will directly affect the descent speed of the airship.

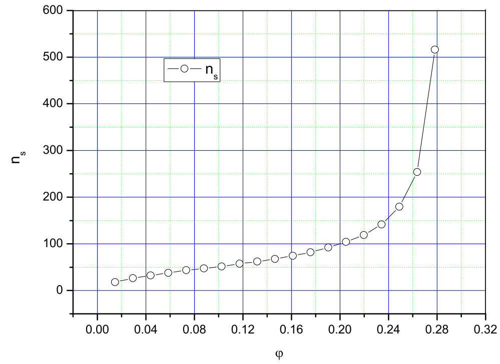

FIGURE 17. The relation of flow coefficient with specific speed of stratosphere blower.

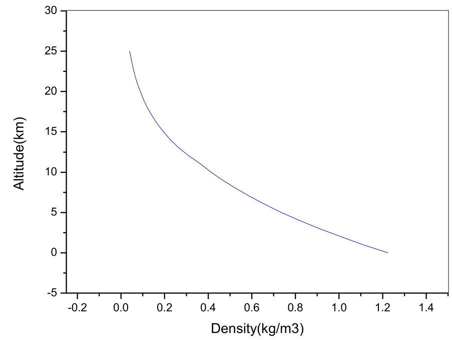

FIGURE 18. The change of air density with change of altitude.

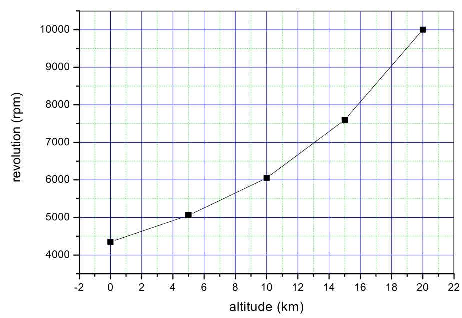

FIGURE 19. The change of revolution of stratosphere blower with the change of altitude.

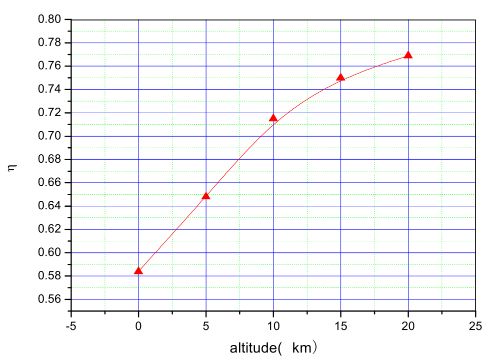

FIGURE 20. The change of efficiency of stratosphere blower with the change of altitude.

It is shown in Fig.22 that under the constant differential pressures and the constant input power, with the altitude decreases. The volume flow of air converted to standard

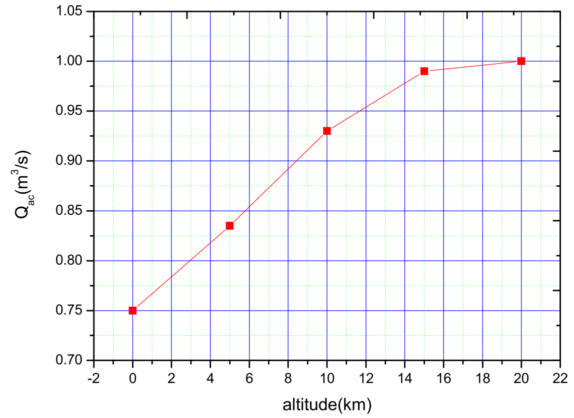

FIGURE 21. The change of actual volumetric venting rate of stratosphere blower with the change of altitude.

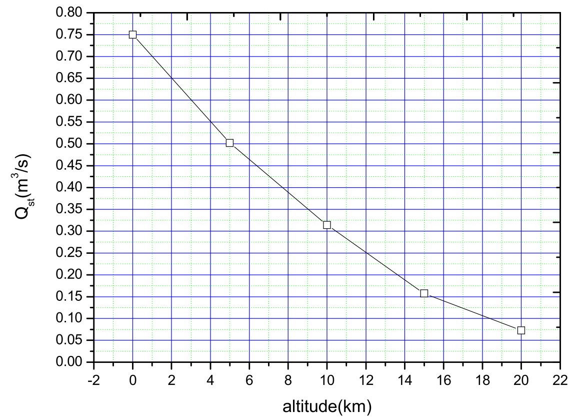

FIGURE 22. The change of standard atmosphere pressure volumetric venting rate of stratosphere blower with the change of altitude.

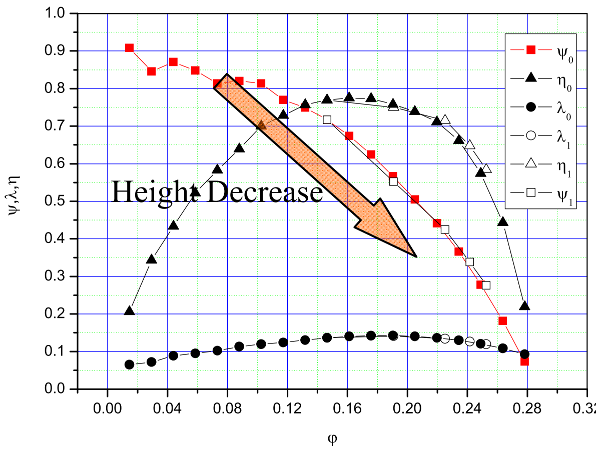

FIGURE 23. The relation of altitude with flux coefficient, pressure coefficient, power coefficient and efficiency of stratosphere blower.

temperature and pressure increases with the altitude decreases.

Next, the blower performance at different altitudes is dimensionless, and then compared with the blower's dimensionless performance curve to show the blower operating conditions as the altitude decreases.

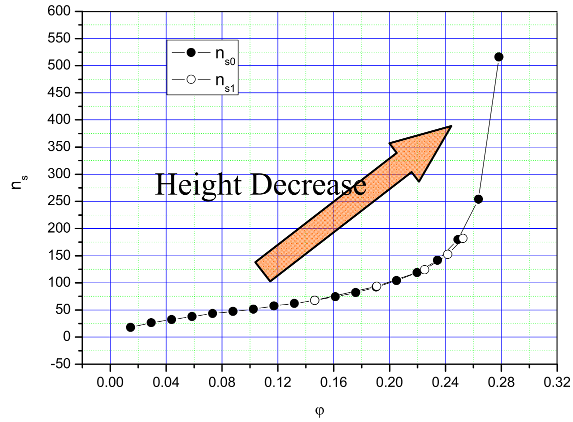

FIGURE 24. The relation of altitude with flux coefficient, specific speed of stratosphere blower.

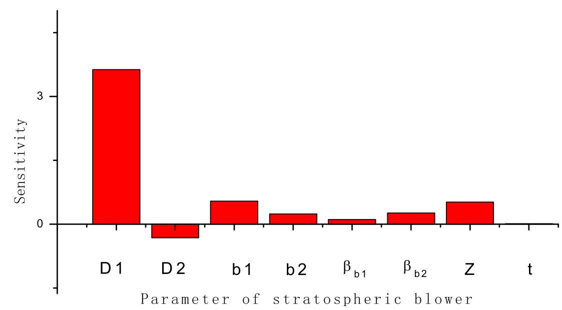

FIGURE 25. The sensitivity of parameters of stratospheric blower to input power.

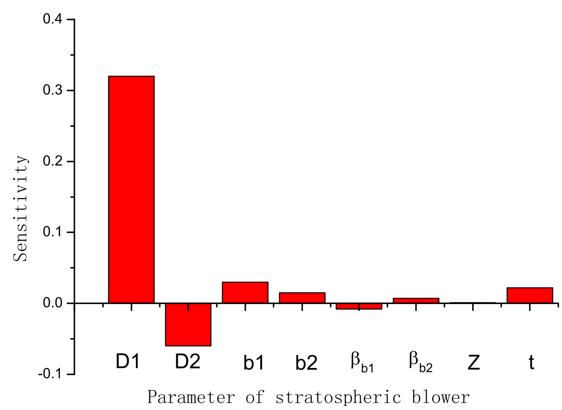

FIGURE 26. The sensitivity of parameters of stratosphere blower to outlet total pressure.

In Figures 23 and 24, $\lambda_0, \psi_0, \eta_0, n_{s0}$ are the performance parameters of the blower at a height of 2000 meters. $\lambda_1, \psi_1, \eta_1, n_{s1}$ indicate the performance parameters of the at different altitudes. As can be seen from the comparison of the dimensionless parameters in Figures 23 and 24, with the power decreases and the static pressure constant, as the altitude decreases, blower flow coefficient gradually increases while the pressure coefficient, the power factor and efficiency gradually decrease. Particularly, the blower specific speed gradually increases.

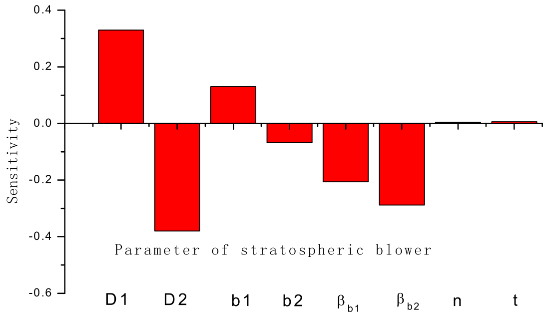

FIGURE 27. The sensitivity of parameters of stratosphere blower to efficiency.

TABLE 8. The sensitivity of stratosphere blower (the volumetric flow is $1m^3/s$).

	input power (w)	outlet pressure (Pa)	efficiency
D2	3.63	0.32	0.33
D1	-0.32	-0.06	-0.38
Outlet width b2	0.54	0.03	0.13
Inlet width b1	0.24	0.015	-0.068
Inlet angle changes β_{b1}	0.11	-0.008	-0.206
Outlet angle changes β_{b2}	0.266	0.007	-0.288
Number of blade Z	0.522	0.001	0.004
Blade thickness t	0.013	0.022	0.006

What's more, λ_1, ψ_1, η_1, n_{s1} correspond to λ_0, ψ_0, η_0, n_{s0} respectively. Therefore, the performance of the blower at different altitudes is equivalent to the one at 20 km with the same flow coefficient. The effect of the Reynolds number effect is negligible [18].

VII. SENSITIVITY ANALYSIS OF GEOMETRICAL PARAMETERS OF STRATOSPHERIC CENTRIFUGAL BLOWER

There are many design parameters during the design process of the stratospheric centrifugal blower. So it is necessary to analyze the sensitivity and impact trend of the design parameters. This section mainly studies the sensitivity of the typical geometric parameters for the stratospheric centrifugal blower.

The expression of the sensitivity is as follow:

$$S = \frac{(R - R_b)/R_b}{(P - P_b)/P_b} = \frac{\Delta R/R_b}{\Delta P/P_b} \tag{5}$$

where P_b is the reference value for inputting the geometry parameters, ΔP is the amount of change for the geometric parameters R_b is the reference parameter based on P_b, R is the response of the reference parameter plus the amount of change $P_b + \Delta P$.

For the sensitivity analysis, the geometric parameters vary by $\pm 10\%$ of the reference value.

Through the data in the above table, some inclusions can be obtained about the influence of each geometric parameter on the blower characteristics.

For the input power of the blower, the parameter that has the greatest effect is the impeller outlet diameter, followed by the impeller outlet width and number of blades. The impact increases with these parameters. For the outlet pressure, the parameter that has the greatest effect is the impeller outlet diameter.

For the efficiency, the parameter that has the greatest effect is the impeller outlet diameter and the inlet diameter, followed by the inlet angle and outlet angle. The increase of the outlet diameter makes the efficiency increase, but the increase of the inlet diameter will induce the efficiency. Besides, the efficiency induces with the increase of the inlet angle and outlet angle.

Given the impact of these sensitive parameters, a number of modifications, designs, and simulations of the parameters are required. In the future, a method of big data can be used to get the optimal geometric parameters of the stratospheric blower [19], [20].

VIII. CONCLUSION

The characteristics of the stratospheric airship loop control system directly affect the airship's flight performance. The blowers serve as the key actuation component in the loop control system and have a significant impact on the performance and handling of the airship. The theoretical contribution of this paper is to establish a theoretical basis and method for modeling and simulation of high altitude blowers by using Cfturbo and Pumplinx software. The practical contribution of this paper is the designed blower can make the stratospheric airship landing safely in accordance with the desired goal.The conclusions drawn in this paper are as follows:

1. CFturbo and Pumplinx can be used to realize the design and performance analysis of blowers under specific requirements;
2. In this paper, for a specific environment of 20,000 meters high, a specific blower suitable for a 160-meter-long stratospheric airship is designed by the CFturbo software. It can make the airship descend at the expected speed and the efficiency of a 20,000-meter stratospheric centrifugal blower can reach 77%.
3. For a particular stratospheric centrifugal blower, the efficiency of the blower (regardless of the change of motor efficiency) and the actual volume flow will decrease as the height decreases with the input power and pressure difference constant. With the decrease of height, blower flow coefficient, the pressure coefficient, the power factor and efficiency gradually decrease. However, the blower's specific speed gradually increases.
4. Through the analysis of the sensitivity of geometric parameters of the blower, the key parameters influencing the characteristics of the blower and their influence laws are obtained, which can provide a reference for the optimal design of the blower.
5. The theoretical contribution of this paper is to establish a theoretical method for modeling and simulation of

high altitude blowers by using Cfturbo and Pumplinx software. The practical contribution of this paper is the designed blower can make the stratospheric airship landing safely in accordance with the desired goal.

These aspects of research can provide a reference for the design and optimization of the stratospheric airship blower.

In future, we shall combine the fuzzy logic technique to study the mathematic modeling of the blower [21]–[23], and investigate its control problem [24]–[26].

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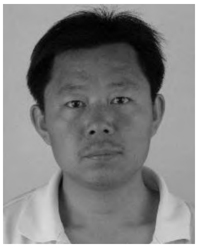

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