

Study on the Profile and Flow Field Variation of Parachute Coating by Seven-hole Probe Method

Kun Song Kim¹, Sun Ri², Sol Song Pak^{3,*}, Nam Song Pak⁴, Kum Song Kim⁵

Abstract

In general, the parachute test is a long test cycle, expensive, and difficult to measure with accuracy, which makes it a very laborious and time-consuming task. Therefore, attempts have been made to overcome this by using a parachute test stand or by simulation, but in our country, there is no numerical simulation of the parachute and there is no research on it. In this paper, the variation of the shape and flow field of the parachute coating during air filling of the parachute is investigated using a dedicated application. To this end, a model of the parachute was developed using fluid-structure interaction technique on the LS-DYNA program, a transient dynamics finite element code. First, combined computational fluid dynamics model and structural dynamics model were created during the air-filling of the parachute, based on the structure of the parachute and the force characteristics during the air-filling process. In addition, a quantitative measurement of the full-state swirling flow field using the seven-hole probe method was carried out to compare the experimental and calculated results, and the mathematical model used was reliable because the topology of both is very similar and the pressure difference coefficient is not large. Based on this, numerical simulations and analysis of the flow field of the entire air-filling stage were carried out to investigate in detail the changes in the shape of the parachute and the internal and external flow fields of the parachute during the entire opening of the parachute.

Keywords: Ringsail parachute, Orion space vehicle, fluid–structure interaction, offloading, drifting

INTRODUCTION

Although the analysis of parachute opening has traditionally relied mainly on experimental studies, the simulation of the test conditions and recording of each parameter during this single dynamic air-filling process was very difficult, due to the generally short air-filling time and sometimes less than half a second air-filling process. Therefore, wind tunnel test studies of parachute are generally referred to as the study of parachute load and air power coefficient [1–4].

In fact, the parachute is a flexible textile, which causes sudden structural deformation during the parachute operation. Therefore, the flow field inside and outside the parachute is very complex and the flow field around the parachute must be analyzed to understand the working characteristics of the parachute. It follows that to obtain the relationship between the change in the shape of the parachute and the change in the flow field, one must rely on dynamic simulations of the air-filling process, thus increasing the theoretical level of analysis of the parachute [5–9].

*Author for Correspondence

Sol Song Pak
E-mail: SS.PAK@star-co.net.kp

Faculty of Dynamics, Kim Il Sung University, Pyongyang,
Democratic People's Republic of Korea

Receiving Date: May 12, 2024

Accepted Date: June 04, 2024

Published Date: June 10, 2024

Citation: Kun Song Kim, Sun Ri, Sol Song Pak, Nam Song Pak, Kum Song Kim. Study on the Profile and Flow Field Variation of Parachute Coating by Seven-hole Probe Method. Journal of Aerospace Engineering & Technology. 2024; 14(1): 26–37p.

Hence, we have performed numerical simulations and analysis of the whole air-filling stage of a circular parachute and have considered the changes in the appearance during the whole opening of the parachute and the changes in the internal and external flow fields of the parachute.

MATHEMATICAL MODEL OF AIR-FILLING PROCESS

Structural Dynamic Model

We hypothesize that for the planar circular parachute model:

1. The influence of gravity on a particle is neglected.
2. Parachute ropes, reinforcing bars and parachute coatings are elastomers.

The parachute covers are connected to each other by a certain number of equal parachute cover widths, while the adjacent parachute cover is connected by a reinforcing bar.

The principle of loading between one particle and another is shown in Figure 1.

According to Newton's law of motion, the structural dynamics equation of each particle is as follows:

$$m_i \frac{dv_{ix}}{dt} = F_p \times \sin \alpha_i - T_i \times \cos \beta_i - T_{i-1} \times \cos \beta_{i-1} - F_z \quad (1)$$

$$m_i \frac{dv_{iy}}{dt} = F_p \times \cos \alpha_i + T_i \times \sin \beta_i - T_{i-1} \times \sin \beta_{i-1} \quad (2)$$

where F_p is the aerodynamic pressure of a parachute particle; the insertion angle of the Y axis, T_i , T_{i-1} : i and $i + 1$ particles; the sum of the elastic and damping forces between the i and $i - 1$ particles; the tension between the parachute particles and the insertion angle of the X axis, and F_z is the lateral tension of the parachute fabric (receiver cable, parachute top hole reinforcement bar).

Computational Fluid Dynamics Model

The thickness of the parachute is much smaller than the geometry of the parachute.

Hence, from a hydrodynamic point of view, the parachute can be considered as a membrane material, and its thickness does not have a significant influence on the flow field, and the influence of the parachute thickness can be neglected when performing hydrodynamic numerical simulations on the parachute [10].

The Navier–Stokes equation is solved to simulate the flow field characteristics of the parachute.

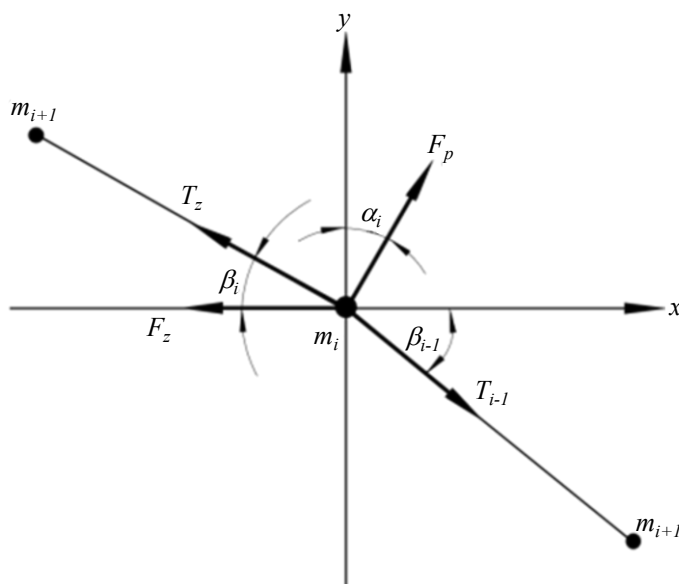


Figure 1. Interaction forces between particles.

The two-dimensional Reynolds-averaged Navier–Stokes equations were chosen as the governing equations and the flow field simulations were performed using a finite-volume structured mesh numerical model.

Then the Navier–Stokes equation can be written as follows:

$$\frac{\partial W}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} = \frac{1}{Re} \left[\frac{\partial E_v}{\partial x} + \frac{\partial F_v}{\partial y} \right] \quad (3)$$

where

W : conservation flow

Re : Reynolds number

E, F : convective flow rates

E_v, F_v : viscous flow rates

In this paper, we have used the porous medium (Porousjump) boundary condition as reference and have performed computational model validation with 602 fiber and 66 silk samples.

$$\Delta p = \left(\frac{\mu}{\alpha} v + C_2 \frac{1}{2} \rho v^2 \right) \Delta m \quad (4)$$

where

α : permeability coefficient of medium

μ : viscosity coefficient

C_2 : pressure jump coefficient

v : velocity perpendicular to the surface of the medium

Δm : medium thickness

Table 1 presents the experimental data for air flow rate and pressure loss of No. 602 gold thread 66 [11], and the fitting of these data using a quadratic polynomial through the origin is performed as shown in Figure 2.

$$\Delta p = 133.34v^2 + 79.386v \quad (5)$$

$$C_2 \frac{1}{2} \rho \Delta m = 133.34 \quad (6)$$

$$\frac{\mu}{\alpha} \Delta m = 79.386 \quad (7)$$

Therefore

$$C_2 = 435395, \alpha = 1.1270 \times 10^{-10}$$

To simulate the air permeability of the parachute coating, a computational model shown in Figure 3 was built [11–15].

Setting the inlet air flow rate to the rate of Table 1, the corresponding pressure loss can be calculated and the results are shown in Table 1.

Table 1. The comparison of calculated and experimental values of air speed and pressure loss.

Air Speed/ ($m \times s^{-1}$)	Pressure Loss P_a (Experimental Values)	Pressure Loss P_a (Calculated Values)
0.583	97.82	91.604
0.972	195.64	203.14
1.225	293.47	297.34
1.445	391.29	393.13
1.61	489.11	473.44
1.835	586.94	594.65

From Table 1, it can be seen that the results of the calculated and experimental values are relatively close. In this paper, the parachute coating material is 411 plain silk and its air permeability can be simulated using this method.

DEVICES

Air-filling time is generally very short and sometimes less than half a second is required to perform air filling, when the variation of the flow field around the parachute is very complex due to the rapid change of the parachute.

Therefore, the simulation of the test conditions during dynamic air filling and recording of parameters of each item are very difficult.

Therefore, quantitative measurements of the flow field at the parachute fill are carried out and the reliability of the calculation results is checked by comparing the measured results with those of this situation.

The test was carried out in an unsteady counter current low-speed wind tunnel, and the photograph of the parachute in the wind tunnel is shown in Figure 4.

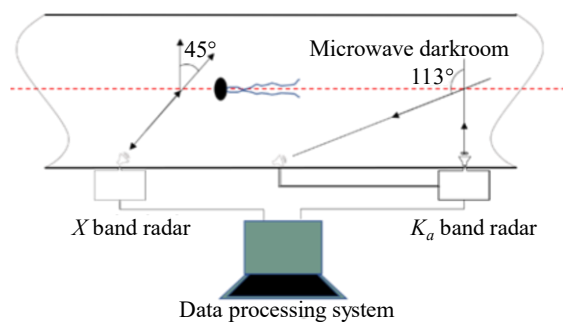


Figure 2. Quadratic polynomial curve fitting result.

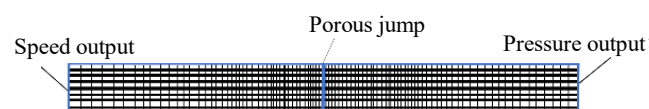


Figure 3. Boundary conditions and lattice structure for the porosity calibration calculations.



Figure 4. Wind tunnel test photograph of parachute.

The inlet of the experimental section is $1.5 \text{ m} \times 1 \text{ m}$ spherical, the total length is 1.7 m, the turbulence is less than 0.05%, the maximum wind speed is 40 m/s, and the minimum stable wind speed is 0.5 m/s.

The internal flow field of the parachute is very complex and the air stream has a relatively large dip. Therefore, the flow field around the seven-hole probe is measured using the seven-hole probe, and the structure of the seven-hole probe is shown in Figure 5.

The seven-hole probe can obtain three-dimensional velocity and pressure information in the flow field, and its measurement accuracy is 1% for large amplitude flow of 78° [9]. To improve the measurement efficiency, several seven-hole probes can be fabricated to simultaneously measure aerodynamic parameters at various points in space.

Since the pore probe has to be calibrated before testing and the calibration coefficient of the pore probe is relatively high, in the actual test, the seven-hole probe converts the seven-hole pressure value of the local point of the flow field from the multipath micropressure to the measuring instrument, converts the analog voltage to the digital volume through a high-precision collection module.

After computer acquisition, the velocity vector is obtained by the coefficient calculation obtained by calibration test, and the measurement results are obtained, such as local total pressure, static pressure, etc. The configuration of the whole test system is shown in Figure 6.

This test used a circular parachute, whose physical parameters are eight pairs of parachutes, 100 mm is the parachute breather diameter, and 600 mm is the parachute cover diameter. The parachute rope is 465 mm long, the material is 3.2-120 Room Rope, and its elastic modulus is 4000 N/m^2 [16]. The nominal area of the parachute is 0.32 m^2 , the material is 411 flat silk, and the elastic modulus is 30000 N/m^2 .

ANALYSIS OF RESULTS

Parachute Outdoor Shape Change and Flow Field Change During Air Filling

The initial state of the calculation is consistent with the experimental state, and the gas flow rate is 20 m/s. The initial air-filling stage is the stage in which the air stream rises from the parachute bottom to the parachute top, and Figure 7 presents the parachute profile change and flow field change diagram of the initial air-filling stage.

As can be seen from the figure, the “horn” results in a large separation zone, and local low pressure occurs in a relatively large area after the “horn”, where the pressure difference inside and outside the parachute is relatively large, and when reaching 1.6, the expansion process of the parachute is accelerated.

The inflated parachute pushes the air stream outward, accelerates the air flow, lowers the external pressure of the parachute, and the parachute internal and external pressure difference coefficient is 1.5.

The situation shown in Figure 7(d) is when the parachute top hole is fully drilled, when the air flow flows to the parachute bottom and again flows out into the parachute top hole.

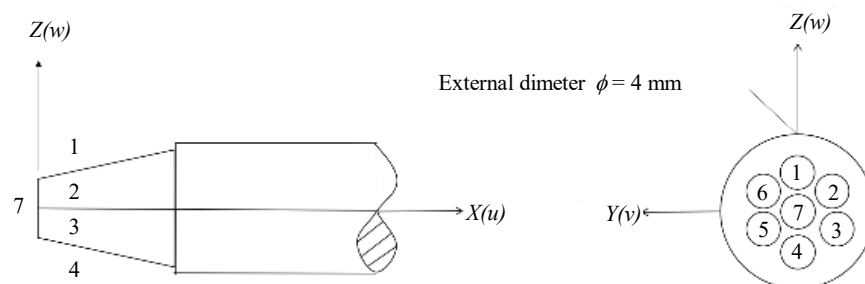


Figure 5. Seven-hole probe.

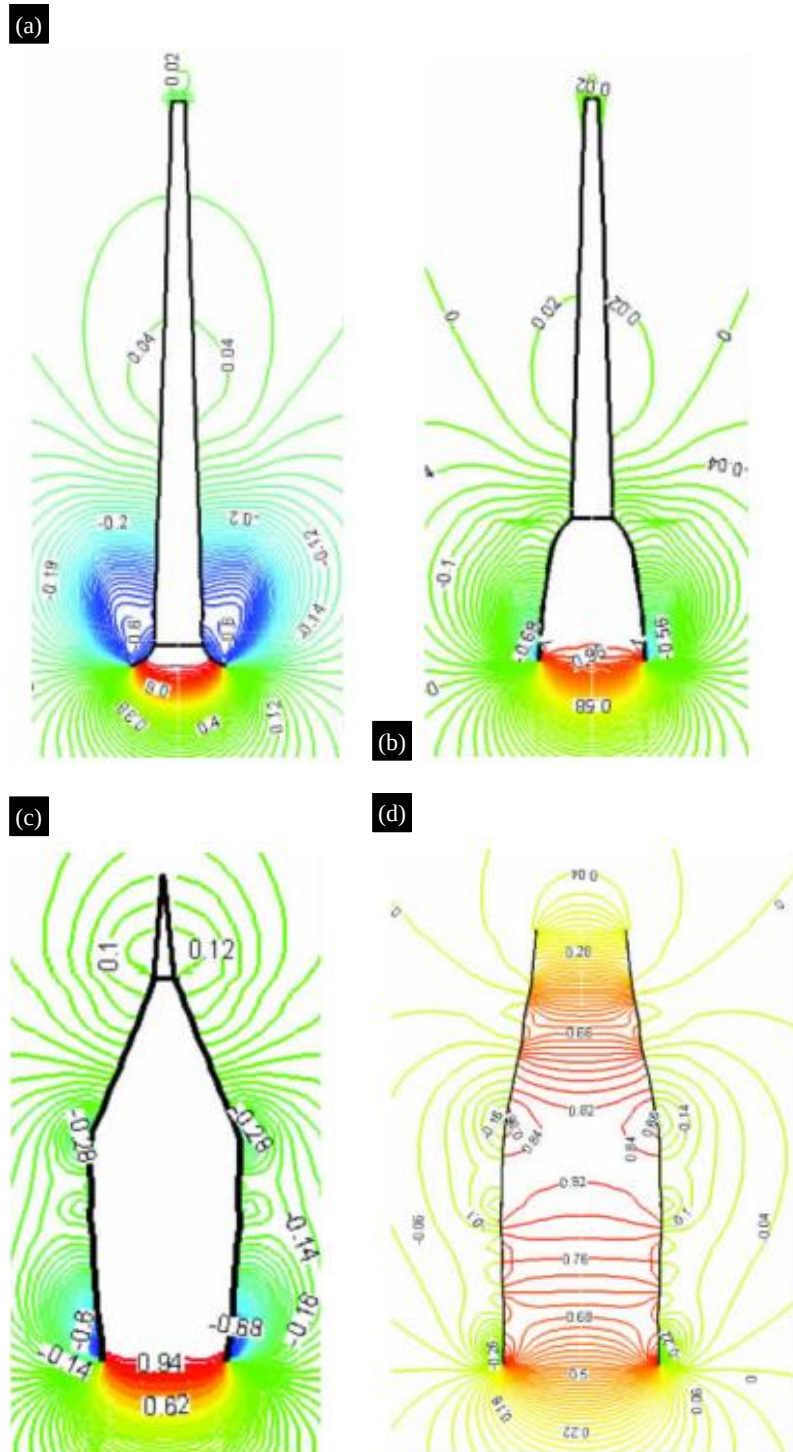
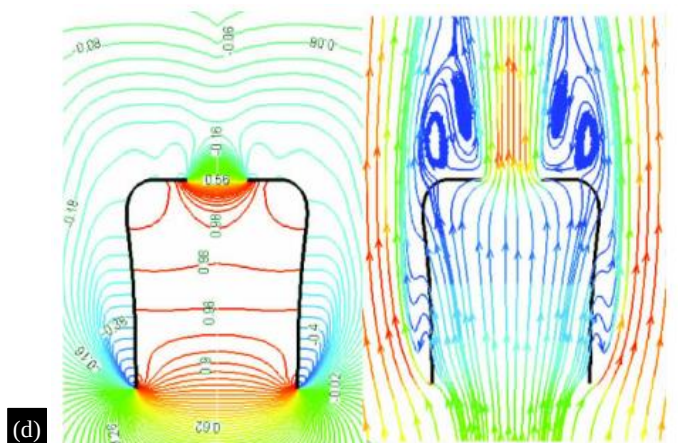
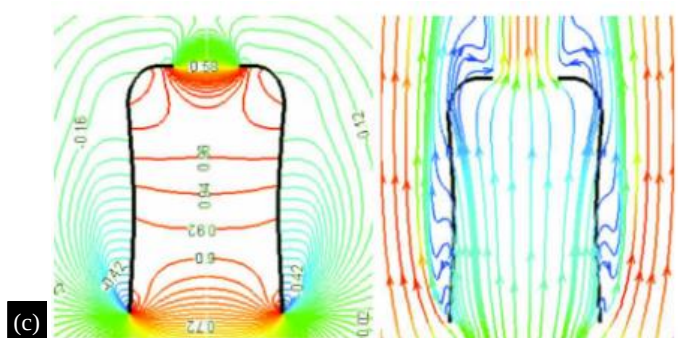
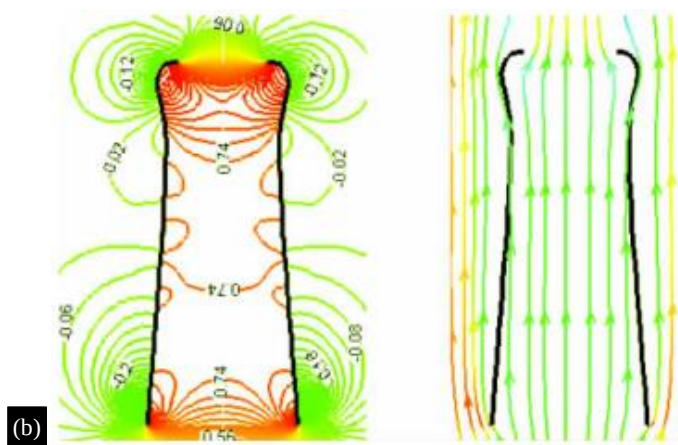
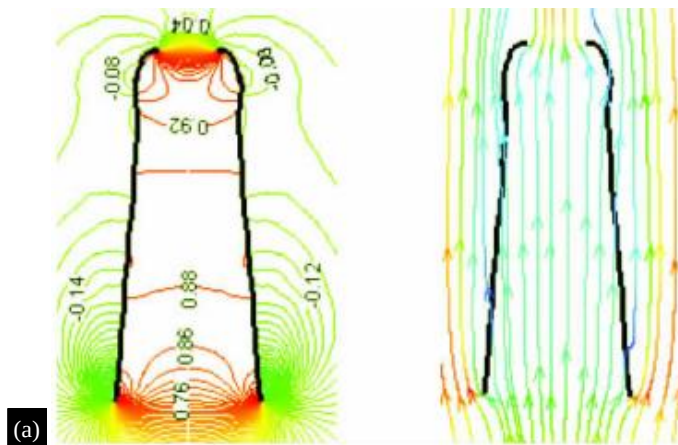


Figure 6. Parachute shape and flow field with time during the initial opening. Figure 6(a) shows the condition when air is fresh at the parachute inlet.

The pressure coefficient inside the parachute still reaches a maximum of 0.85, and the pressure coefficient outside the parachute drops to -0.15 due to the influence of the smooth parachute profile.

This shows that the effect of the ventilation of the parachute on the internal static pressure of the parachute is relatively small and the effect on the parachute outer surface is relatively large, and thus the effect on the parachute outer surface is relatively large.



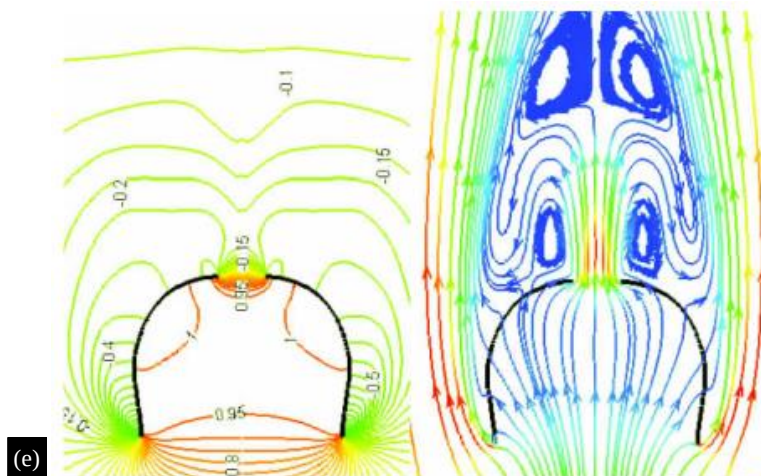


Figure 7. Simulation processes.

The situation shown in Figure 7(a) is the beginning of the air-filling phase of the main parachute, where the parachute top opening is larger and the air flow is weakened by the delay in the parachute.

Also, due to the aeration of the parachute fabric, the airflow retardation process continues from the parachute inlet to the parachute top, and the parachute internal pressure coefficient increases from 0.76 near the parachute inlet to 0.9 above the parachute top.

No obvious flow separation occurs and the flow retardation effect inside the parachute becomes more damped with a pressure coefficient of 0.74.

Different from the situation in Figure 7(a), the effect of the parachute fabric air permeability on the internal rest of the parachute is relatively weakened, as the parachute top hole area is increased, the structural ventilation rate is increased.

As shown in Figure 7(c), the parachute diameter continues to expand and exhibits a straight cylindrical shape. As can be seen from the streamlines in the figure, the streamlines near the outer surface of the parachute are torsion-induced but no vortex formation, which can be attributed to the effect of the air permeability of the parachute fabric.

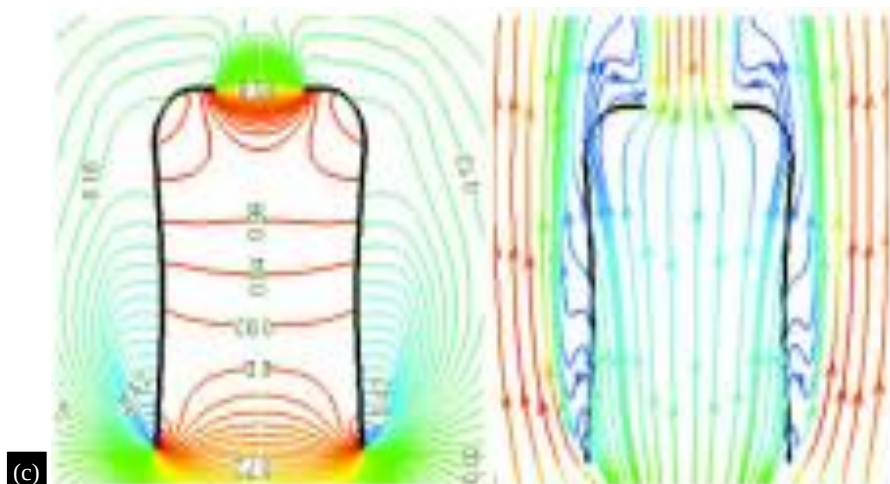
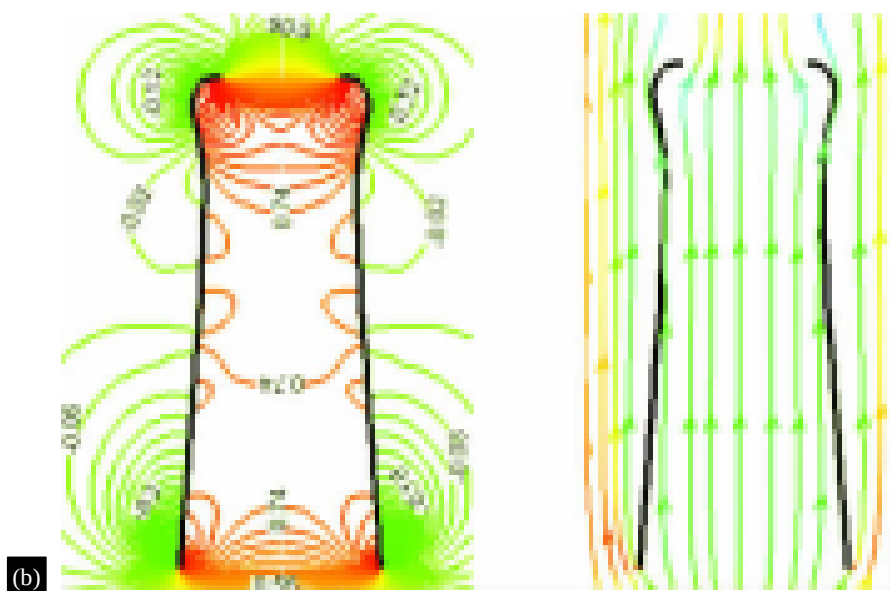
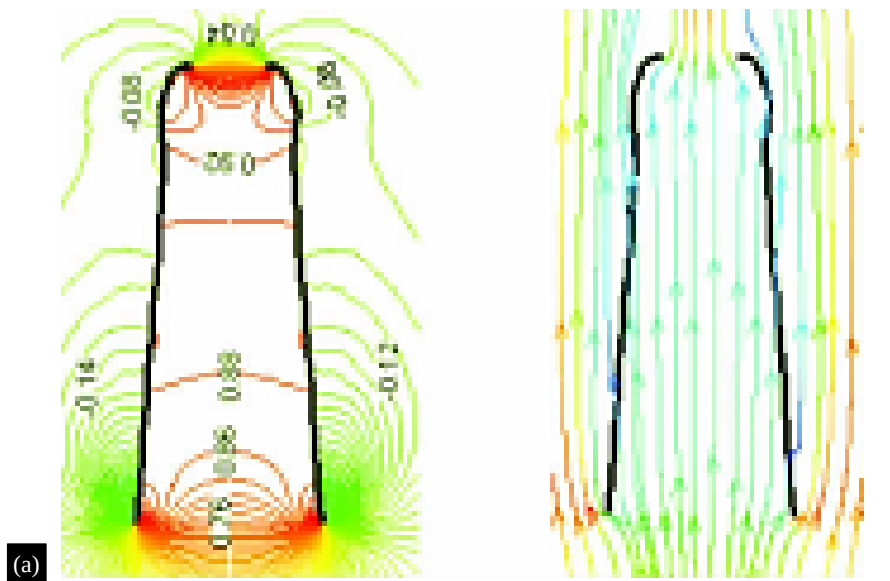
In Figure 7(e), the parachute diameter continues to broaden and the parachute tail becomes circular. The vortex region expands as the diameter of the parachute increases. From the pressure contour, the parachute tail pressure continues to increase with the increase of the vortex zone, so the ventilation rate of the parachute jacket decreases with the air flow rate entering the parachute jacket, and therefore the internal pressure of the parachute jacket rises and approaches 1.0.

Comparison of Calculations and Tests

Shown in Figure 8 is the pressure, the measured pressure unit is mm H₂O, and the flow rate of the test is 20 m/s. The maximum pressure in the parachute jacket shown in the figure is about 240 Pa (24.37 mm H₂O), and the reduced pressure coefficient is about 0.98.

The lowest pressure in the outer vortex core region of the parachute coating is -95 Pa (-9.58 mm H₂O), and the reduced pressure coefficient is about -0.4. Comparing the pressure coefficient in Figure 8(e), these two errors are not significant.

Therefore, the mathematical model used is reliable and it is possible to qualitatively analyze the flow field characteristics of the coating flow through its calculation.



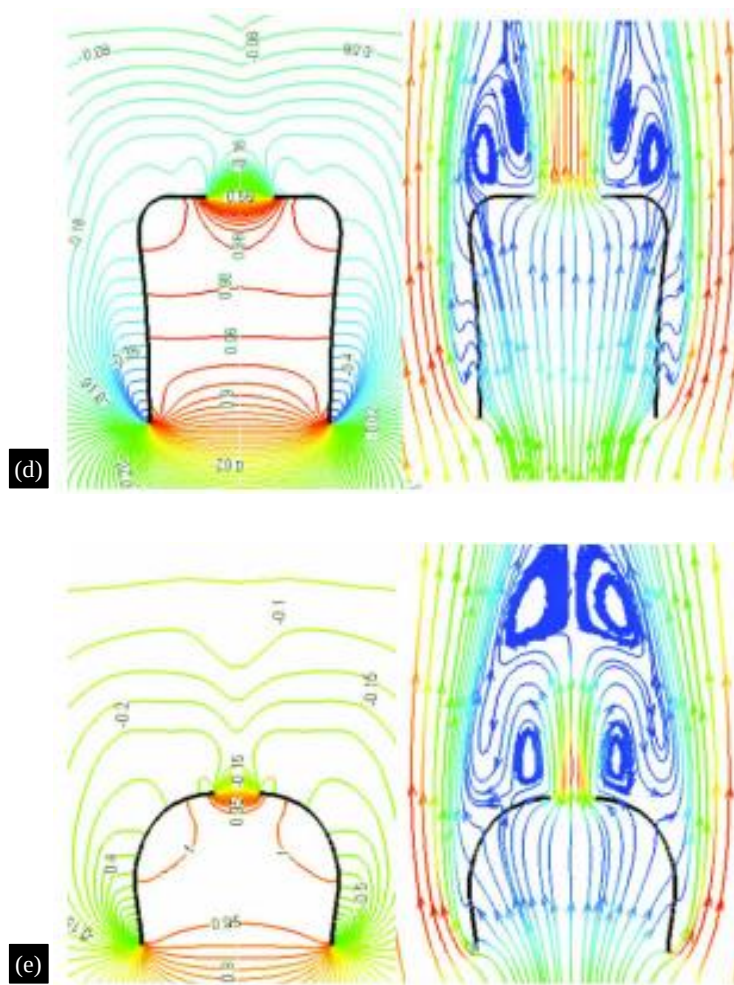


Figure 8. Time-dependent canopy morphology.

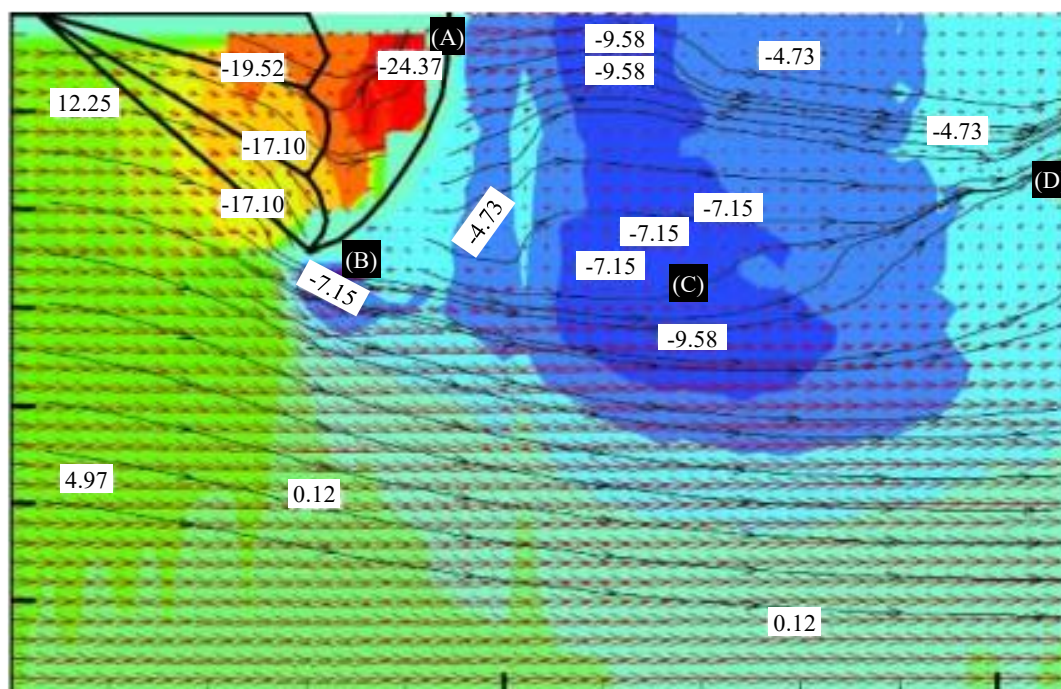


Figure 9. Wind tunnel flow field measurements.

CONCLUSIONS

This paper considers the change of the shape of the parachute during air filling of a circular parachute and the change of the internal and external flow field of the parachute.

Through the calculations, the following conclusions are drawn:

1. The change in appearance of the parachute during the initial air-filling stage is
After opening the parachute bottom, the air stream enters the parachute and under the action of the air stream, the parachute does not open from bottom to top in turn, and the parachute breathing hole opens first until the air stream is filled with the parachute top.
In the whole initial air filling stage, the parachute profile maintains a relatively smooth, straight-line shape and is not horn type.
In the main air-filling stage, the air first causes the parachute top to expand, and then the expansion section extends to the bottom of the parachute until the parachute is fully expanded.
2. For a circular parachute with upper respiratory vents, the structural air permeability of the parachute after the respiratory vent is opened by the air stream has a significant influence on the flow field.
However, from the variation of the internal pressure coefficient, the air permeability has a relatively small effect on the parachute internal pressure and a relatively large influence on the parachute external flow field, thus having a relatively large influence on the pressure of the parachute external surface.
3. After the air enters the parachute, the air separation occurs at the parachute tail, forming two opposite rotating vortices within a vortex region.
4. Comparing the calculated results, it can be seen that the topology of the calculated and experimental results is similar.

REFERENCES

1. Tezduyar T, Aliabadi S, Behr M, Johnson A, Mittal S. Parallel finite-element computation of 3D flows. *Computer*. 1993; 26 (10): 27–36.
2. Tezduyar TE, Aliabadi SK, Behr M, Mittal S. Massively parallel finite element simulation of compressible and incompressible flows. *Computer Methods Appl Mech Eng*. 1994 (1–2): 119: 157–177.
3. Mittal S, Tezduyar TE. Massively parallel finite element computation of incompressible flows involving fluid–body interactions. *Comput Methods Appl Mech Eng*. 1994; 112 (1–4): 253–282.
4. Mittal S, Tezduyar TE. Parallel finite element simulation of 3D incompressible flows—fluid–structure interactions. *Int J Numer Methods Fluids*. 1995; 21: 933–953.
5. Johnson AA, Tezduyar TE. Advanced mesh generation and update methods for 3D flow simulations. *Comput Mech*. 1999; 23: 130–143.
6. Kalro V, Tezduyar TE. A parallel 3D computational method for fluid–structure interactions in parachute systems. *Computer Methods Appl Mech Eng*. 2000; 190 (3–4): 321–332.
7. Stein K, Benney R, Kalro V, Tezduyar TE, Leonard J, Accorsi M. Parachute fluid–structure interactions: 3-D computation. *Computer Methods Appl Mech Eng*. 2000; 190 (3–4): 373–386.
8. Tezduyar T, Osawa Y. Fluid–structure interactions of a parachute crossing the far wake of an aircraft. *Computer Methods Appl Mech Eng*. 2001; 191 (6–7): 717–726.
9. Ohayon R. Reduced symmetric models for modal analysis of internal structural-acoustic and hydroelastic-sloshing systems. *Computer Methods Appl Mech Eng*. 2001; 190 (24–25): 3009–3019.
10. Tezduyar TE, Sathe S, Keedy R, Stein K. Space–time techniques for finite element computation of flows with moving boundaries and interfaces. In: Gallegos S, Herrera I, Botello S, Zarate F, Ayala G, editors. *Proceedings of the III International Congress on Numerical Methods in Engineering and Applied Science*, Monterrey, Mexico. CD-ROM; 2004.
11. van Brummelen EH, de Borst R. On the nonnormality of subiteration for a fluid–structure interaction problem. *SIAM J Sci Comput*. 2005; 27 (2): 599–621.

-
12. Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE. Influence of wall elasticity on image-based blood flow simulation. *Jpn Soc Mech Eng J Ser A*. 2004; 70: 1224–1231. In Japanese.
 13. Michler C, van Brummelen EH, de Borst R. An interface Newton–Krylov solver for fluid–structure interaction. *Int J Numer Methods Fluids*. 2005; 47: 1189–1195.
 14. Gerbeau J-F, Vidrascu M, Frey P. Fluid–structure interaction in blood flow on geometries based on medical images. *Computers Struct*. 2005; 83 (2–3): 155–165.
 15. Tezduyar TE, Sathe S, Keedy R, Stein K. Space–time finite element techniques for computation of fluid–structure interactions. *Computer Methods Appl Mech Eng*. 2006; 195 (17–18): 2002–2027.
 16. Tezduyar TE, Sathe S, Stein K. Solution techniques for the fully-discretized equations in computation of fluid–structure interactions with the space–time formulations. *Computer Methods Appl Mech Eng*. 2006; 195 (41–43): 5743–5753.