JOURNAL OF AIRCRAFT
Vol. 47, No. 4, July–August 2010

Engineering Notes

Experimental Investigations on Aerodynamic Characteristics of the ZHIYUAN-1 Airship

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DOI: 10.2514/1.C000243

I. Introduction

STRATOSPHERE airships have an enormous potential as platforms for different purposes such as monitoring, transportation, telecommunication, and so on [1–5]. For the purpose of verifying some core technologies of stratosphere airship, the remote and autonomous control fuel-cell-powered ZHIYUAN-1 airship (see Fig. 1) was manufactured at the School of Aeronautics and Astronautics of Shanghai Jiao Tong University, China, in 2009. This airship serves both as a reference configuration for theoretical investigations and as a flying test platform for studies in aerodynamic, flight mechanics and control, aeroelasticity, structural design, and fuel cell propulsion systems.

The aerodynamic characteristics of the airship are very important for the designs of control system and propulsion system. The conventional configuration layout of the airship consists of the hull, fins, and gondola. The studies of part aerodynamics and interfaces are very important for the aerodynamic configuration layout design of airship. Moreover, the availability and accuracy of aerodynamic calculation methods such as computational fluid dynamics and panel-boundary methods need verify for these airship configurations at low-speed and high Reynolds number conditions.

For these reasons, the wind-tunnel tests of scale ZHIYUAN-1 airship were performed. The dimensions of the real and scale ZHIYUAN-1 airship as the experimental model in the wind-tunnel tests are shown in Table 1.

This paper is organized as follows: The test facilities and wind-tunnel models are described in Sec. II. In Sec. III, experimental investigations on scale ZHIYUAN-1 airship are presented. In final section, we draw some conclusions on aerodynamic characteristics of general layout airship configurations.

Received 12 January 2010; revision received 27 March 2010; accepted for publication 27 March 2010.

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II. Test Facilities and Wind-Tunnel Models

A. Φ3.2 m Wind Tunnel

The experiment was performed at the Φ3.2 m wind tunnel at low-speed research institute of China Aerodynamics Research & Development Center. The Φ3.2 m wind tunnel is a single-return continuous-flow tunnel with a dual closed/open test section. The wind tunnel consists of the tunnel body; power supply system; measuring, control and processing system; and model support system. The specifications of the Φ3.2 m wind tunnel are as follows: Test section dimensions are Φ3.2 m × 5 m, maximum air speed in the test section is 115 m/s (with open test section) and 145 m/s (with closed test section), maximum test Reynolds number is 2.7×10^6, and the turbulence level is $\leq 0.2\%$.

B. Model Support System

The model support system in this experiment is a wire and stern support system. This system (see Fig. 2) consists of wires frame, support frame, cross beam, abutment, stern bar, and so on. The stiffness of the stern support bar is increased by steel string for the purpose of vibration resistance. The diameter of the stern support bar is 70 mm; the diameter of the steel string is 4 mm.

C. Experiment Method and Condition

The integral forces and moments were measured using the general force measure method. The model is supported by wire and stern frame. The forces and moments were obtained through a six-component strain balance. The angle of attack and sideslip angle were obtained using the sensor of angle of attack and sideslip angle.

The scale of the model used in Φ3.2 m wind tunnel is 1:13.7, leading to a model length of $L = 1.8286$ m. The onset flow velocity is 60.39 m/s and volume Reynolds number of $Re_v = 2.58 \times 10^6$. The turbulence level is 0.1%, and the temperature is 25°C. The angle of attack and sideslip angle were measured based on the lateral and longitudinal symmetry planes, respectively. The range of angle of attack is −30–30°; the range of sideslip angle is −25–25°.

D. Experimental Model

The layout of the experimental airship model is classical. It has a gondola and four mutually perpendicular rear fin surfaces, each incorporating an aerodynamic-flap-type control surface. The geometry parameters are shown in Table 1. The airship's geometry configuration is defined as follows.

Fig. 1 Remote and autonomous control fuel-cell-powered ZHIYUAN-1 airship.

Table 1 Dimensions of the ZHIYUAN-1 airship

	Real airship	Scale model
Length, m	25.0	1.8286
Maximum diameter, m	7.576	0.5543
Fineness ratio of the hull	3.3	3.3
Volume of the hull, m^3	750.0	0.2935
Surface area, m^2	480.388	2.5701
Location of maximum diameter, m	9.840	0.7197
Moment center, m	12.001	0.8778
Reference area, m^2	82.544	0.4416
Reference length, m	25.0	1.8286
Volume Reynolds number[a]	$1.8–9.3 \times 10^6$	2.58×10^6

[a]Volume Reynolds number was adopted with a cubic root of the volume as the characteristic length.

Table 2 Geometry parameters of the fins

Parameters	Values, m
Root chord $b0$	0.1617
Tip chord $b1$	0.0936
Semispan h	0.1504
Leading edge sweep angle	40 deg
Coordinates of fins based on hull nose	
A	(1.5618, 0.1748)
B	(1.6655, 0.1368)
C	(1.7233, 0.1368)
D	(1.7496, 0.2872)
E	(1.7174, 0.2872)
F	(1.6560, 0.2872)

1. Hull Configuration

The contour of the hull configuration of experimental model is shown in Fig. 3. The X is the coordinate in the axial direction; the R is the coordinate in the radial direction.

2. Fin and Control Surface Configuration

The + layout of the fins is used for this airship model. The airfoil of the fins is NACA0010. The parameters of the fins are shown in Table 2 and Fig. 4.

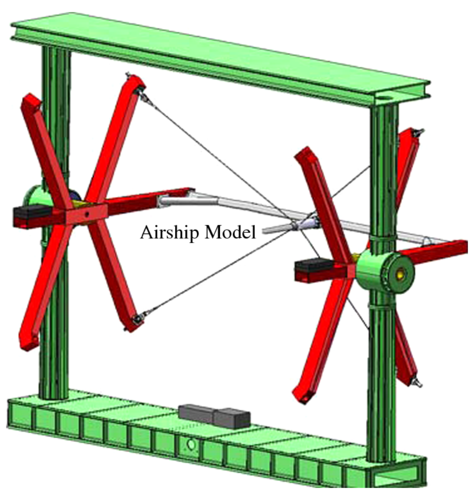


Fig. 2 Sketch map of experimental support system and model position.

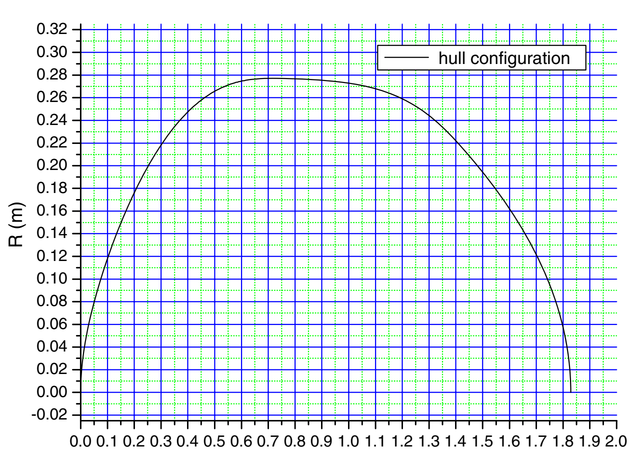


Fig. 3 Hull configuration of the experimental model.

3. Gondola Configuration

The experiment model uses an outside hanging gondola. The configuration and geometry parameters of the gondola are shown in Fig. 5.

4. Fabrication of Experimental Model

For the experiment of free transition and forced transition, the model was fixed with strips in the head, middle, and tail location (see Fig. 6). The hull is made of glass-fiber-reinforced plastic. The metal frame and circle bar structure are used to increase the stiffness of model. The fins are made of metal plane and pine wood. The metal rudders are connected with the fins through angle parts. The rudder angle is changed through different angle parts. The gondola is manufactured by pine wood.

III. Experimental Investigations on ZHIYUAN-1 Airship

A. Hull Aerodynamics

Figures 7–9 show the drag coefficients, lift coefficients, and pitching moment coefficients of the hull against angle of attack measured in the Φ3.2 m wind tunnel under the condition of free transition and forced transition. All three coefficients are related to the hull, i.e., reference area is the volume powered by two-thirds and reference length is the length of the model hull. The center of volume of the hull was chosen as reference point for the pitching moment. The values of these parameters are shown in Table 1.

From the experimental results shown in Fig. 7, The drag coefficient of the hull at zero angle of attack is 0.00692 under free transition, while the drag coefficient becomes 0.0146 with forced transition. The drag increases once because of the change of flow characteristics. The reason is that the friction drag is the major part of the drag of the airship hull, which is about 90% of the total drag. The laminar friction drag is smaller than that of turbulence. The strips make the flow characteristics change from the laminar to turbulence and thereby increase the drag.

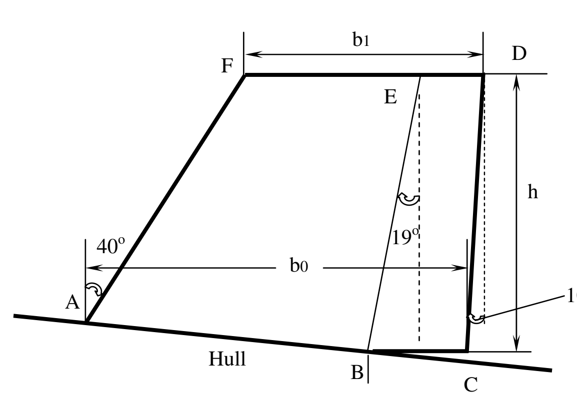
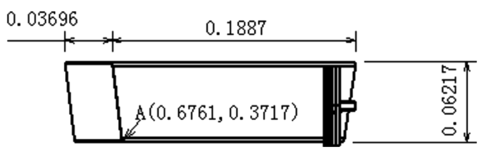
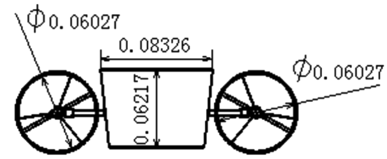


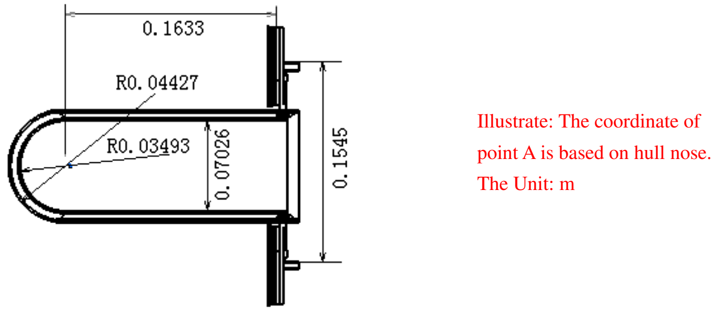
Fig. 4 Fin configuration of the experimental model.



a) Side view



b) Front view



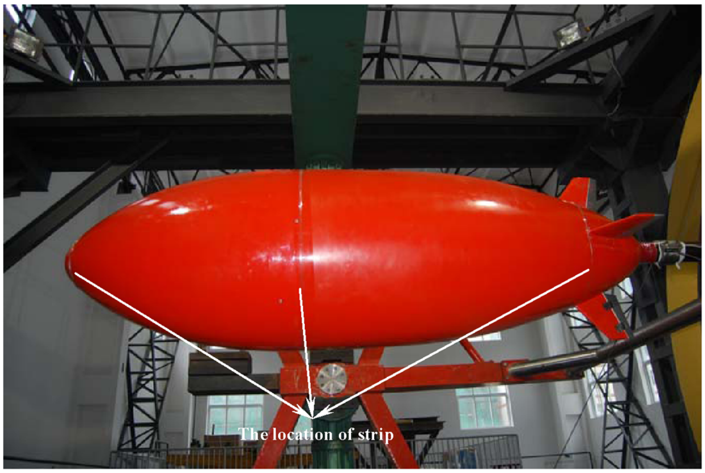
c)Top view

Fig. 5 Three-view drawing of the gondola: a) side view, b) front view, and c) top view.

a) Hull model

b) Hull-fins model

c) No strip airship model



d) Fixed strip airship model

Fig. 6 Model of the ZHIYUAN-1 airship: a) hull model, b) hull-fin model, c) no-strip airship model, and d) fixed-strip airship model.

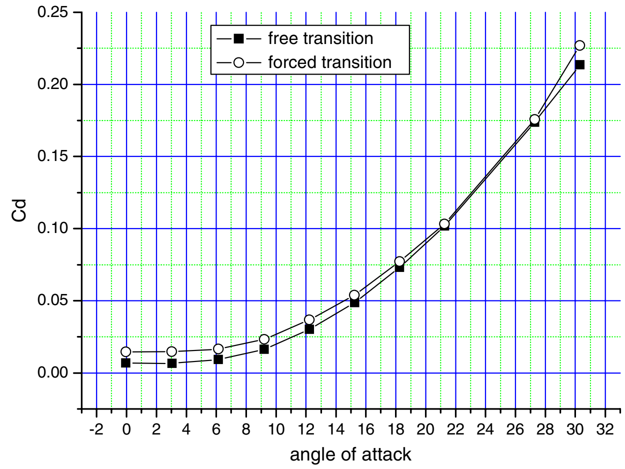


Fig. 7 Comparison of drag coefficients C_d between the free transition and forced transition of the hull of the ZHIYUAN-1 airship.

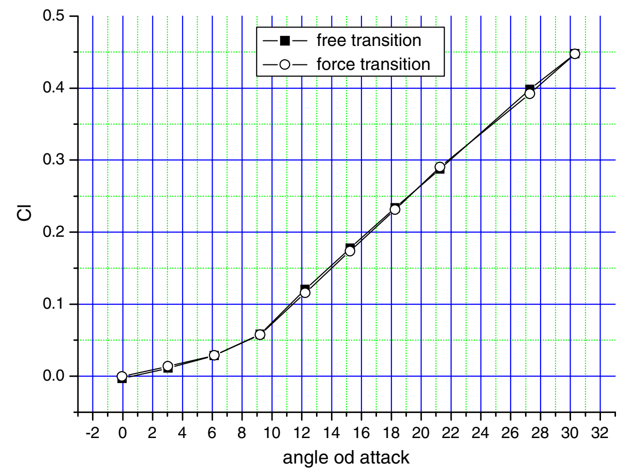


Fig. 8 Comparison of lift coefficients C_l between the free transition and forced transition of the hull of the ZHIYUAN-1 airship.

As the experimental results shown in Figs. 8 and 9, The lift coefficients and pitching moment coefficients are almost the same under free transition and forced transition, the reason is that the lift and pitching moment are produced by the pressure distributions on the hull, the transition has little effect on the pressure distributions on the hull of airship.

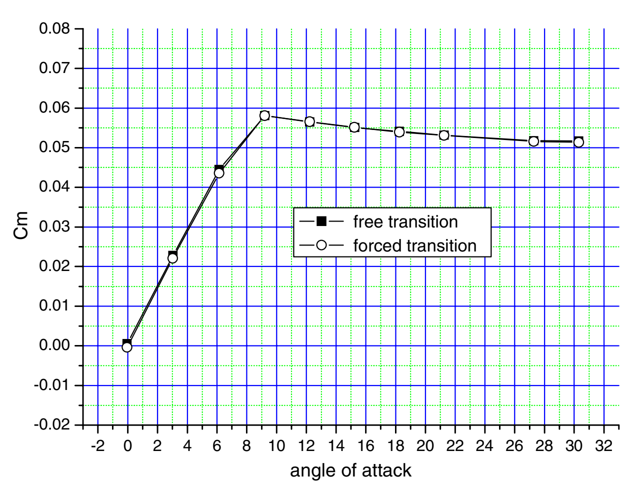


Fig. 9 Comparison of pitching moment coefficients C_m between the free transition and forced transition of the hull of the ZHIYUAN-1 airship.

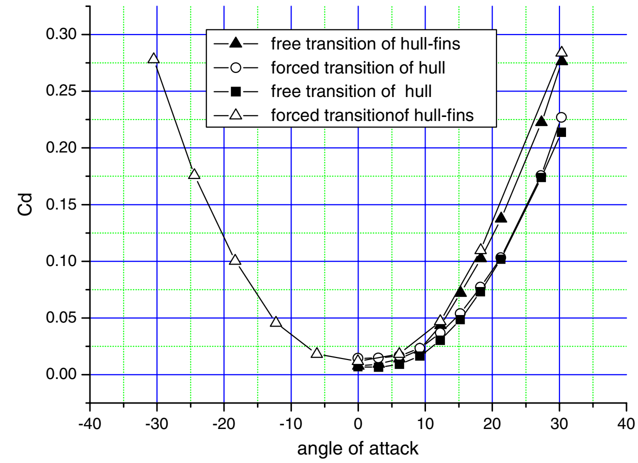


Fig. 10 Comparison of C_d between the free transition and forced transition of the hull fins of the ZHIYUAN-1 airship.

B. Hull Fin Aerodynamics

Figures 10–12 show the drag coefficients, lift coefficients, and pitching moment coefficients of the hull fins against angle of attack measured in the Φ3.2 m wind tunnel under the condition of free transition and forced transition.

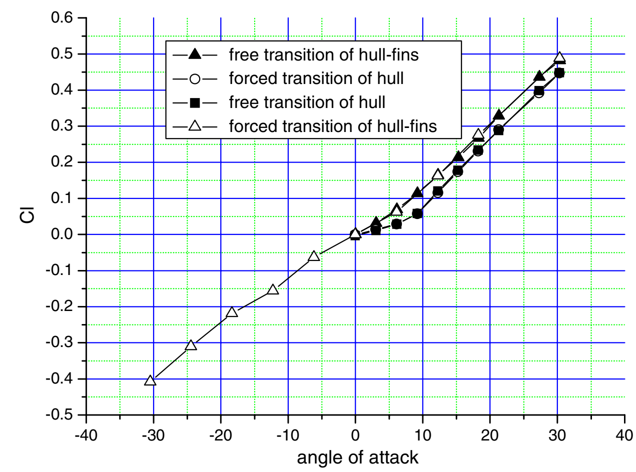


Fig. 11 Comparison of C_l between the free transition and forced transition of the hull fins of the ZHIYUAN-1 airship.

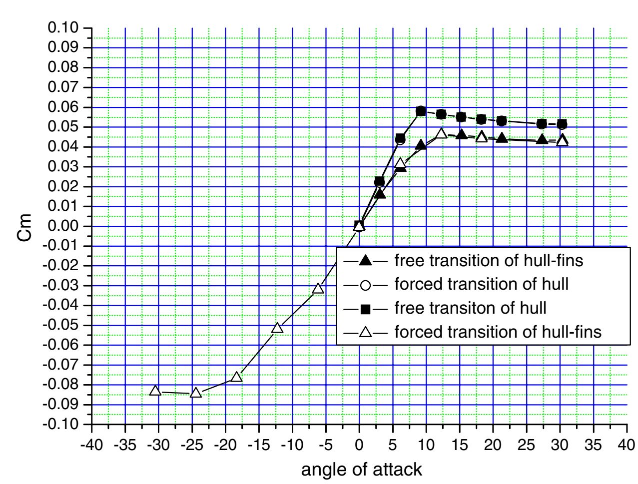


Fig. 12 Comparison of C_m between the free transition and forced transition of the hull fins of the ZHIYUAN-1 airship.

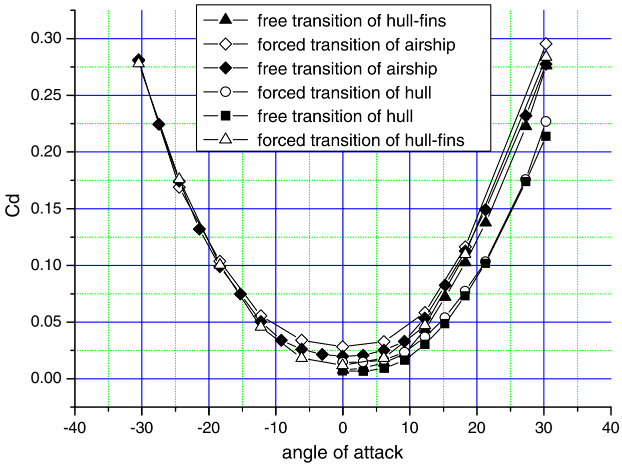


Fig. 13 Comparison of C_d between the free transition and forced transition of the hull fins and gondola of the ZHIYUAN-1 airship.

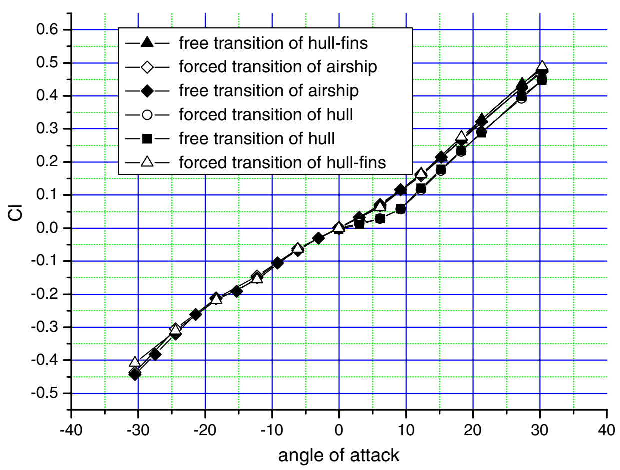


Fig. 14 Comparison of C_l between the free transition and forced transition of the hull fins and gondola of the ZHIYUAN-1 airship.

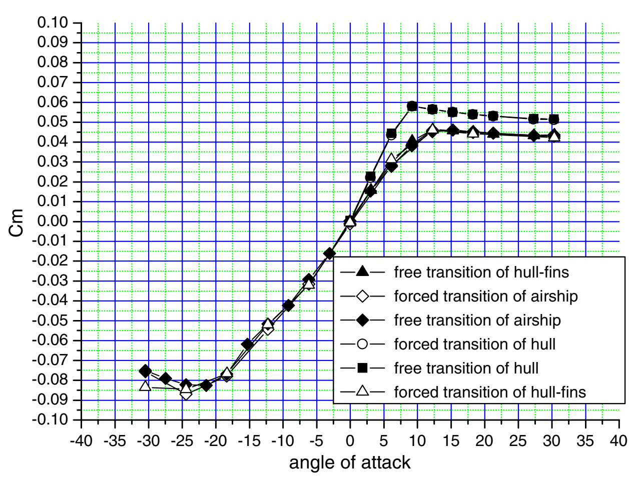


Fig. 15 Comparison of C_m between the free transition and forced transition of the hull fins and gondola of the ZHIYUAN-1 airship.

Table 3 Drag coefficient at zero angle of attack of the airship with different configurations

Model	*Cd*0 (free transition)	*Cd*0 (forced transition)	Percent
Hull	0.00692	0.0146	110.9
Hull fins	0.00785	0.01646	109.7
Hull fins and gondola	0.01983	0.02829	42.6

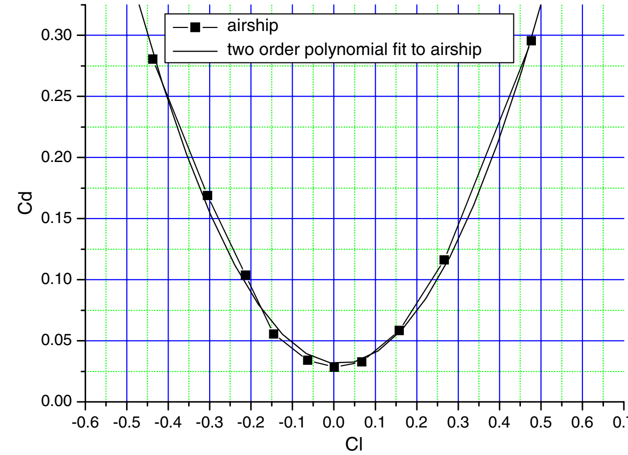


Fig. 16 Lift–drag curves of the ZHIYUAN-1 airship.

The drag coefficient of the hull fins at zero angle of attack is 0.00785, which is about 13.4% (0.00093) higher than the drag coefficient of the hull alone under the condition of free transition, and the drag coefficient of the hull fins at zero angle of attack is 0.01646, which increases by about 12.7% (0.00186) compared with the drag coefficient of the hull alone under the condition of forced transition.

Form the results shown in Figs. 11 and 12, the fins increase the lift and therefore increase the static stability pitching moment in the same angle of attack.

C. Airship with Hull Fins and Gondola Aerodynamics

Figures 13–15 show the drag coefficients, lift coefficients, and pitching moment coefficients of the airship against angle of attack measured in the Φ3.2 m wind tunnel under the condition of free transition and forced transition.

Under the condition of free transition, the drag coefficient of the airship at zero angle of attack is 0.01983, which increases by about 186.5% (0.01291) compared with the drag coefficient of the hull alone under the condition of free transition. Under the condition of forced transition, the drag coefficient of the airship at zero angle of attack is 0.02829, which increases by about 93.76% (0.01369) compared with the drag coefficient of the hull alone. The comparison of drag coefficient with different layouts is shown in Table 3 under free and forced transition conditions.

It can be seen from the results in Figs. 14 and 15 that the gondola hardly contributes to the lift and static stability pitching moment at the same angle of attack.

The lift–drag polar curve in Fig. 16 is almost a parabolic shape. This is due to the combination quasi-constant friction drag and a quadratic increase of the induced drag with lift [6–8].

IV. Conclusions

Extensive wind-tunnel tests were performed for the ZHIYUAN-1 airship configuration. Through the analysis of experimental results of different layouts and flow conditions, we can obtain the following conclusions:

1) The drag almost doubled because of the change of flow condition from laminar to turbulence. Maintaining the laminar flow or delaying the transition location is very important for the reduction of drag of the airship configuration. The transition almost does not affect the pressure distributions on the hull of airship.

2) The external gondola hardly contributes to increment the lift and static stability pitching moment but can increase the drag very largely. If possible, the gondola should be installed on the inside of the airship.

3) The airship lift–drag curves are consistent with the parabola law: $C_d = C_{d0} + k \cdot C_l^2$.

4) Whether laminar flow can be realized in practice depends on a multitude of different factors such as freestream disturbances and surface roughness (nose-mooring apparatus seams, load patches,

etc.). Therefore, the forced transition data on both hull and fins are very useful. The free-transition data can be used to verify the accuracy of computational fluid dynamics methods.

Acknowledgments

The presented work was carried out within the scope of the ZHIYUAN-1 airship research group at the School of Aeronautics and Astronautics of Shanghai Jiao Tong University. The authors would like to thank all members of the airship research group. The authors gratefully acknowledge the members of the Low Speed Research Institute of the China Aerodynamics Research and Development Center (CARDC).

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