文章编号：2097-1974(2025)05-0031-08 DOI：10.7654/j.issn.2097-1974.20250502

吸气式高超声速飞行器气动布局研究

杜志博[1,2,3]，刘明坤[4]，张中洲[2,3]，刘凯鹏[1]，李天龙[1]
(1. 哈尔滨工业大学机器人技术与系统国家重点实验室，哈尔滨，150001；
2. 北京亦庄星箭科技产业发展有限公司，北京，100176；
3. 北京亦庄可重复使用火箭技术创新中心有限公司，北京，100176；4. 中国人民解放军77611部队，拉萨，850000)

摘要：气动布局作为高超声速飞行器的重要支撑技术，是设计良好飞行性能指标、实现良好飞行品质的关键，也是其他各专业的重要基石。吸气式高超声速飞行器作为现代高超声速飞行器重要的研究领域，是实现可持续高超声速飞行的重要途径之一。通过对典型吸气式高超声速飞行器气动布局的梳理，分析气动布局的设计理念，从组合循环动力出发，着重分析动力和布局的关系，从而为气动布局工作提供设计参考。

关键词：高超声速；飞行器；吸气式；气动布局；组合动力
中图分类号：V411 **文献标识码**：A

Research on Aerodynamic Configuration of Hypersonic Air-breathing Vehicles

DU Zhibo[1,2,3], LIU Mingkun[4], ZHANG Zhongzhou[2,3], LIU Kaipeng[1], LI Tianlong[1]
(1. State Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin, 150001;
2. Beijing E-town Commercial Aerospace Technology Development Co., Ltd., Beijing, 100176;
3. Beijing E-town Reusable Rocket Technology Innvation Center Co., Ltd., Beijing, 100176;
4. PLA Rocket Force Unit 77611, Lhasa, 850000)

Abstract: Aerodynamic configuration design is an important technology for hypersonic vehicles. Combined with other relative specialties, it is the key to obtain good flight performance and ensure essential flight quality. As a fundamental research area of modern hypersonic vehicles, air-breathing vehicle has become an indispensable way to realize the sustainable hypersonic flight. The typical hypersonic air-breathing vehicles are focused on and the design concept of configurations is investigated. Proposed from the perspective of combined-cycle propulsion systems, the relationship between propulsion systems and aerodynamic configuration is studied which provides a reference for the aerodynamic configuration design work.

Keywords: hypersonic; aircraft; air-breathing; aerodynamic configuration; combined-cycle propulsion systems

0 Preface

The term "Hypersonic" was firstly presented in a thesis by the Chinese famous scientist Hsue-Shen Tsien in 1946[1]. A hypersonic flow generally refers to a flow-field speed of Mach 5 or greater，which can be achieved by rockets，air-breathing or re-entry vehicles from the orbit. During the development of hypersonic theory，hypersonic flight has been accomplished by launching ballistic missiles and satellites in the early stage：the X-15 realized the first hypersonic flight with a rocket；the X-20 proved the single-stage entry into orbit could be implemented through a rocket；the X-30 adopted the hypersonic flight capability of taking-off and landing with an air-breathing propulsion system；ASALM and X-43A have accomplished hypersonic flight with ramjet and scramjet engines respectively[2].

In general，hypersonic technology can be divided into two categories according to propulsion systems：rocket-based engine and air-breathing-based engine. Currently，the majority of rocket-based vehicles on service are non-recycle. Compared with the conventional rockets，air-breathing engines make full use of air during

收稿日期：2025-09-15；修回日期：2025-09-19

combustion, which greatly reduce the necessity of massive oxidant. Hence hypersonic air-breathing technology has become one of the most crucial ways to achieve sustainable hypersonic flight. Many countries carried out pre-researches on hypersonic air-breathing vehicles in recent years. The essential motivation is that it can be applied to the strategic goal of the world transportation system and hypersonic speed intercontinental arrival.

As a "preliminary officer" of the hypersonic aircraft conceptual design, the general idea of aerodynamic configuration design is to reduce the aerodynamic drag force as much as possible and improve the flight performance of the aircraft. According to statistics, for a DC-10-sized aircraft, a 1% increase in lift-to-drag ratio would save \$100 000 in annual fuel costs[3]. Meanwhile, increasing the lift-to-drag ratio would also result in a growth in flight range. Aerodynamic configuration design also plays a key role in the aircraft control system and the structure design as well[4].

Therefore, the aerodynamic configuration design can be considered as the "soul" of the aircraft conceptual design. With the development of various types of aircrafts and design technologies, people are continuously searching for better aerodynamic design methods to obtain higher performance. This paper introduces the typical aerodynamic configuration design of the hypersonic air-breathing vehicles and analyzes the key technologies involved. Based on the theory introduced above, the design experience of the configuration design is summarized and future research and development works are discussed.

1 Aerodynamic Configuration of Air-breathing Hypersonic Vehicles

Throughout the world, there is no unified aerodynamic design method for hypersonic vehicles. The aerodynamic shape are generally attributed to four major categories: axisymmetric body (e. g. GTX (Fig. 1), Fast Hawk, HSSW hypersonic missiles, etc.), wing body (e. g. 34, X-37, HOPE-X, etc.), lifting body (e. g. X-33, X-38, etc.) and wave rider (e. g. X-43, X-51A, etc.) configuration.

Combined with the typical hypersonic air-breathing vehicles, the characteristics of each configuration layout are evaluated below.

1.1 Axi-symmetric Configuration

The axi-symmetric configuration is a commonly used aerodynamic shape, such as the GTX, the Fast Hawk and the HSSW hypersonic missile.

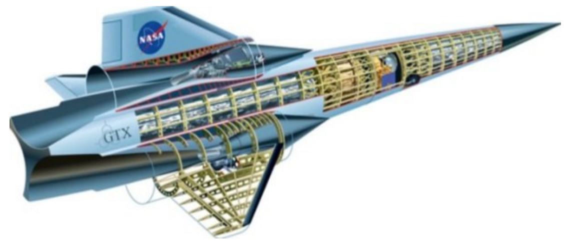

Fig.1 NASA GTX reference vehicle

The main part of this configuration is the slender body. It usually has a large slenderness ratio with small stabilizers and a sharp-pointed nose, and in most cases it is a tailless configuration. In terms of design philosophy, the forebody provides a precompression surface for the inlet, and multiple engines can be arranged on the aft-body easily. The configuration layout is appropriate for the integration design of airframes and propulsion systems. Currently, the relevant technology of the configuration tends to be mature and the manufacture is sample. However, the lift coefficient of the configuration is low during hypersonic flight. The vehicle is hard to achieve horizontal taking-off and landing due to inadequate lift near the ground caused by its axi-symmetric structure.

1.2 Wing Body Configuration

The wing body configuration is similar to a normal airplane (Figure 2). The fuselage and wings are apparently distinguished from each other. It is mainly applied to single-stage or two-stage space vehicles with horizontal or vertical taking-off and horizontal landing functions.

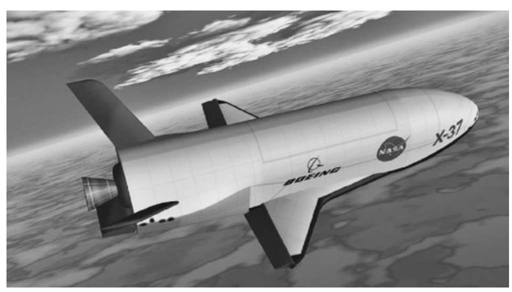

Fig.2 X-37

With respect to design philosophy，like a normal airplane，the fuselage section is round or nearly circular. The wings are installed in the middle of the fuselage. They provide most of the lift at low flight speed. During hypersonic flight，the lift is mainly generated by wings and fuselage. Such a combined configuration layout has clear design thoughts，easy manufacturing process，mature maneuverability and thermal protection technology，hence the design progress tends to be short，which helps to obtain reliable experimental results and conduct further optimizations.

For the aerodynamic characteristics，the wing body configuration has less aerodynamic drag，more favorable lift characteristics and higher lift-to-drag ratio compared with other configurations. The position of the pressure center is not largely affected by the Mach number；the internal volume is larger than that of the waverider. Subsequently，it has good maneuverability and flight stability. However，the pre-compression to air flow is relatively inefficient，and there are complex disturbances in the flow field around wing and inlets. The engine/body integration design still encounters many obstacles till now.

Aircrafts such as the X-34，X-37 and the HOPE-X have adopted this aerodynamic configuration.

1.3 Lifting Body Configuration

Compared to conventional aircrafts， the lifting body configuration is a completely new concept. The configuration has stronger maneuverability and higher lift-to-drag ratio characteristics at lower flight speeds. For hypersonic flights，the heat flux is lower which reduces the demand for thermal protection. It has become a candidate configuration of the Reusable Launch Vehicle （RLV）in the United States. The X-38（Figure 3）and X-33（Figure 4）[5-6] are typical representatives of the lifting body.

Generally，the lifting body refers to a vehicle profile with a lift-to-drag ratio larger than 1.2. The internal volume utilization ratio of the lifting body configuration is higher compared with others. Flying at high angles of attack and hypersonic speed，the design concepts of the lifting body commendably balance the contradiction between aerodynamic heating and large lift-to-drag ratio.

Unlike the conventional aircraft layout using wings to produce lift，the 3D-designed fuselage of lifting body configuration generates the majority of lift through flights，and the tail serves as an aerodynamic control surface. This concept avoids the additional aerodynamic drag force and coupling interference between the traditional aircraft body and wings. Hence the lifting body obtains a higher lift-to-drag ratio at a low flight speed.

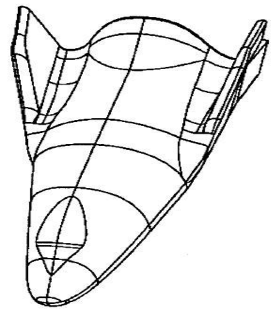

Fig.3 X-38

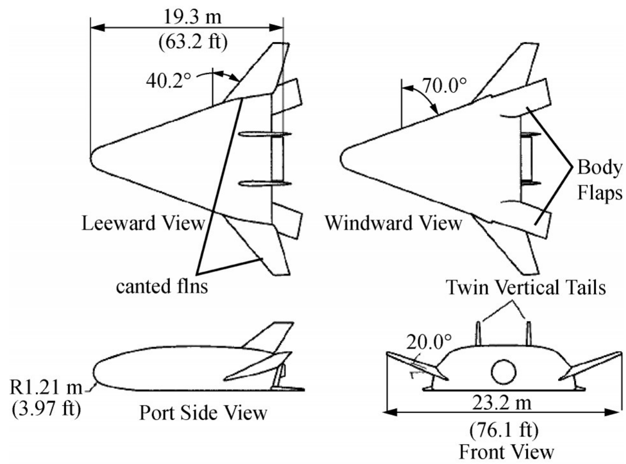

Fig.4 X-33 drawings and dimensions

Concerning with the axi-symmetric and the wing-body configuration，the design methods and manufacture processes of the lifting body are more complex. For instance，the hypersonic lifting body configuration usually adopts air-breathing engine in which is hard for three-dimensional design，hence the engine's performance require improvements through further optimization design.

1.4 Waverider Configuration

The waverider concept was firstly proposed by Prof. Nonweiler of the United Kingdom in 1959 [2]. The original intention was to solve the aerodynamic characteristics loss caused by airflow leakage from the lower surface to the upwind side. Usually，for a waverider，the shock wave attaches on the leading and side edges. The high pressure flow could hardly leak to the upper surface from the lower surface, which maintains the pressure on the lower surface and greatly enhance the lift force. The shape is designed along the flow path with almost no lateral components, which guarantees the uniformity of the airflow at the cross section of the engine inlet and allows researchers to derive the body outlines from the known flow field [7-8] (Figure 5).

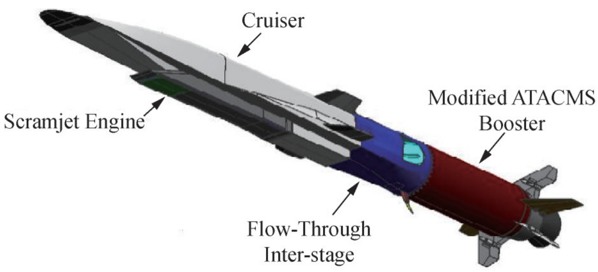

Fig.5 X-51A [9]

The waverider [10] has the highest aerodynamic efficiency compared with other configurations, but the design process is challenging: the aerodynamic efficiency decays quickly under states off design points; the flat fuselage reduces the availability of the internal space, and the coordination of longitudinal and lateral stability control is hard. In particular, the waverider is less likely to satisfy the loading requirement for the aircraft. Although the challenges still exist, in aspect to the flow characteristics and the high lift-to-drag ratio design conception, the waverider configuration can provide worthy references for the lifting and the wing body design.

1.5 Comparison of Aerodynamic Configurations of Several Hypersonic Air-breathing Vehicles

Table 1 shows the comparison of different aerodynamic configurations.

Tab.1 Comparison of aerodynamic configurations of various hypersonic vehicles

Configurations	Advantages	Disadvantages	Applications
Axi-symmetric body	Small resistance, high lift-to-drag ratio; Good maneuverability; Simple structure, light weight; Economical, widely used in various types of missiles	Low lift coefficient at high Mach numbers; Hard to takeoff horizontally	GTX Fast Hawk; HSSW; hypersonic; missile
Wing-body	Low drag, high lift-to-drag ratio; Lightweight structure and large internal volume; Good flight stability	Complex shape; Hard to design excellent aerodynamic performance	X-37A; X-34; HOPE-X
Lifting body	Strong maneuverability, high lift-to-drag ratio without wings; Low heat flow rate at hypersonic speeds; Higher internal volume utilization; Good aerodynamic characteristics at high angles of attack and hypersonic speed	Complex shape, hard to design and manufacture; Poor economy	X-33; X-38; X-43A; HTV-2
Waverider	High lift, low drag, high lift-to-drag ratio, good maneuverability at high Mach numbers; More suitable for jet engines or ramjets	Small internal volume; hard to prevent heat; Hard to coordinate flexibility and stability	X-51A; X-43A; HTV-2

2 Hypersonic Air-breathing Vehicles Propulsion and Configurations

Currently, the integrated design for configurations and propulsion systems is a perspective research direction in hypersonic vehicle design area. At hypersonic speeds, the most significant feature of air-breathing vehicles is the coupling between subsystems is closer than others. Hence it is necessary to combine the engine and the airframe to avoid adverse interference and achieve design purpose.

2.1 Combined-cycle Propulsion Systems

In order to achieve air-breathing hypersonic flight, the priority is to select the appropriate propulsion systems. The velocity range of hypersonic aircrafts is Ma 0~25, and the flight altitudes vary from atmosphere to space. Currently, there is no single-type engine that can work in such a widely changed conditions.

The combined-cycle propulsion system, which combines two or more types of engines through thermal cycle and structure layout (turbojet, ramjet, rocket, etc.), is a new multiple motivation model, and it can break through the limitations of single motivation. The system fully develops the technical advantages of different powers within respective proper working scopes，expanding the flight envelope of both velocity and airspace. Hence it is capable of maneuvering two-stage to orbit flight. In the future，it is possible to achieve reusable single or two-stage to orbit.

At present，the combined-cycle propulsion system mainly consists of three types of power：Rocket Based Combined-Cycle（RBCC），Turbine Based Combined-Cycle（TBCC）and Pre-cooled Combined Cycle.

2.1.1 Rocket Based Combined-Cycle (RBCC)

As an advanced propulsion system，RBCC can use oxygen in the atmosphere to accomplish autonomous taking-off and landing. RBCC achieves the advantages of two individual prolusion systems by combining high thrust to weight ratio and low specific impulse rockets with low thrust to weight ratio and high specific impulse ramjet engines.

According to the range of Mach number，the RBCC propulsion system has four primary operating modes：rocket-ejector（*Ma* 0~3），ramjet mode（*Ma* 3~6），scramjet（*Ma* 6~15）and rocket-only mode（*Ma*>15）.

The main advantages of RBCC are：a）compact structure，small volume and light mass；b）high reliability，simple maintains，easy to achieve repeatable operation；c）high specific impulse，high thrust to weight ratio.

The X-34 is a typical representative of the wing-body configuration. It is one of exemplifications for flight vehicles and operation technologies for future low-cost reusable launch vehicles（RLVs）with capabilities of autonomous ascent，reentry and landing. The vehicle is equipped with double strake wings with large sweep angle. The dihedral angle 6° is chosen in order to rolling control. Pitching control is accomplished by symmetrical ailerons of deflection，while nonsymmetrical ailerons of deflection lead to rolling control. Another component providing pitching control is the body flaps，which is installed under the engine nozzle at the rear fuselage. The X-34 adopts a rectangular inlet for propulsion systems. The configuration used in Figure 6 can provide the beneficial condition of thrust，reducing interference between engines and vehicle body[11].

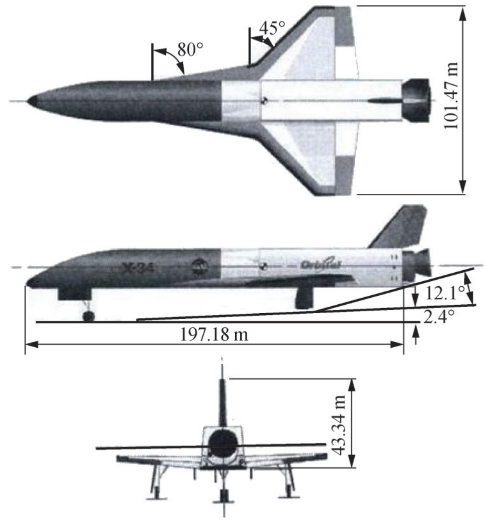

Fig.6 X-34

2.1.2 Turbine Based Combined-Cycle (TBCC)

The Turbine Based Combined-Cycle（TBCC）engine is one of the most appropriate power systems for future hypersonic vehicles. Hypersonic vehicles equipped with such engines have the maneuvering and reusable capabilities with horizontal taking-off and landing.

The SR-72 hypersonic unmanned reconnaissance aircraft（Figure 7）is a typical representative of TBCC system vehicles，and it was presented on November 1，2013. As an inherited model of the SR-71[12]，their size and flight range are similar，but the flight speed is twice that of the SR-71. This is a hypersonic reconnaissance plane combines intelligence，searching，surveillance and combat capabilities.


Fig.7 Lockheed Martin SR-72 rendering

SR-72 adopts the wing-body configuration. In order to achieve resistance reduction and heat protection，a large slenderness ratio fuselage and sweep trapezoidal wings are used. An underfuselage inlet provides high lift-to-drag radio. The TBCC engine is installed under the vehicle at the connection position between the wings and the fuselage. Two-dimensional external compression inlets are used to pre-compress the incoming flow to increase the flow flux at high angle of attack.

2.1.3 Pre-cooled Combined Cycle

In the 1950s, the concept of pre-cooled combined cycle engine was proposed. After decades of development and demonstration, the system program has been rapidly improved and optimized, and key technologies have also been demonstrated. The pre-cooled combined cycle power adopts the air pre-cooling technology, which broadens the working Mach number range of the air-breathing hypersonic vehicles and achieves high specific impulse performance. According to the development of technologies such as engines and materials, the reusable first-stage aircraft is expected to be achievable. In the future, it can be used as main engines of a single-stage orbiting vehicles.

The SKYLON (Figure 8) adopts the wing-body configuration. The design features a large cylindrical payload. The SKYLON uses a large slenderness fuselage (including a propellant tank and payload bay) and a pair of delta wings placed in the middle of the fuselage. The low-aspect-ratio delta wings dramatically reduce drag during supersonic flight. Besides, a large vertical tail is used to ensure lateral aerodynamic characteristics. In order to balance the moment generated by the vertical tail, a dihedral angle design is accepted to ensure the lateral stability of the vehicle. The double-sided SABRE engines are placed in arc-shaped axi-symmetric engine compartments on the tip, which act as winglets to reduce the induced drag. Another benefit of such engine arrangement is that the engines are far away from the fuselage and exhaust is less likely to affect the tail.

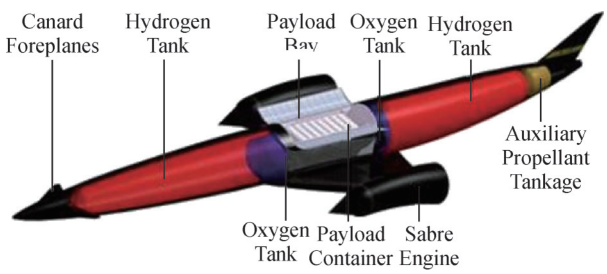

Fig.8 SKYLON C1 Cutaway

Compared with conventional single-use carrier rockets, SKYLON offers significant improvements in reducing the cost of entering space, improving reliability and efficiency. However, the thermal elasticity problem has become an unavoidable problem, especially for a long period of accelerated rise. The cumulative effect of heat load should be focused on.

2.2 Combined-cycle Propulsion and Configurations

Aerodynamic design of hypersonic air-breathing vehicles is not just confined to the aerodynamic configurations, also includes a comprehensive design requirements associated with the aerodynamic characteristics. Among these design elements, the placement of power relative to the body, the matching of aerodynamic layout and dynamics, the need for proper configuration of the layout configuration are all important directions that are worthy of our in-depth study.

With the development of the combined cycle propulsion systems, a variety of hypersonic air-breathing vehicles have continuously emerged, resulting in a number of aerodynamic configurations adapted to the current combined-cycle powers. Table 2 summarizes the aerodynamic configurations of typical combined-cycle propulsion systems and analyzes the requirements of different combined-cycle powers, providing references for hypersonic shape selection.

Table 2 shows that the vehicles with RBCC and TBCC are involved in the four configurations above. According to the task requirements, the selection of axi-symmetric body, lifting body and waverider is mostly a demonstration of vehicle performance and key technologies, while wing-body is mainly applied to the study of the two-stage to orbit vehicle. From the perspective of literature, air-breathing hypersonic vehicles powered by pre-cooled combined cycle are mainly used to achieve reusable delivery targets. Most foreign scholars have accepted the wing-body configuration.

Conclusions above have triggered our deep thinking on the relationship between propulsion systems and aerodynamic configurations. Each type of power has their advantages and disadvantages. In theory, all of them can be used for specific load transportation and sustainable hypersonic flight.

As for mission requirements，such vehicles are applied to the flight from subsonic to hypersonic speed and from ground to space，which involve different flight conditions at different altitudes. The necessary preconditions are：adequate fuel，reasonable matching among propulsion systems，configurations and excellent aerodynamic characteristics. These preconditions are coupled and contradictory. The design principle for these aircrafts is to achieve the full potential of propulsion systems，which helps to provide a solution to complex aerodynamic configurations.

Tab.2 Typical configurations of different propulsion systems

Propulsion Systems	Configuration	Typical Aircraft	Application
RBCC	Axi-symmetric body	GTX	Exploring the single-stage entry capability of the payload into low Earth orbit
	Wing-body	Astrox-RBCC levelII of two-stage entry aircraft	Research on near space and RBCC two-stage to orbit technology
		D-21	Verification on the reliability of the transition between the eject mode and the ramjet mode
		Sentinal	Exploring the first-class power of military aircraft
	Waverider	X-43B	Verification on the engine's performance and durability in space
TBCC	Wing-body	SR-71	Conducting global reconnaissance missions with manned driving and obtain intelligence in the shortest possible time
		SR-72	A hypersonic reconnaissance plane that combines intelligence, surveillance and combat capabilities
		HTV-3X	Mainly repeatable flight of *Ma* 6 aircraft, verification of aerodynamic performance of a hypersonic vehicle, aerodynamic thermal protection system, and turbo-scramjet combined cycle engine technology
		LAP CATA2	Exploring the *Ma* 4~8 hypersonic vehicle first stage propulsion concept
	Lifting body	HTV-2(with lifting body and waverider features)	Verification on the key technologies of Flacon planning
	Waverider	X-43B	Same as above
Precooled combined Cycle	Wing-body	SKYLON	Reusable space aircraft
		The first stage of the United States two-stage to orbit vehicle using the SABRE engine	Two-stage to orbit spacecraft deployment

The wing-body configuration is widely used in hypersonic vehicles design，which is closely related to its distinctive advantages. Nowadays，combined-cycle aerospace vehicles are in the early stages of analysis，verification and testing. Compared to the others，the wing-body provides effective lift，making it easier to gain high lift-to-drag ratio by drag reduction design. The round or nearly circular fuselage section can accommodate more space to improve the transport capacity. In terms of propulsion layout，the free arrangement method quickly forms a variety of layout solutions and flight performance data，which provides valuable design guidelines. Furthermore，the uncomplicated manufacturing and mature heat protection experience facilitates later optimization and modification.

Compared with the wing-body，the selection of other three configurations is more suitable for the technical verification of the ramjet engine. For instance，as the analysis above，the axi-symmetric body is more suitable for hypersonic integrated design. The design concept of the lifting body commendably balances the contradiction between aerodynamic heating and high lift-to-drag ratio at high angle of attack in hypersonic flight，hence it is the most suitable configuration. While the waverider breaks the lift-to-drag barrier，which uses an integrated design to facilitate modularization of the engines. In the future，the design principle of the waverider can be used to enhance the aerodynamic characteristics of other configurations.

From the above discussion，combined-cycle propulsion and configurations not only play their respective advantages，but also need to exert their overall performance.

a) There is no uniform configuration in academic choice. Hypersonic air-breathing vehicles have the possession of diversity and uniqueness. The mission requirements are the premise of aerodynamic design，which are supposed to match the reasonable shape.

b) Based on the analysis in Table 2，TBCC is more applicable for horizontal taking-off and landing missions. However，the efficiency of the RBCC's ejection mode is too low to carry plenty of fuel. Therefore，RBCC is more suitable for vertical taking-off and horizontal landing.

c) In hypersonic cruising，there is a strong coupling between propulsion systems and body. The integration design has become the imperative tendency of hypersonic aerodynamic configuration.

3 Conclusions

This article discusses and analyzes the typical aerodynamic configurations in details. Through the analysis of the aerodynamic characteristics，this paper summarizes the advantages and disadvantages of different layouts，forming a more global and objective understanding of the shape design. In the hypersonic flight，the aerodynamic environment is multifarious and intricate. As a significant way to achieve sustainable hypersonic flight，the air-breathing vehicle is currently a worldwide hot spot. In the latter part of this article，this article focuses on the analysis of typical representative of the hypersonic air-breathing propulsion systems. Combining propulsion and layout，the relationship between combined-cycle propulsion and configurations is analyzed specifically.

Hypersonic aerodynamic design demands not only a deep understanding of aerodynamics，but also a comprehensive level of other disciplines such as propulsion，structure，and control. The goal is to design aerodynamic configurations with good aerodynamic performance，high flight efficiency to meet the requirements of related professions. This is also a breakthrough to achieve hypersonic flight.

References

[1] TSIEN H S. Similarity laws of hypersonic flows[J]. Mathematics and Physics, 1946(25): 247-251.

[2] FENG Zhigao, GUAN Chengqi, ZHANG Hongwen. An introduction to hypersonic aircraft[M]. Beijing: Beijing Institute of Technology Press, 2016.

[3] LYNCH F T. Commercial transports-aerodynamic design for cruise performance and efficiency[J]. Dauglas Aircraft Company, 1981: 7026.

[4] GAO Zhenghong; WANG Chao. Aerodynamic shape design methods for aircraft: status and trends[J]. Acta Aerodynamica Sinica, 2017, 35 (4): 516-528.

[5] HIRSCHEL E H. The Technology development and verification concept of the german hypersonic technology program[R]. Dasa-LME12-HYPAC-STY-0017-A, 1995.

[6] KELLY J, MURPHY, ROBERT J N, et al. X-33 hypersonic aerodynamic charac-teristics[J]. Journal of Spacecraft and Rockets, 2011, 38(5): 670-683.

[7] FERGUSON Frederick, DASQUE Nastassja, DHANASAR Mookesh. CFD analysis of waveriders derived from axisymmetric flowfields for reentry applications[R]. AIAA 2012-1255, 2012.

[8] YANG Yong. Waverider configuration design, optimization and numerical simulation of aerospace plane[D]. Harbin: Harbin Institute of Technology, 2012.

[9] HANK J M, MURPHY J S, MUTZMAN R C. The X-51A scramjet engine flight demonstration program[R]. AIAA 2008-2540, 2008.

[10] NONWEILER T R F. Aerodynamic problems of manned space vehicles[J]. Journal of the Royal Aeronautical Society, 1959, 63(9): 521-528.

[11] OLDS J. Opetions for flight testing Rocket-Based Combined-Cycle (RBCC) engines[R]. AIAA 96-2688, 1996.

[12] ZHANG Huajun, GUO Rongwei, LI Bo. Research status of TBCC inlet and its key technologies[J]. Acta Aerodynamica Sinica, 2010, 28 (5): 613-620.

作 者 简 介

杜志博（1993—），男，工程师，博士研究生，主要研究方向为飞行器气动设计、热防护设计。

刘明坤（1994—），男，工程师，主要研究方向为无人机应用。

张中洲（1987—），男，工程师，主要研究方向为火箭总体设计。

刘凯鹏（1994—），男，博士研究生，主要方向为电磁微结构优化。

李天龙（1988—），男，教授，主要研究方向为微纳机器人、新材料与智能制造。