Current Status and Applications of Bluff Body Aerodynamics Theorem

Zijie Zhao
Ulink College of Shanghai, Shanghai, 201615, China
zhaozijie@chd.edu.cn

Abstract. With the development of aerospace science and technology, the aerodynamic characteristics of spacecraft has become an important research topic. The aerodynamic configuration of reentry spacecraft represented by the bluff body theory has been widely used in various spacecraft. A large number of studies show that it has good effects in reducing aerodynamic heating caused by turbulence and improving the reentry stability of spacecraft. At the same time, the research of aerodynamic characteristics can not only solve the problems in many engineering fields, but also promote the development of many other disciplines, such as fluid mechanics. Aerodynamic characteristics play a more and more important role in the aerospace field, not only providing ideas for spacecraft design and application analysis, but also providing solutions for spacecraft in flight. The research topic of this paper is to summarize and review the research and exploration of this aerodynamic configuration at home and abroad. Through the application of bluff body in different functions of spacecraft and the specific analysis of historical accidents, this paper summarizes the importance of bluff body theory to the safety of spacecraft during reentry.

Keywords: Bluff body; Aerodynamic; Space shuttle; Return capsule.

1. Introduction

The exploration of unknown world is endless for human beings [1]. Russian aeronautic and rocket science pioneer Konstantin Eduardovich Tsiolkovsky, who was known as “the father of rocketry”, once said: “the Earth is the cradle of humanity, but one cannot remain in cradle forever”. The deep research on modern large rocket and space vehicle started in the late period of World War II. V-2 rocket developed by Nazi German scientist Wernher von Braun became the first artificial object to reach the space by crossing the Kármán line on 20 June 1944 and became the ancestor of modern rocket [2]. This is the milestone of aeronautical history. During the around 8 decades since then, human have reached unprecedented achievements in the field of space exploration and technology development [3].

Currently, due to overexploitation of natural resources, and by facing the threat of climate crisis, more and more people turned their sight to the deep vast outer space again [4]. On the condition of space exploration techniques and developments are greatly emphasized by the nations all around the world, as an important and indispensable branch of aeronautical and space research, hypersonic research is a fundamental field of the whole space research program and closely associated with its success or not [2]. To break off the cradle that ties the human on the Earth, the hindrance of atmosphere is the first step for us to breakthrough. Thus, the research of aerodynamic feature of space vehicle under hypersonic condition have an imperative meaning for the future space exploration development.

Hypersonic flow around blunt bodies are a classical problem in aerodynamics, which widely exists in all kinds of aeronautical vehicles and has been deeply studied for a long time [5]. This paper will analyze and discuss the application and current situation of blunt body theory in hypersonic field, and look forward to the further development and improvement of this theory in the future. This paper will discuss the role and effect of blunt body in relieving aerodynamic heating caused by air friction and shock wave from the aerodynamic feature aspects of reusable space vehicle (represented by space shuttle) and disposable reentry capsule of spacecraft respectively, and review the research history of this theory at home and abroad in the past decades, summarize the research status of theoretical practice and application of blunt body.

2. Reusable Space Vehicle

2.1. Brief history of space shuttle

The space shuttle is a reusable law-orbital space lunch system which operated by NASA within 1981 and 2011. in August 10, 1968, George Edwin Mueller, who was the head of the Office of Manned Space Flight of NASA at that time, announced a program for developing reusable space shuttle. The first model "Enterprise", used for testing propose, completed in Rockwell North America company in September 17, 1976 and being put into test flight at Edwards Air Force Base and laying a good foundation for the subsequent space shuttle development. On April 12, 1981, the first fully functional space shuttle "Columbia" was lunched from Launch Pad 39A at the Kennedy Space Center in Florida into space for STS-1 mission [6]. From then on, STS mission lasted for 30 years until "Atlantis" landed on July 21, 2011, culminating the space shuttle age.

2.2. Aerodynamic feature and casese

The shuttle's STS mission is primarily responsible for launching payloads from the earth to near-Earth orbits, as well as tasks such as the construction of the International Space Station and the maintenance of the Hubble Space Telescope [7]. When the orbital mission is completed, the shuttle will carry the astronauts from low-orbit into the atmosphere and eventually land horizontally on the runway of the Space Center. During a mission cycle, the space shuttle travels to and from outer space by twice passing through the atmosphere of the Earth, where the stage in which the shuttle travels back from the space and passing though atmosphere is called the reentry stage. During this phase, the viscous atmosphere will cause severe friction on the shuttle's insulating tile, producing temperatures as high as thousands of degrees Celsius, this phenomenon is known as aerodynamic heating. When the shuttle reentries into the atmosphere, its maximum velocity is about 25 times than the speed of the sound, but the relative velocity of the gas on its surface is 0, which causes the vortices to roll up and turn into turbulence in its boundary layer [8]. Gas compression and friction cause the temperature to rise sharply. Compared with the external supersonic flow, the velocity in the boundary layer is much slower, and the heat generated by gas friction is quickly transferred to the surface of the shuttle. Excessive temperatures can greatly endanger the safety of space shuttles. The catastrophe of space shuttle Colombia, which disintegrated during the reentry phase on February 1, 2003 [9]. The cause of the crash was that the thermal insulation material fragments on the shuttle's outer storage box dropped off under the action of severely aerodynamic forces during launch and hit the left-wing front edge of Colombia, damaging the shuttle's thermal insulation system that provides protection during reentry phase, causing the reentry thermal tile to disengage. High-temperature airflow enters and destroys the internal structure of the wing through tiny holes in the wing during the reentry phase, leading the shuttle to disintegrate rapidly in the air, causing the misfortune of seven astronauts [10].

2.3. Theory application

It is not difficult to conclude from the above catastrophe that, in order to enhance the flight safety of the reentry stage, the heat energy generated by the compression and friction of the gas caused by the boundary layer turbulence must be released into the surrounding atmosphere as much as possible, thereby lowering the surface temperature of the spacecraft. In hypersonic airflow, the absolute speed of the object itself is much greater than the absolute speed of sound wave propagation caused by its own vibration. A large amount of disturbance cannot disperse uniformly in front of the object, resulting in a sudden compression of the gas near the surface of the object, creating a shock wave. Shocks are an obstacle to the movement of a spacecraft, which results in the loss of mechanical energy that the spacecraft originally possesses. The lost energy is converted into heat that is transferred to the shock wave, which is then dispersed into the surrounding atmosphere to reduce the aerodynamic heating of the spacecraft itself. For the space shuttle itself, the bottom area is much bigger than the reentry capsule, detached shock wave can extended further, thus to decrease the heat energy per unit area.

When the shape of the spacecraft is a sharp wedge, its half-apex angle is small, and the resulting shock wave will be attached to the surface of the spacecraft, called an attached shock. At this time, because the shock wave is attached to the surface of the spacecraft, its divergence angle is small, its wave resistance to the spacecraft is small, and the heat it can carry is small. As a result, most of the energy still exists on the surface of the spacecraft in the form of heat, which provide less help to alleviate the aerodynamic heating phenomenon. However, when the shape of the spacecraft is blunt, the half-top angle of the spacecraft is much larger than the cusp wedge, and the resulting shocks will be detached from the surface of the spacecraft, called in detached shocks (Fig. 1).

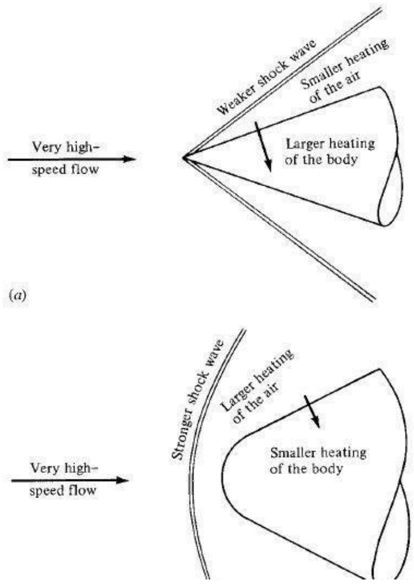

Fig. 1 Explanation of aerodynamic heating performance difference between bluff body and sharp body [1]

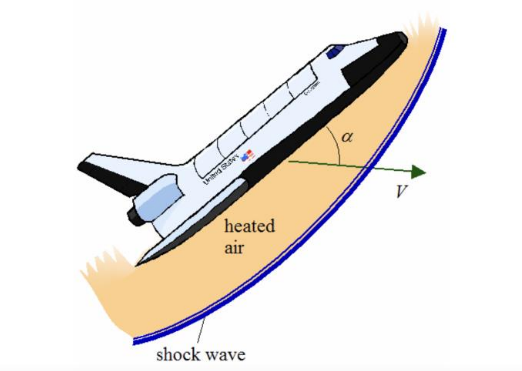

Fig. 2 Schematic diagram of the aerodynamic heating zone of the space shuttle reentry [4]

A large part of the isolated shocks is very close to the positive shocks. The pressure behind the shocks rises very high, and the wave resistance of the object is very large. This is exactly what a spacecraft needs to reentry into the atmosphere [7]. The larger cross-section area caused by blunt-head body brings greater air resistance, and the wave resistance of isolated shocks enlarges the obstruction effect, which makes the kinetic energy of the spacecraft rapidly transform into heat energy and transferred onto the shock wave. The detached shock wave brings the heat energy away from space shuttle itself and diffuse them into the surrounding atmosphere. This greatly alleviating the aerodynamic heating effect (Fig. 2).

3. Disposable reentry capsule

3.1. Typical character

In addition to the reusable space shuttles, the pillars of space researches are manned spacecraft that can no longer be replenished and reused. The former Soviet Union launched the first manned spaceship Vostok in 1961, successfully sending astronaut Yuri Gagarin into space, setting a milestone in the history of space race and starting a new era of space exploration. Classic spacecraft such as Soviet/Russian Soyuz spacecraft, American Apollo spacecraft and Chinese Shenzhou series spacecraft generally consist of an orbiter capsule, a propeller capsule and a return capsule [9]. Some spacecraft with special functions will have additional capsules such as air-lock and Moon-landing capsules.

3.2. Application of the theory

The return capsule will take on the task of re-entering the atmosphere and undergo high-temperature ablation caused by aerodynamic heating. Therefore, the return capsule of spacecraft are mostly designed as the shape of bells with blunt outsole, similar to Roly-poly toy with the large bottom and small heads (Fig. 3). This design is very sophisticated. A blunt head diffuses a large amount of heat into the surrounding atmosphere in the form of detached shocks in aerodynamics, quickly and effectively reducing the impact of aerodynamic heating. As mentioned earlier, the difference between zero relative velocity of gas on the surface of a spacecraft and the hypersonic velocity of the surrounding atmosphere causes the airflow in the boundary layer to turn into turbulent flow, whereas the diameter of the bell-shaped bottom of the blunt-head body is much larger than the diameter of the top of the return capsule, creating a frustum-shaped body with a sharp angle between the bottom and the side, where the turbulence generated by the boundary layer is detached from the surface of the return capsule.

Fig. 3 Distribution Diagram of Aerodynamic Shadow Zone of Return Cabin in Reentry Phase [3]

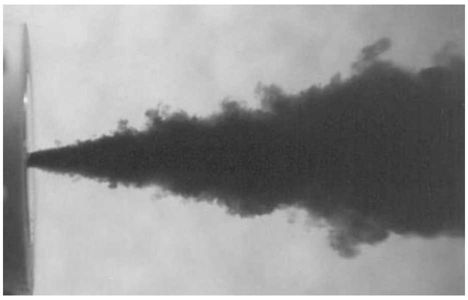

Fig. 4 Turbulence image from nozzle [2]

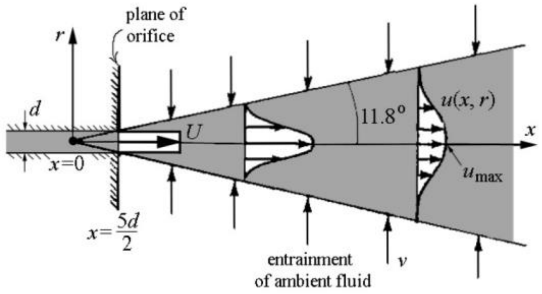

Fig. 5 Theoretical diagrams of turbulence and airflow velocity profiles

In this process, the aerodynamic effect produced by the circular cross-section area at the large bottom of the blunt head body is similar to the turbulence caused by the jet issuing from the nozzle of a pipe (Fig. 4 and Fig. 5). Experiments show that the angle of the jet widens is a constant number for 11.8 degrees. Therefore, the larger cross-section area diameter of the blunt head and the large bottom creates a larger aerodynamic shadow area, which makes the rest of the whole return capsule exist in this aerodynamic shadow area. In this aerodynamic shadow area, the velocity distribution of the gas is also bell-shaped. The velocity profile along the main axis remained the maximum, but its peak flattens as distance increases from the bottom. The cross-sectional diameter of the return capsule decreases with the distance from the base as the frustum shape, making its coordinate with the velocity profile. For the farthest distance from the base, the difference between the airflow velocity on the center axis and the airflow velocity in the surrounding atmosphere became smaller. As the distance from the base decreases, the outward surface of the return capsule gradually expands outward, tending to the area where the airflow velocity changes more gently, which minimizes the difference between the airflow velocity in the boundary layer and the airflow velocity in the surrounding atmosphere. This design minimizes the turbulence on the surface caused by the friction of the airflow due to velocity difference and thus minimizes the heat hazard that generated during reentry phase to protect the safety.

4. Conclusion

Blunt body theory has various applications since it is raised by NASA aeronautical engineer H. Julian Allen. His findings revolutionized the fundamental design of spacecraft reentry shapes. The research on this theory has greatly changed the future of hypersonic aircraft. The seemingly unconventional design breaks the stereotyped impression that the higher the flight speed, the “sharper” the aircraft shape should be. This inherent impression led to the slender vehicle represented by USAF F-104 fighter. However, slender aircraft, such as the F-104 fighter, have frequent accidents in continuous flight at high speeds above Mach 2, and are even nicknamed “Widow Maker”. Since blunt body theory was applied to spacecraft such as space shuttle and reentry module, it has played an inestimable role in heat dissipation during reentry, by redistribute the heat energy to the surrounding atmosphere though detached shock wave. It has pointed out a methodology that unconventional design that can be the key to broken the technological barrier.

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