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Design and Numerical Simulation of a Common Nozzle of multi-Channel TBCC Engine

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Abstract

Hypersonic flight is regarded as the third "revolution" in the history of aeronautical development following the propeller propulsion and the jet propulsion, which is the commanding height of aerospace technology in the twenty-first century. The core of hypersonic technology is propulsion technology. At present, it cannot satisfy full-speed flight of a hypersonic vehicle from the level to the supersonic speed depend on a single turbine or a ramjet. The combined cycle engine composed of turbine and ramjet is referred to as Turbo-Based Combined Cycle (TBCC) engine, which is a potential power form to achieve full-speed flight. When TBCC engine is switched from turbine-based mode to ramjet mode, there is an insufficient thrust problem called "thrust traps". Rockets can be used to ensure the continuity of the thrust during the modal transformation process. In this paper, a common exhaust system is designed for this type of multi-channel TBCC power system consisting of a turbine, a scramjet, and an ejector rocket. The scramjet channel is designed first using an asymmetric single expansion ramp nozzle, while the turbine and rocket channel using Laval nozzles. The exhaust gas of these two channels flows into the scramjet nozzle. Throat area of the turbine nozzle and the rocket nozzle can be adjusted according to the flow requirements. Numerical simulations show that the proposed method can be used to design a common nozzle that meets thrust requirements of hypersonic vehicles for the full-speed flight.

Keywords: *Common nozzle, TBCC, Multi-channel, Numerical simulation*

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1. Introduction

Hypersonic flight is regarded as the third "revolution" in the history of Aeronautical development following the propeller propulsion and the jet propulsion, which is the commanding height of aerospace technology in the twenty-first century. Developing hypersonic technology is important for a country to keep air and space security and promote scientific and technological progress, and the core of hypersonic technology is propulsion technology.

Comparison of specific impulses of different engines is shown in Fig.1. It can be observed that specific impulses of different types of engine vary with the flight Mach number. The operating range of turbo engines (TE) is Ma0 to Ma2.5, the operating range of ramjets (RJ) is Ma3 to Ma5, and the operating range of scramjets (SRJ) is above Ma4. The rocket can work at full speed, but it has the lowest efficiency and is currently not reusable, nor can it achieve horizontal take-off and landing. So the full-speed advanced power system must be realized by combining the existed mature power systems.

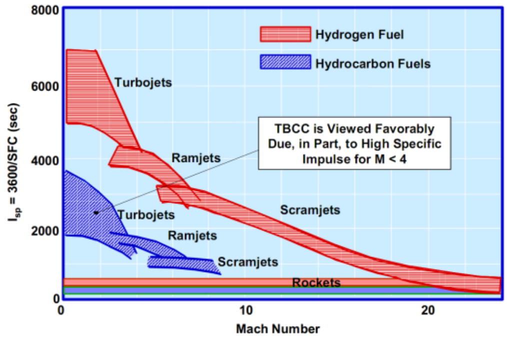

Fig 1. Comparison of specific impulses of different engines

The combined cycle engine which is composed of turbine-based engines used in the low speed range (Ma0 to Ma3) and ramjet engines used in the high speed range (Ma3 to Ma7) is referred to as Turbo-Based Combined Cycle (TBCC) engine. When the TBCC engine is switched from turbine-based mode to ramjet mode, there is an insufficient thrust problem called thrust traps. In order to ensure the continuity of the thrust during the modal transformation process, rockets can be used to fill in "thrust traps". So the combination of the turbo-based engine, the ramjet and the rocket is an ideal power system that can be used for future level take-off and landing, full-speed flight. For turbine/rocket/ramjet multi-channel combined engines, it is necessary to design high efficiency common nozzles. However, there were few scholars focus on this type of common nozzles at home and abroad at present, and the design methodologies are still immature.

Methods of characteristic (MOC) and the minimum length nozzle (MLN) theory were used to design the asymmetric nozzle of scramjet, and nozzles of the turbine and rocket were integrated into scramjet nozzle to generate the common exhaust system. Flow field and thrust characteristics of the common nozzle under typical conditions are analysed by CFD software.

2. Design methodologies

2.1. Scramjet nozzle

A two-dimensional asymmetric nozzle was designed using the minimum length nozzle (MLN) theory. The design parameters are given in Table 1.

Table 1. Design parameters

Gamma	Inlet Mach number	Inlet total pressure	Outlet static pressure	Asymmetric factor F
1.33	1.283	289837	2971.695	0.3

Asymmetric factor F can be expressed as

$$F = \frac{\delta_U}{\delta_L} \tag{1}$$

δ_U is the initial expansion angle of the upper wall, δ_L is the initial expansion angle of the lower wall. δ_U is related to v_e and v_{in} , and can be written as

$$\delta_U = \frac{v_e - v_{in}}{2} \tag{2}$$

v_e is the Prandtl-Meier expansion angle corresponding to the outlet Mach number of the nozzle, v_{in} is the Prandtl-Meier expansion angle corresponding to the inlet Mach number of the nozzle. δ_L can be obtained from F and δ_U as

$$\delta_L = F \times \delta_U \tag{3}$$

Flow field of the scramjet nozzle at the design point was carried out by the inviscid numerical simulation, and the Mach contour was in good agreement with the expected results, as shown in Fig. 2.

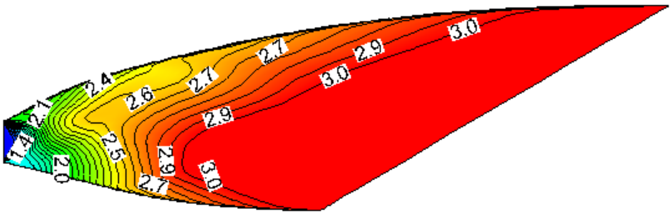

Fig 2. Mach contour of the scramjet nozzle

Three-dimensional asymmetric nozzle was obtained by extension two-dimensional nozzle profile of the scramjet, as shown in Fig.3. Due to the long length of the nozzle profile, compression trimming is required to reduce the length.

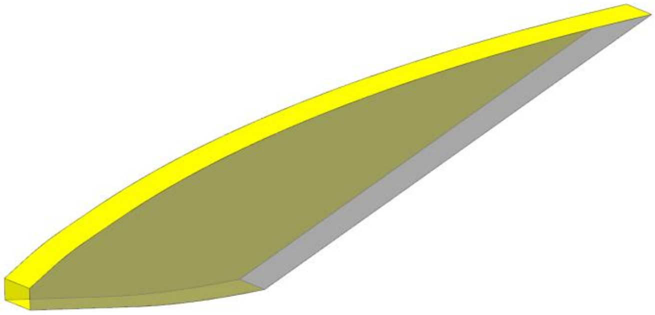

Fig 3. the three-dimensional asymmetric nozzle of the scramjet

2.2. Turbine and Rocket nozzle

The turbine and rocket channel use Laval nozzles. The area of the nozzle at different sections is related to the mass flow rate as follows

$$\dot{m} = k \frac{P_t}{\sqrt{T_t}} A q(\lambda) \tag{4}$$

k is gas constant, P_t is the total pressure, T_t is the total temperature, $\dot{m}$ is the mass flow rate, $q(\lambda)$ is the flow coefficient, and A is the area of the nozzle. The area of the channel is calculated according to the maximum mass flow rate, such as in this paper the maximum mass flow rate of a single turbine engine channel is 84.45kg/s, and the maximum mass flow rate of the rocket engine channel is 147.6kg/s. When calculating the maximum area of the throat of each channel, $q(\lambda)$ is equals to 1. Design parameters of each channel are listed in Table 2.

Table 2 Design parameters of the turbine and rocket channel

	Max mass flow rate/kg/s	k	**Inlet total temperature /K**	**Inlet total pressure/Pa**	$q(\lambda)$	**Inlet area/m2**
Turbine channel	84.45	0.039	2200	300482	0.668	0.5060
Rocket channel	147.6	0.0404	303	112981	0.057	1.4232

2.3. Common nozzle of four-channel TBCC engine

A common nozzle is designed for four-channel TBCC engine, as shown in Fig.4. The area of the throat in the turbine or rocket channel can be adjusted to improve the thrust performance at the off-design condition. Flow field of the nozzle was simulated by FLUENT software, and the Mach contour was shown in Fig.5. The thrust and lift characteristics of the common nozzle will be analysed in the subsequent work.

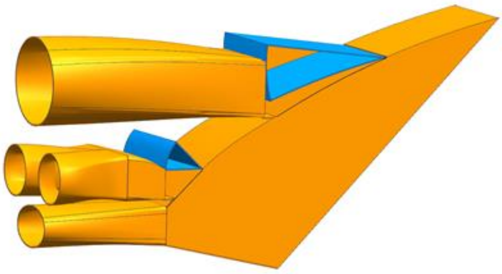

Fig 4. Common Nozzle of Four-Channel TBCC engine

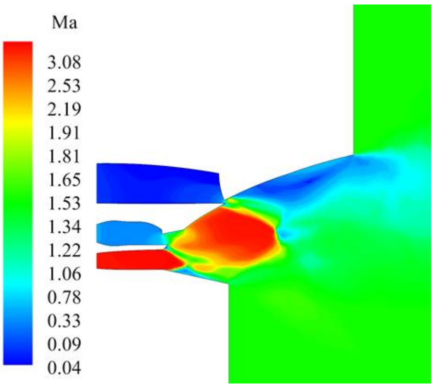

Fig 5. Mach Contour of Common Nozzle