Available online at www.sciencedirect.com
ScienceDirect
Chinese Journal of Aeronautics 23(2010) 647-652
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Continuous Detonation Engine and Effects of Different Types of Nozzle on Its Propulsion Performance

Shao Yetao, Liu Meng, Wang Jianping*

State Key Laboratory of Turbulence and Complex System, College of Engineering, Peking University, Beijing 100871, China

Received 11 January 2010; accepted 1 August 2010

Abstract

The rotating propagation of a continuous detonation engine (CDE) with different types of nozzles is investigated in three-dimensional numerical simulation using a one-step chemical reaction model. Flux terms are solved by the so-called monotonicity-preserving weighted essentially non-oscillatory (MPWENO) scheme. The simulated flow field agrees well with the previous experimental results. Once the initial transient effects die down, the detonation wave maintains continuous oscillatory propagation in the annular chamber as long as fuel is continuously injected. Using a numerical flow field, the propulsion performance of a CDE is computed for four types of nozzles, namely the constant-area nozzle, Laval nozzle, diverging nozzle and converging nozzle. The gross specific impulse of the CDE ranges 1 540-1 750 s and the mass flux per square meter ranges 313-330 kg/(m^2·s) for different nozzles. Among these four types of nozzles, Laval nozzle performs the best, and these parameters are 1 800 N, 1 750 s and 313 kg/(m^2·s). A nozzle can greatly improve the propulsion performance.

Keywords: continuous detonation engine; propulsion performance; nozzle effects; Laval nozzle; hypersonic

1. Introduction

After one hundred years of research and advancements, it has been steadily becoming more difficult to achieve further improvements in conventional constant-pressure combustion engines in terms of high efficiency. Urgency now surrounds the development of new-concept propulsion systems to meet demands for higher velocity and higher efficiency. Taking advantage of the nearly isochoric combustion process, detonation is inherently seen as a way to achieve higher thermodynamic efficiency than usual deflagration-based propulsion devices such as gas turbine engine and ramjet engine. In particular, detonation allows more intense and steadier combustion, therefore comparatively small combustors are capable of creating enormous thrust. And also, it is simple and light, and does not require turbo-pumps or compressors. Such benefits have gained worldwide interest in research into detonation engines.

Now, how to design a detonation engine to create thrust becomes a challenge. The pulse detonation engines (PDEs)[1-2] have been widely investigated during the past three decades. This has shown without doubt that PDEs have many advantages. Nevertheless, there are several hurdles that need to be overcome in PDE research. For one, it is difficult to achieve high operational frequency resulting consequently in low mass flux at a PDE. For another, high ignition energies are needed for each pulse cycle making ignition difficult. As a result, a reliably-functioning detonation engine has not been developed until now. Developing a detonation engine operating without need of periodic ignition and continuously injecting fuel would greatly reduce difficulties in designs of, in particular, detonation combustion aerospace thrusters. In this article, the recently investigated continuous detonation engine (CDE) (also known as rotating detonation engine (RDE)) is simulated, which is expected to meet the above demands.

In a CDE, detonation wave (DW) propagates in azimuthal direction which is perpendicular to but not against fuel injection direction. As DW propagating direction and fuel injection direction are independent, DW can continuously propagate in a wide range of injection velocity from low subsonic to hypersonic[3] and need not multi-time ignition naturally. These characteristics would greatly reduce the difficulties in the design of a detonation engine.

*Corresponding author. Tel.: +86-10-82529038.
E-mail address: wangjp@pku.edu.cn
Foundation item: Aeronautical Science Foundation of China (2008ZH71006)

doi:10.1016/S1000-9361(09)60266-1

The basic concept behind a CDE was first proposed by B. V. Voitsekhovskii[4]. Experimentally, he achieved short-lived continuous detonation fuelled by ethylene or acetylene. In recent years, CDE has been extensively studied both theoretically and experimentally, by F. A. Bykovskii, et al.[5-7]. J. Kindracki, et al.[8] have experimentally obtained very promising thrust performances from a rocket-type CDE. F. Falempin, et al.[9] have performed some preliminary tests to evaluate the capability of C/SiC composite materials to sustain the high temperature of about 1 000-2 000 K at the head part of the combustor. In numerical aspect, S. A. Zhdan, et al.[10] have made a wave structure analysis on a two-dimensional plane domain. M. Hishida, et al.[11] have performed a detailed analysis of a CDE. They have discovered Kelvin-Helmholtz (K-H) instabilities and cell structures in CDE. Y. T. Shao, et al.[12] and X. H. Jiang, et al.[13] have done three-dimensional simulations to analyze CDE's flow field and wave structure for a constant area tube, respectively.

Up to now, numerical works on CDEs mainly focus on the DW structure. In this article, detailed analyses of the propulsion performance of a CDE with four different types of nozzles, constant-area nozzle, Laval nozzle, diverging nozzle and converging nozzle, have been carried out. Constant-area tube studies[10-12] have shown that the detonation product flows out of the combustor exit at high temperature, wasting a lot of energy. Like a rocket engine, a continuous combustion engine with a nozzle may efficiently expand the product to create more thrust. In addition, previous performance studies have mainly computed the gross specific impulse, and hence, they have not considered the enormous injection momentum that may provide higher propulsion performance. With this background, CDEs with four types of nozzles are numerically simulated to investigate their propulsion performance.

2. Computation Scheme

2.1. Governing equation

A one-step chemical reaction model is used in this simulation. Three-dimensional Euler equations in generalized coordinates are used as governing equations as follows:

$$\frac{\partial \boldsymbol{U}}{\partial t}+\frac{\partial \boldsymbol{E}}{\partial \xi}+\frac{\partial \boldsymbol{F}}{\partial \eta}+\frac{\partial \boldsymbol{G}}{\partial \zeta}=\boldsymbol{S} \tag{1}$$

where the dependent variable vector $\boldsymbol{U}$, convective flux vectors $\boldsymbol{E}$, $\boldsymbol{F}$ and $\boldsymbol{G}$, and source vector $\boldsymbol{S}$ are defined as

$$\boldsymbol{U}=[\rho \quad \rho u \quad \rho v \quad \rho w \quad e \quad \rho\beta]^{\mathrm{T}}$$

$$\boldsymbol{S}=[0 \quad 0 \quad 0 \quad 0 \quad 0 \quad \rho\dot{\omega}_\beta]^{\mathrm{T}}$$

$$\boldsymbol{E}=[\rho\bar{U} \quad \rho\bar{U}u+p\xi_x \quad \rho\bar{U}v+p\xi_y \quad \rho\bar{U}w+p\xi_z \quad \bar{U}(p+e) \quad \rho\bar{U}\beta]^{\mathrm{T}}$$

$$\boldsymbol{F}=[\rho\bar{V} \quad \rho\bar{V}u+p\eta_x \quad \rho\bar{V}v+p\eta_y \quad \rho\bar{V}w+p\eta_z \quad \bar{V}(p+e) \quad \rho\beta]^{\mathrm{T}}$$

$$\boldsymbol{G}=[\rho\bar{W} \quad \rho\bar{W}u+p\zeta_x \quad \rho\bar{W}v+p\zeta_y \quad \rho\bar{W}w+p\zeta_z \quad \bar{W}(p+e) \quad \rho\bar{W}\beta]^{\mathrm{T}}$$

$$\bar{U}=u\xi_x+v\xi_y+w\xi_z$$

$$\bar{V}=u\eta_x+v\eta_y+w\eta_z$$

$$\bar{W}=u\zeta_x+v\zeta_y+w\zeta_z$$

The pressure p and total energy e are calculated using equations of state:

$$p=\rho RT \tag{2}$$

$$e=\frac{p}{\gamma-1}+\beta\rho q+\frac{1}{2}\rho u^2+\frac{1}{2}\rho v^2+\frac{1}{2}\rho w^2 \tag{3}$$

where ρ is density, R gas constant, T temperature, γ specific heat ratio and q heat release per unit mass.

The mass production rate is

$$\dot{\omega}_\beta=\frac{\mathrm{d}\beta}{\mathrm{d}t}=-A\beta\exp(-E_a/(RT)) \tag{4}$$

where β is the mass proportion of reaction mixture gas (β=1 represents a fresh gas mixture, whereas β=0 indicates the detonation products are in equilibrium), A preexponential factor and E_a activation energy per unit mass. A detailed description of all the parameters can be found in Ref.[14]. Flux terms are solved by using the five-order so-called monotonicity preserving weighted essentially non-oscillatory scheme (MPWENO)[15], and the time integration is performed by using the third-order total variation diminishing (TVD) Runge-Kutta method. Grid numbers are 31 (radial direction) × 800 (azimuthal direction) ×301 (axial direction), with mesh size of about 0.4 mm.

2.2. Grid dependency

The chemical induction distance is about 250 μm for the Chapman-Jouguet (CJ) detonation of the present gas mixture. To simulate this problem, a grid size of less than 25 μm may be needed, however, it is too computationally extensive to carry out three-dimensional simulation of a practical-size configuration with detailed reaction model. As this article aims to investigate CDE's main propagation characteristics and its propulsive performance but not detailed wave structure, a one-step reaction model with average grid size of 0.4 mm and a maximum Courant number 0.3 is used.

First, the thermochemical model and computation scheme have been validated for some simple one-dimensional test cases with grid size of 0.1 mm, 0.2 mm and 0.4 mm, respectively. Stoichiometric H_2/air mixture at 400 K and 0.18 MPa is directly ignited by hot spot of 2 000 K and 5 MPa. After propagation of 160 μs, except the van-Neumann spike pressure, the wave structure almost coincides together for these three grid size cases, shown in Fig.1. At CJ point the pressure and temperature are 2.5 MPa and 3 050 K which are close to theory value. The computed propagation velocity is 1 980 m/s, which is close to CJ value of 1 984 m/s too. Furthermore, for three-dimensional simulation of contant-nozzle tube case, another fine grid system with average grid size of 0.2 mm is computed to check the grid dependency. Fig.2 shows the comparison of the pressure contours computed based on these two grid systems from 400 to 850 μs of about 18 000 iteration steps. It can be seen that the flow fields approximately coincide with these two grid systems. The above comparison proves the numerical convergence and grid dependency.

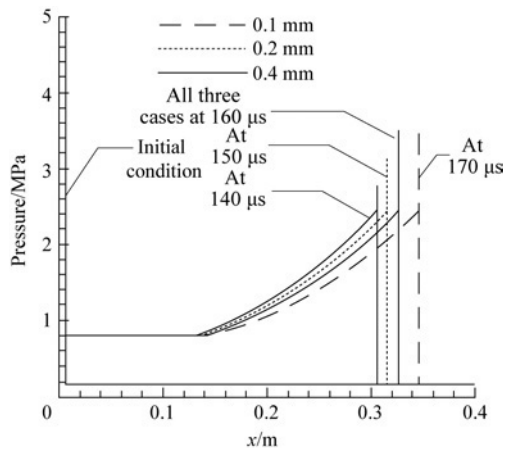

Fig.1 One-dimensional detonation wave propagation cases with three grid sizes respectively.

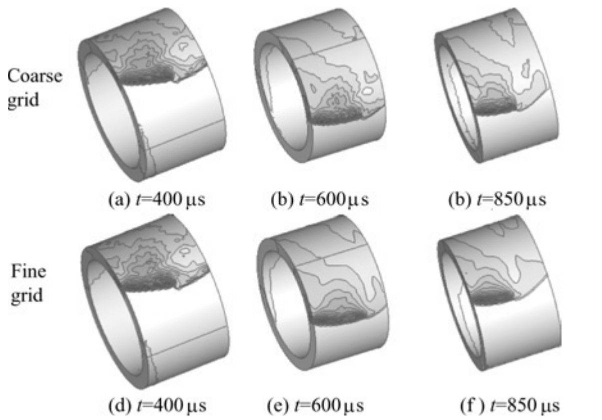

Fig.2 Comparison of instantaneous pressure contour based on coarse and fine grid systems from 400 μs to 850 μs.

2.3. Physical model

To begin with, an overview of the continuous propagation of a continuous detonation engine is presented in Fig.3. The dark regions indicate newly injected combustible fresh gas mixture and the remainder represents detonation products. Fresh gas is continuously injected into the detonation chamber from the left, and detonation products are ejected to the right to provide thrust. The annular gap between the two coaxial cylinders constitutes the combustor. The inner radius of the constant-area part is 40 mm and the outer radius is 53 mm. Schematic diagrams of the axial cross-sections of the four nozzles are shown in Fig.4. The front parts of the combustors have the same configurations. The Laval nozzle and diverging nozzle have the same exit area. The exit width of the converging nozzle is 0.62 times of the combustor width. The geometrical parameters are designed according to the ratio of the pressure of the steady state detonation product to the environment pressure.

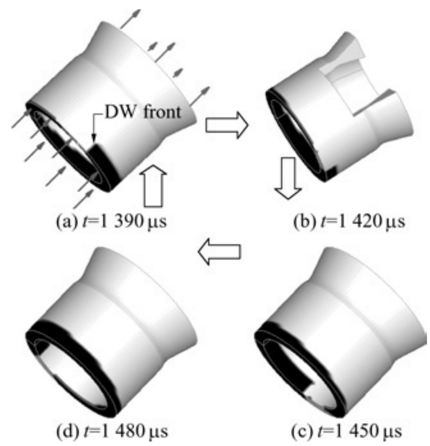

Fig.3 Reaction process parameter β contour at four instantaneousness during continuous propagation of a CDE with a Laval nozzle from 1 390 to 1 480 μs.

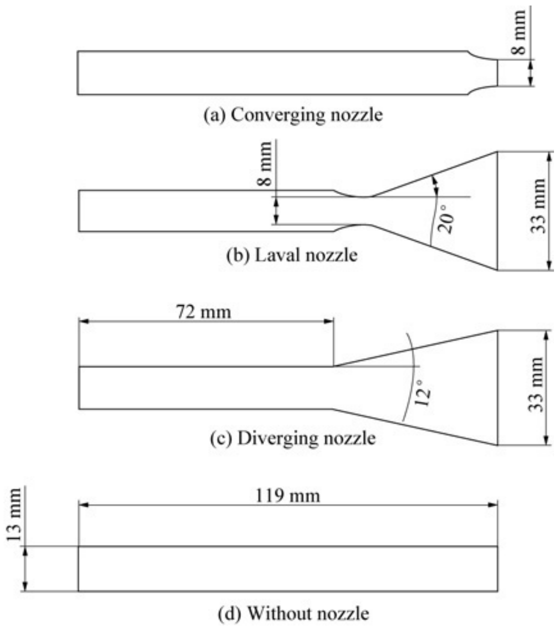

Fig.4 Cross-sections of CDE configurations studied.

The front section of the combustor is initially injected with quiescent, combustible gas mixture at pressure $p = 0.103$ MPa and temperature $T = 300$ K. The other part is filled with air. In the experiment[8], the DW is ignited by a branching pre-detonation tube that is connected tangentially to the outer wall of the combustor. In numerical simulation, for simple, pre-detonation ignition is substituted by a section of classical one-dimensional CJ detonation. After ignition, the DW continuously propagates azimuthally around the combustor. From 1 390 μs to 1 480 μs, the DW has propagated 9/16 round. Till to 1 480 μs, the detonation wave has propagated nine rounds and propagates at quasi- steady state continuously. A premixed stoichiometric H_2/air mixture injection condition is set according to the local wall pressure following Laval tube theory. The inlet stagnation pressure is $p_0 = 2$ MPa and the environment pressure p_∞ is 0.05 MPa. The injection hole exit area normalized by the hole throat area is $A_w/A_{throat} = 10$.

From the isentropic relation, there is the following expression:

$$\frac{A_w}{A_{throat}} = \frac{1}{Ma}\left[\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}Ma^2\right)\right]^{\frac{\gamma+1}{2(\gamma-1)}} \tag{5}$$

where Ma is the Mach number just in front of the head wall and $\gamma = 1.4$. The injection boundary condition is specified according to the local environment pressure p_w just near the wall.

(1) When $p_w > 2$ MPa: the reaction mixture could not be injected into the chamber. A rigid wall condition is set locally.

(2) When 1.994 MPa$<p_w<$2 MPa: mass fluxes through both throat and injection walls are subsonic.

(3) When 0.244 MPa$<p_w<$1.994 MPa: the throat maintains choke conditions, and the mass flux of injection remains constant. Shock waves develop downstream of the throat and fresh gas is injected at subsonic velocities.

(4) When $p_w<$0.244 MPa, the injection is not affected by the wall pressure. Whole field downstream of the throat is supersonic.

The side wall boundary conditions correspond to adiabatic, slipping and noncatalytic fluid flow. In real engine, the injected combustible gas would be heated by the high temperature wall[9] which would be helpful for fuel and air mixing. This mechanism has not been considered here. Conditions on the outflow boundary correspond to a non-reflecting surface[16].

3. Presentation of Results

3.1. Flow field structure

Fig.5 shows the pressure contours at 1 500 μs when the DW has propagated more than nine rounds. The DW can continuously propagate in this quasi-steady state for a long time. The DW maintains an acute angle to the head wall so that it moves against the injection flow direction, thereby avoiding being blown downstream. Now the CJ velocity is divided into two velocity components, i.e., axial component and azimuthal component. The axial component velocity has the same value with the injection velocity in front of the detonation wave but opposite direction. The azimuthal component velocity is the DW rotating velocity. According to the triangle relation, the azimuthal component of the DW velocity is lower than the classical CJ velocity. There is an oblique shock wave associated with the DW that extends to the exit to compress the former cycle detonation product. The numerical results for the above wave structures qualitatively agree with experimental results[5]. At the head wall, it is seen from the pressure contours that reflecting shock waves repeatedly reflect between the inner wall and outer wall and finally become a sound wave. Because of the curvature of the cylinders, the DW front on the inner expansion wall goes ahead of the wave front on the outer wall by about 3°. Conversely, the maximum pressure on the outer compression wall is about 13 MPa, which is nearly twice the pressure of 7 MPa on the inner wall.

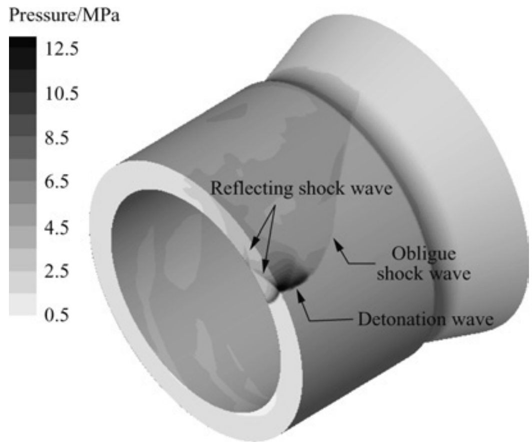

Fig.5 Pressure contour at 1 500 μs.

Fig.6 shows the Mach number contours in Laval nozzle combustor. It is seen that the flow is mainly subsonic in front of the throat. As the detonation product flows through the diverging section, it accelerates to a high Mach number greater than 2. The maximum Mach number is 2.5 for the axial velocity of 2 100 m/s at the exit. Fig.7 shows the instantaneous pressure history at a point near the head (radius = 48 mm, z = 1 mm) for the period of 0-1 500 μs. It is seen that once the initial transient effects die down, the DW maintains continuous oscillatory propagation in the annular chamber as long as fuel is continuously

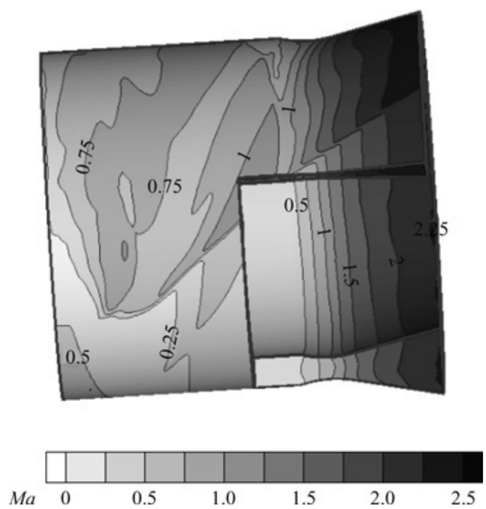

Fig.6 Mach number contours at 1 500 μs.

injected. According to Fig.7, in the period of 336-1 486 μs, the DW has propagated through seven rounds, and the DW rotating velocity is thus $V_R = 7\times2\pi r/\Delta t$ =1 841 m/s. This value is about 5% less than the classical CJ velocity of about 1 984 m/s. This deficit is mainly caused by the incline of the DW discussed at the beginning of this section. And also, unlike the case for the CJ theory model, one side of the DW is in soft contact with the detonation product. This condition would also reduce the detonation velocity a little.

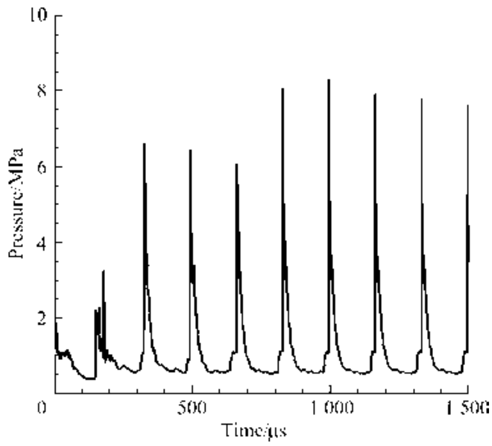

Fig.7 Pressure history at a point near head of combustor (r = 46 mm, z = 1 cm) for period of 0-1 500 μs.

3.2. Propulsive performance

The gross thrust F, the fuel mass flow rate per square meter $\dot{m}$, the gross specific impulse I_{sp}^{g} not including the momentum of the incoming gas, and the net specific impulse I_{sp}^{n} are calculated according to the following equations.

$$F(t)=\oint_{exit}(\rho w^2+p-p_\infty)\mathrm{d}A \tag{6}$$

$$\dot{m}(t)=\frac{1}{A_{head}}\oint_{head}\rho w\mathrm{d}A \tag{7}$$

$$I_{sp}^{g}(t)=\frac{\oint_{exit}(\rho w^2+p-p_\infty)\mathrm{d}A}{A_{head}g\dot{m}_f} \tag{8}$$

$$I_{sp}^{n}(t)=\frac{\oint_{exit}(\rho w^2+p)\mathrm{d}A-\oint_{head}(\rho w^2+p)\mathrm{d}A}{A_{head}g\dot{m}_f} \tag{9}$$

where w is the axial velocity, $\dot{m}_f$ mass flow rate fuel, and A_{head} the cut area at the tube head. Fig.8 shows the thrust history of the models for the period 0-1 500 μs. After the flow field becomes steady, the models continuously create enormous, almost steady thrust. The CDE with the diverging nozzle creates about 1 900 N thrust, which is considerable for such a small combustor. The CDE with the constant-area nozzle outputs the least thrust of about 1 600 N.

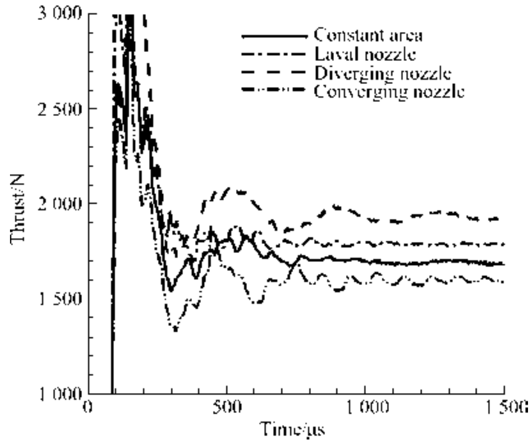

Fig.8 Thrust history of four CDEs with different nozzles.

Fig.9 shows the fuel-based gross specific I_{sp}^{g} history. The gross specific impulse ranges 1 540-1 750 s for the four types of nozzles. The Laval nozzle has the best performance of about 1 750 s. All previous articles[10-12] use the criterion of the gross specific impulse to determine the gross propulsive performance. Clearly, higher I_{sp}^{g} could be achieved with greater injection momentum according to this criterion. In this article, the net specific criterion is used to compare the momentum increase due to continuous detonation combustion.

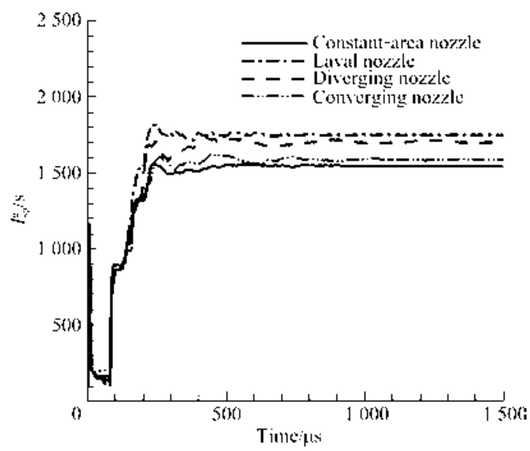

Fig.9 Gross specific impulse history for period of 0-1 500 μs.

Fig.10 shows that the net specific impulses specifically produced by the four nozzles vary from 60 s to 630 s. For these cases, a Laval nozzle has the best efficiency over the other three nozzles.

The average mass flux $\dot{m}$ values are shown in Fig.11. The mass flux per square meter ranges 313-330 kg/(m^2·s) for the different nozzles. It is seen that these values vary little, and the average mass flow rate is about 320 kg/(m^2·s), which is significantly favorable value. This demonstrates the mass flow rate advantage of a CDE.

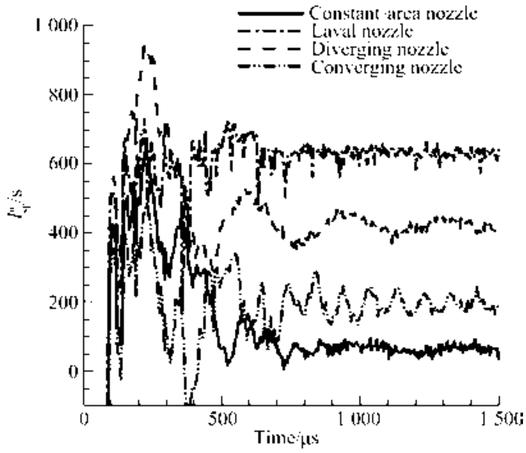

Fig.10 Net specific impulse history for period 0-1 000 μs.

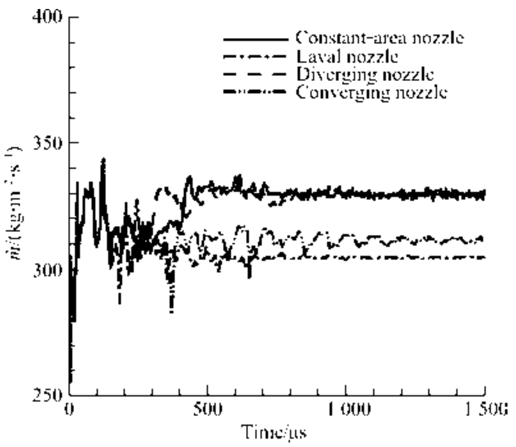

Fig.11 Average mass flow rates per square meter for four types of nozzles.

4. Conclusions

The typical flow field structure of a CDE is numerically obtained and found to agree well with the results of previous experiments. The key propulsion performance parameters, namely thrust, specific impulse and the mass flow rate, are exhaustively analyzed for the CDE. Different effects of different kinds of nozzles on the CDE performance are compared. We find that the Laval nozzle has the best performance of 1 800 N thrust, 1 750 s gross specific impulse and 313 kg/(m^2·s) mass rate. The Laval nozzle has some advantages over other three nozzles.

As CDE concept is an essentially innocative combustor design concept of propulsion system, it is easy to substitute conventional aviation system's combustor to achieve higher performance. Once proven to be effective, it would be a good candidate for the new generation aerospace propulsion system.

References

[1] Roy G D, Frolov S M, Borisov A A, et al. Pulse detonation propulsion: challenges, current status, and future perspective. Progress in Energy and Combustion Science 2004; 30(6): 545-672.

[2] Li Q, Fan W, Yan C J, et al. Experimental investigation on performance of pulse detonation rocket engine model. Chinese Journal of Aeronautics 2004; 17(1): 9-14.

[3] Shao Y T, Wang J P. Change in continuous detonation wave propagation mode from rotating detonation to standing detonation. Chinese Physics Letter 2010; 27(3): 034705.

[4] Voitsekhovskii B V. Stationary spin detonation. Soviet Journal of Applied Mechanics and Technical Physics 1960; 3:157-164. [in Russian]

[5] Bykovskii F A, Zhdan S A, Vedernikov E F. Continuous spin detonations. Journal of Propulion and Power 2006; 22(6): 1204-1216.

[6] Bykovskii F A, Mitrofanov V V, Vedernikov E F. Continuous detonation combustion of fuel-air mixtures. Combustion, Explosion and Shock Waves 1997; 33(3): 344-353.

[7] Bykovskii F A, Vedernikov E F. Continuous detonation of a subsonic flow of a propellant. Combustion, Explosion, and Shock Waves 2003; 39(3): 323-334.

[8] Kindracki J, Wolanski P, Gut Z. Experimental research on the rotating detonation in gaseous fuels-oxygen mixtures. 22nd International Colloquium on Dynamics of Explosions and Reactive Systems. 2009.

[9] Falempin F, Daniau E A. A contribution to the development of actual continuous detonation wave engine. AIAA-2008-2679, 2008.

[10] Zhdan S A, Bykovskii F A, Vedernikov E F. Mathematical modeling of a rotating detonation wave in a hydrogen-oxygen mixture. Combustion, Explosion, and Shock Waves 2007; 43(4): 449-459.

[11] Hishida M, Fujiwara T, Wolanski P. Fundamentals of rotating detonations. Shock Waves 2009; 19(1): 1-10.

[12] Shao Y T, Wang J P，Tang X M, et al. Three dimensional numerical simulation of continuous rotating detonation engine flowfields. Journal of Aerospace Power 2010; 25(8): 1717-1722. [in Chinese]

[13] Jiang X H, Fan B C, Gui M Y, et al. Numerical investigations on the three-dimensional flow patterns of the continuous rotation detonation. 22nd International Colloquium on Dynamics of Explosions and Reactive Systems. 2009.

[14] Ma F H, Choi J Y, Yang V G. Propulsive performance of airbreathing pulse detonation engines. Journal of Propulsion and Power 2006; 22(6): 1188-1203.

[15] Balsara D S, Shu C W. Monotonicity preserving weighted essentially non-oscillatory schemes with increasingly high order of accuracy. Journal of Computational Physics 2000; 160(2): 405-452.

[16] Gamezo, V N, Desbordes D, Oran E S. Two-dimensional reactive flow dynamics in cellular detonation waves. Shock Waves 1999; 9(1): 11-17.

Biography:

Shao Yetao Born in 1981, he received B.S. degree from Jilin University in 2005 and Ph.D. degree from Peking University in 2010 respectively. His main research interests are CFD and detonation propulsion.
E-mail: shaoyt@163.com