3D numerical study on continuous detonation engine using reactive Navier-Stokes equations

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1 Introduction

The thermodynamic cycle of a detonation engine is close to the isochoric cycle. It has higher thermodynamic efficiency than classical aircraft and rocket engines at the same initial state. Due to the self-sustaining and self-compression properties of detonation wave (DW) [1], combustible gas is compressed by the shock wave, the detonation engine does not require turbo-pumps or compressors. So the structure of the detonation engine is simple. To make further advances in propulsion devices, the detonation engine had been extensively studied. Nicholle [2] first suggested the utilization of detonation wave in pulse detonation engines (PDEs) in 1957. Now, it is limited by high operational frequency and high ignition energies. B.V. Voitsekhovskii [3] proposed the continuous rotating detonation engines (CDEs) in 1959 as shown in Fig.1 a co-axial annual combustor model of CDEs. The CDEs just need a single ignition, detonation wave can continuously propagate around the combustor. However, due to the fact that CDEs has the feature of high temperature, high pressure, and high speed, the measurable parameters are restricted, the importance of numerical simulation [4-7] is highlighted. But the influence of no-slipping boundary conditions, viscosity and thermal conduction is often absent in conventional CDEs simulations by using Euler equations. The objective of this paper is to investigate the influence of no-slipping boundary conditions, viscosity and thermal conduction on detonation propagation using the reactive Navier-Stokes (N-S) equations and compare the results with that solved using the reactive Euler equations.

2 Physical model and numerical methods

The combustor of the CDEs is a co-axial annual cavity (Fig.1). The inner radius is 4cm and the outer radius is 4.6cm. The chamber length is 9cm.The premixed stoichiometric hydrogen/air gases are injected into the combustor along the axial direction.

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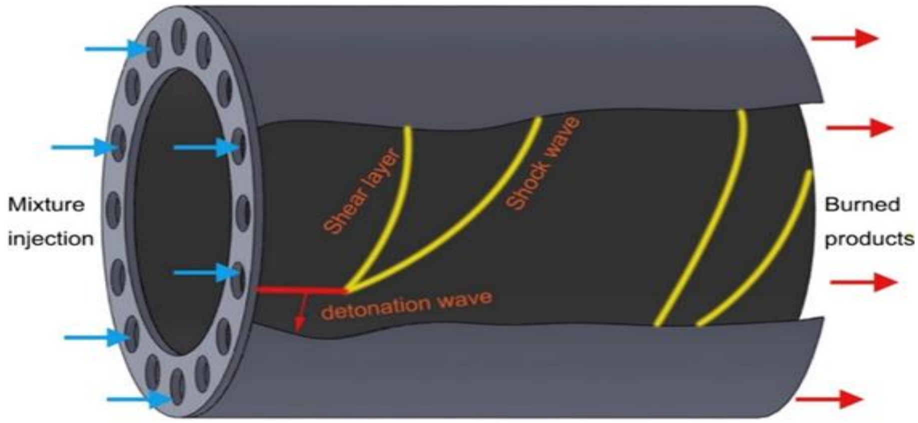


Fig. 1. Schematic of a co-axial annular combustor model of a CDEs.

The left side of Fig. 1. is the head-end, which has been assumed as Laval nozzle inflow boundary condition. The ratio of the nozzle exit area to the nozzle throat area is set to 10. Non-reflecting boundary condition is used at the exit. No slipping and adiabatic boundary conditions are used on the solid walls. Besides, mesh refinement is used near the solid wall. At the initial time, the flow-field is filled with premixed stoichiometric hydrogen/air gas. The pressure is 3 atm and the temperature is 300 K. Pre-detonation ignition is substituted by a section of one-dimensional Chapman-Jouguet (CJ) detonation wave. The injection stagnation pressure is 20 atm and the temperature is 600k. After ignition, the DW continuously propagates around the combustor [8-10].

Currently, most of the numerical investigations of CDEs are based on the Euler equations, particularly for three-dimensional simulations. In this paper, three-dimensional reactive N-S equations with a one-step Arrhenius chemistry model in generalized coordinates.

Flux terms are solved by using the 5-step monotonicity preserving weighted essentially non-oscillatory (MPWENO) scheme, viscous terms and thermal conduction terms are solved by using the 2-order central difference schemes [8-12]. The temporal terms are discretized with the 3-step TVD Runge-Kutta method [13].

3 Results and discussion

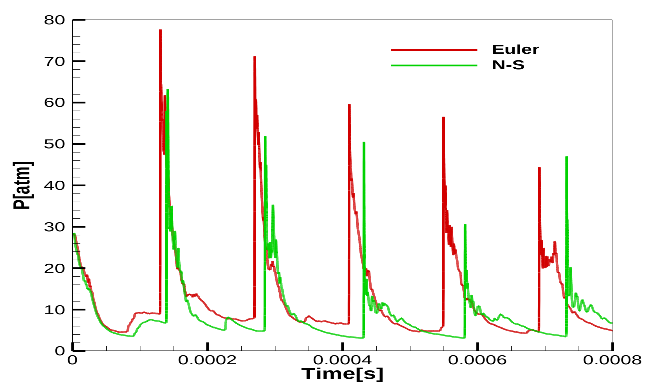


Fig. 2. Pressure-time profile at the point (radius=4.4cm, $\theta = \pi/2$, z=0.3cm) during 0-800μs

This paper investigates the influence of no-slipping boundary conditions, viscosity and thermal conduction via a comparative analysis of the simulation results with the reactive N-S equations and the reactive Euler equations. The reactive Euler equations ignore viscosity, thermal conduction and slip boundary conditions are used on the solid walls. Those are different from the reactive N-S equations.
The detonation wave velocity is 1827.29 m/s if the equations are the reactive N-S equations and the velocity is 1877.27 m/s when the reactive Euler equations are used (see Fig.2). The theoretical value is 1984 m/s. The velocity is decreased when the equations are the reactive N-S equations, because no-slipping boundary conditions and viscosity can induce dissipation of kinetic energy. But the influence is limited.

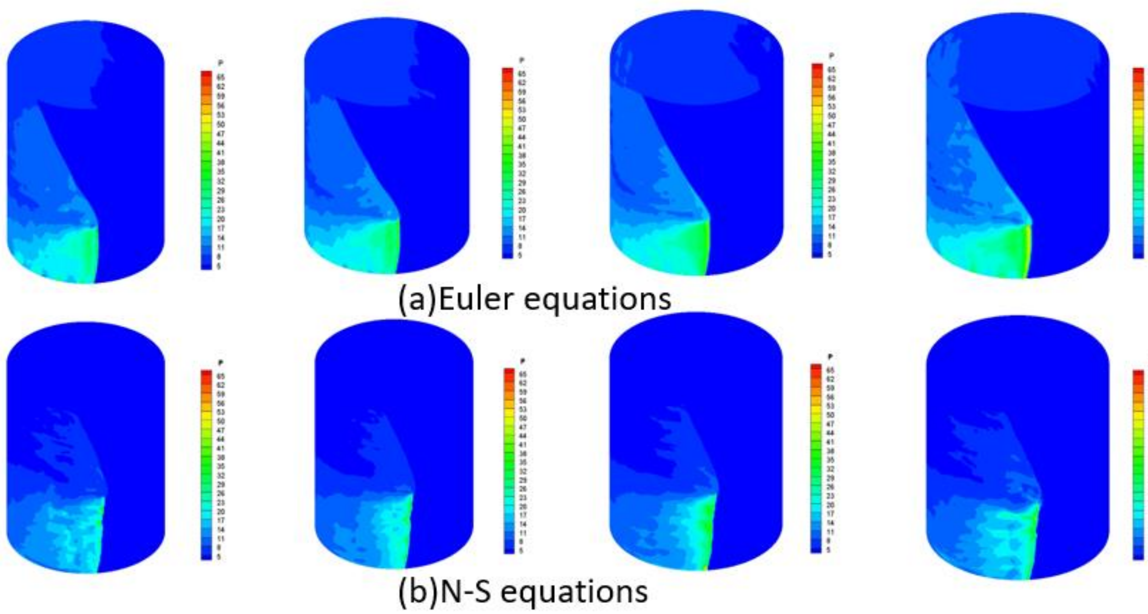


Fig. 3 Pressure contours of (a)Euler equations, (b)NS equations (radius=4cm,4.2cm,4.4cm,4.6cm)at 800μs

From Figure3 we can see that the height of the detonation wave front is higher if we use N-S equations, because smaller background pressure and the velocity deficit induce the height of combustible gas is higher. The strength of detonation wave and flow field is weaker, it is because the pressure and temperature of the combustible gas in front of the detonation wave is lower. Because the same reason, the strength of oblique shock wave is weaker. The angle between the oblique shock wave and the detonation wave is larger.

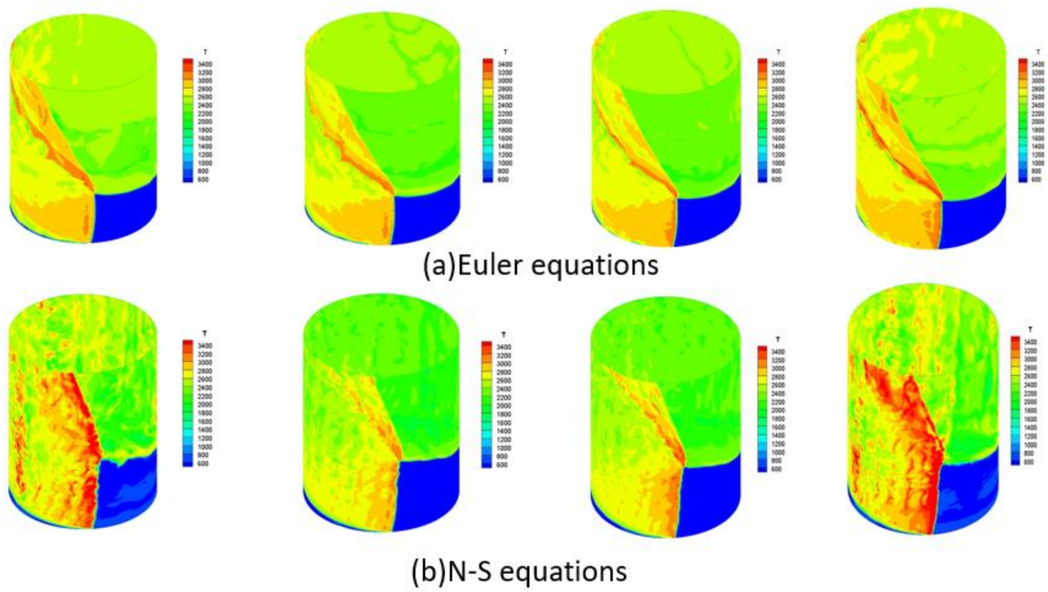
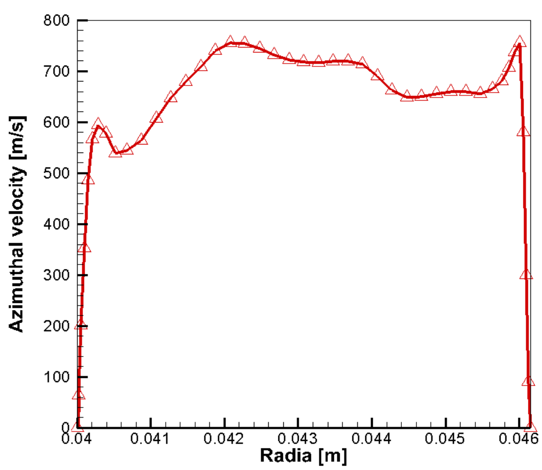
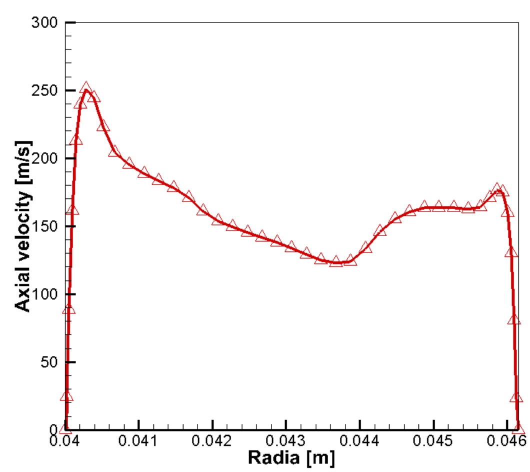


Fig. 4 Temperature contours of (a)Euler equations, (b)NS equations (radius=4cm,4.2cm,4.4cm,4.6cm)at 800μs

The temperature of burned products behind the detonation wave of Fig. 4(b) is higher than Fig. 4(a) when examining the color of the contours. The temperature changes a little in the radius direction when governing equations are Euler equations.Near the wall , the temperature is higher if we use N-S equations, It is because of dissipation of kinetic energy in the boundary layer. The height of the detonation wave front is higher if we use N-S equations, because smaller background pressure and the velocity deficit induce the height of combustible gas is higher.





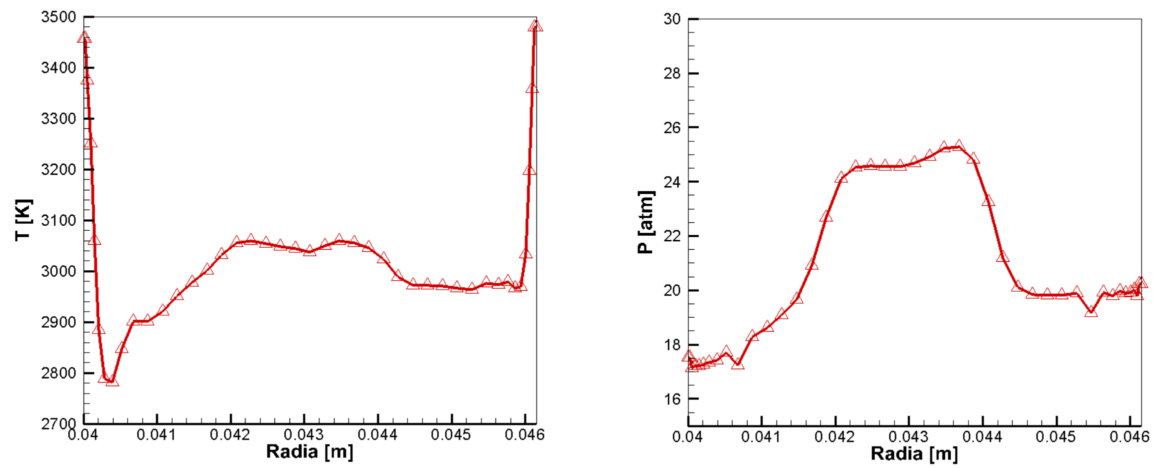


Fig. 5. Azimuthal velocity (a), axial velocity (b), pressure (c) and temperature (d) profile at the line (θ =1.12 π , z=0.01cm, radius 4-4.6cm) at 800μs.

The velocity boundary layer is obvious in Figure. 5(a) and (b). The temperature boundary layer is also obvious from Figure. 5(d). Figure. 5(c) gives the pressure change along the radius line. The temperature is very high near the wall. Because the velocity gradient is very large, dissipation of kinetic energy is obvious near the wall. The pressure is nearly unchanged in the boundary layer

4 Conclusion

The main points are as follows: If we use N-S equations, The velocity of detonation wave is deficit. The temperature is higher in the boundary layer. The height of the detonation wave front is higher. The strength of detonation wave, the flow field and the strength of oblique shock wave is weaker. The angle between the oblique shock wave and the detonation wave is larger. The velocity enlarge quickly, the temperature decreases rapidly and the pressure is nearly unchanged in the boundary layer.

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