Numerical Study on Effect of an Inner Cylinder on Flow Field of Carbon/Air Rotating Detonation Engines

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1 Abstract

This paper describes a numerical investigation of the effect of an inner cylinder on the two-phase flow field of a rotating detonation engine fueled by carbon and air. Results show that the mixing quality of the hollow combustor without an inner cylinder is more poor, the height and velocity of the detonation wave are lower, and the pressure presents a greater fluctuation. The local equivalence ratio before the detonation wave of the hollow combustor is higher than that of the annular combustor with an inner cylinder. The air above the particle layer deflagrates with the incompletely burned particles after the region with high temperature and high pressure, making the contact surface uneven and a lack of the low temperature stripe.

2 Introduction

Rotating detonation is an important approach to realize pressure-gain combustion, which can help to improve the performance of propulsion devices. According to experimental and numerical studies on rotating detonation engines (RDEs) with gaseous fuels, extensive understanding on rotating detonation has been obtained, such as the thermodynamic performance, detonation instabilities, ignition process, and combustion mode, etc. These achievements have laid a foundation for multiple engineering applications of RDEs.

However, compared with gaseous fuels, the solid fuels have some advantages, including lower cost, higher density and heating values per unit volume. For instance, coal is a kind of solid fuel primarily used for electric power generation, which currently supplies 41% of global electricity needs[1]. If coal was applied to RDEs in the detonation cycle, the efficient utilization of coal could be realized. Bykovskii et al.[2-3] were the first to develop an experimental continuous detonation combustor for coal-hydrogen-air mixtures. The composition of the char and volatile components in the coal was found to have a significant influence on the detonation waves. Dunn et al.[4] added carbon to a hydrogen-air RDE, and obtained gas-solid RDW propagation under various total mass flux, hydrogen-

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air equivalence ratios, and total carbon concentrations. The results show that when carbon is injected into a hydrogen-air mixture with a low equivalence ratio (Er), the stability of the RDW decreases and the velocity fluctuations reach ~100 m/s. In subsequent experiments[5], the combustion of carbon particles in the detonation wave released heat that sustained the movement of the detonation wave. The combustion heat was found to have a linear relationship with the amount of carbon particles added. But experimental limitations have prevented the full information of the flow field from being revealed. In this paper, three-dimensional numerical simulations of a RDE using carbon-air were carried out. The characteristics of flow filed of the RDE is revealed to fill the gaps left by experimental studies on solid fuel RDEs.

3 Physical Model and Numerical Method

Figure 1 shows the physical model of the RDE. The inner radius is R_{in}=20 mm, the outer radius is R_{out}=30 mm, and the total length is L=50 mm. The computed domain is meshed with hexahedron cells, and the main cell sizes are between 0.25 and 0.5 mm. The grid is refined near the walls, and the minimum cell size is 0.05 mm. The carbon-air mixture with an equivalent ratio of 0.7 (air and carbon of mass flow rate are 0.5 kg/s and 0.03 kg/s, respectively) is injected axially into the combustor. The region $0 \leq y \leq 10$ mm is filled with carbon/air mixture, and a small region with a pressure of 2.0 MPa, temperature of 2000 K, and tangential velocity of 2000 m/s is used to initiate the rotating detonation wave (RDW), which is the ignition zone in Fig. 1.

The transient implicit density-based solver is used to solve the three-dimensional Reynolds-averaged Navier-Stokes (RANS) governing equations with source terms. The shear-stress transport (SST) k-ω turbulence model is employed. The discrete phase model (DPM) and multiple surface reaction model are employed to determine the flow and combustion of carbon particles, and the laminar finite rate reaction model is used for the two-step gaseous chemical reactions[6]. The least squares cell based method is used to calculate gradients and derivatives for spatial discretization. The scheme of first order upwind is used for turbulent kinetic energy and specific dissipation rate, and the second-order implicit method is applied for time differencing. The time step is 0.05 μs.

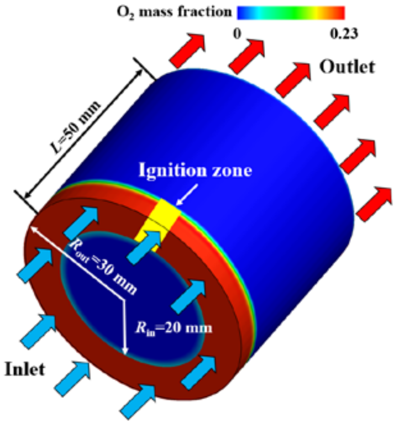

Figure 1: Physical model and initial flow field

4 Results and Discussions

4.1 The effect of the inner cylinder on the RDW

In this paper, three-dimensional numerical simulations were carried out for the combustors with and without an inner cylinders under the same operating conditions. As shown in Fig. 2, there is only one RDW in the two combustors, and the RDW heights of the combustors with and without an inner cylinder are 15.1 mm and 19.4 mm respectively. Since the volume of the combustor without an inner cylinder is larger, there is more space to release the high pressure behind the RDW. What's more, the pressure of the combustor is lower, making the reactant injection velocity higher, so a higher triangular fuel layer is formed in a cycle.

Figure 3 shows pressure traces and RDW velocities of the two combustors. The hollow combustor has a higher RDW velocity and larger fluctuations than the annular combustor. According to the results of previous studies[7-8], the detonation products in the central region in the hollow combustor are similar to the inner cylinder of the annular combustor. However, the diameter of the detonation products is smaller than that of the inner cylinder, resulting in a higher RDW velocity. The axial velocity of the hollow combustor is higher in Fig. 2(c), which leads to poor mixing of reactants before the RDW, reduces the RDW intensity, and decreases resistance to expansion wave interference. As a result, the peak pressure fluctuations are obvious.

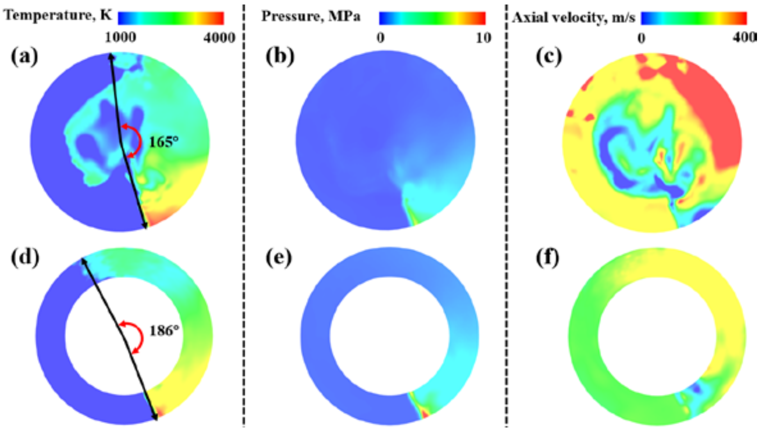

Figure 2: (a) Temperature, (b) Pressure and (c) Axial velocity contours of the hollow combustor at z=5 mm. (d) Temperature, (e) Pressure and (f) Axial velocity contours of the annular combustor at z=5 mm.

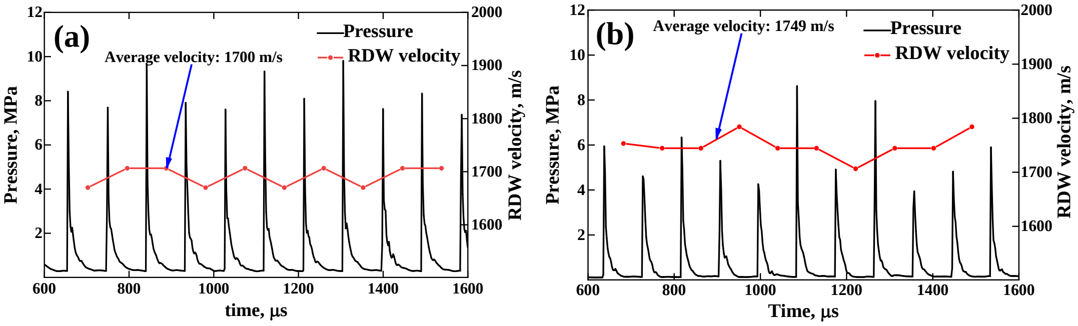

Figure 3: (a) Pressure traces and the RDW velocity of the annular combustor, (b) Pressure traces and the RDW velocity of the hollow combustor.

4.2 Characteristics of two-phase flow

The flow field of the annular combustor is shown in Fig. 4. The flow field is similar to that of gaseous RDEs[9], including the RDW, oblique shock wave (OSW) and triangular fuel layer, but there is a low-temperature strip (LTS) instead of the slip line behind the RDW, which separates the present detonation products from the detonation products of the previous cycle. Since air has a higher injection velocity than the particles, the air filling height along the z axis is higher than the particle filling height in the reactant region. The height difference means the air near the products will pass the intersection between the RDW and the OSW, resulting in the LTS full of air in Fig. 4(a) and 4(c)[6], and the local equivalence ratio before the RDW is higher than the global equivalence ratio, making particles behind the RDW burn incompletely. Thus solid-gas RDEs may operate well in fuel-lean conditions.

As shown in Fig. 4(a) and 4(b), the newly injected particles and air deflagrate under the high temperature region behind the RDW, while the z velocity of particles decreases due to the high pressure in this region, which causes the particles to accumulate. The particles cannot be completely burned even under the fuel-lean condition. The incompletely burned particles flow downstream near the LTS and react with air again over time, making the temperature of the OSW higher.

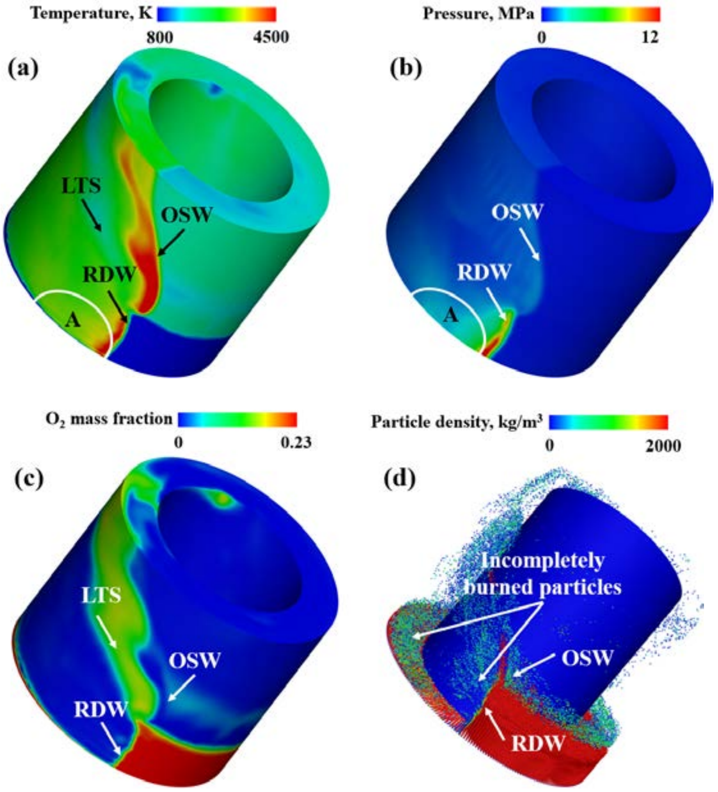

Figure 4: The flow field of the annular combustor. (a) Temperature contours, (b) Pressure contours, (c) Mass fraction contours of O_2 and (d) Particle density contours. A region has high temperature and high pressure.

Some air will flow toward the region near the center with little fuel in Fig. 5(c) and 5(d) due to the injection configuration of the hollow combustor, and this mixture does not contribute to the detonations[8]. Therefore, the local equivalence ratio in the region where the RDW propagates is higher than the annular combustor, and the number of incompletely burned particles increases significantly in Fig. 6(d). According to the above analysis, the injection velocity of the reactants in the hollow combustor is higher, causing the air above the particle layer to deflagrate with the incompletely burned particles in the high-temperature and high-pressure region in Fig. 5(a) and 5(b). Therefore, the contact surface is uneven and there is no LTS in Fig. 5(a) and 5(c).

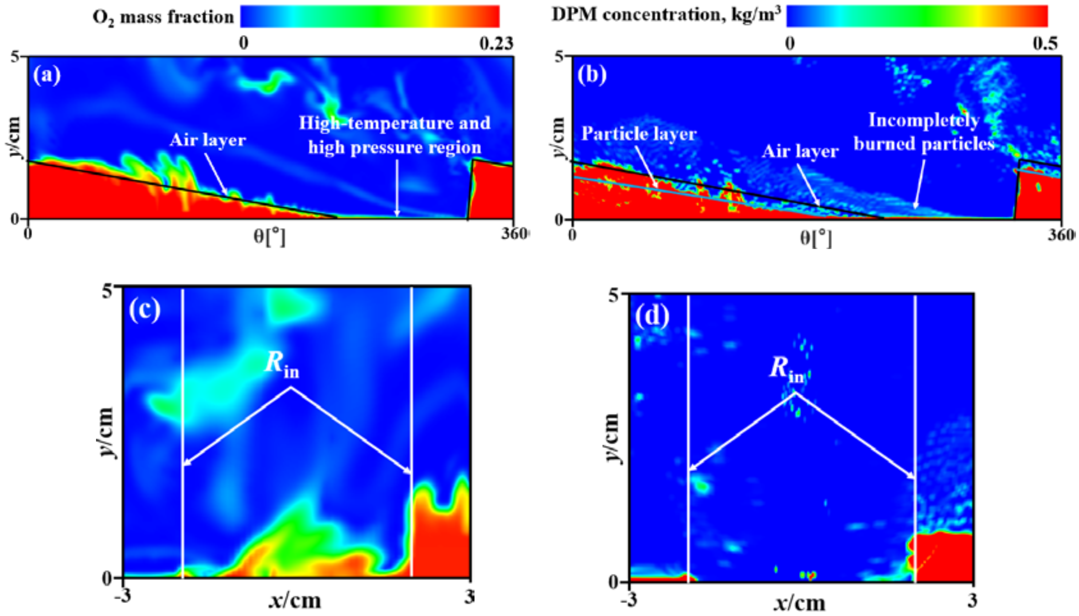

Figure 5: (a) Contours of mass fraction of O_2 along the outer wall, (b) Contours of DPM concentration along the outer wall, (c) Contours of mass fraction of O_2 at y=0 mm surface and (d) DPM concentration contours at y=0 mm surface of the hollow combustor. DPM concentration is the total concentration of the particles in all phases in a cell.

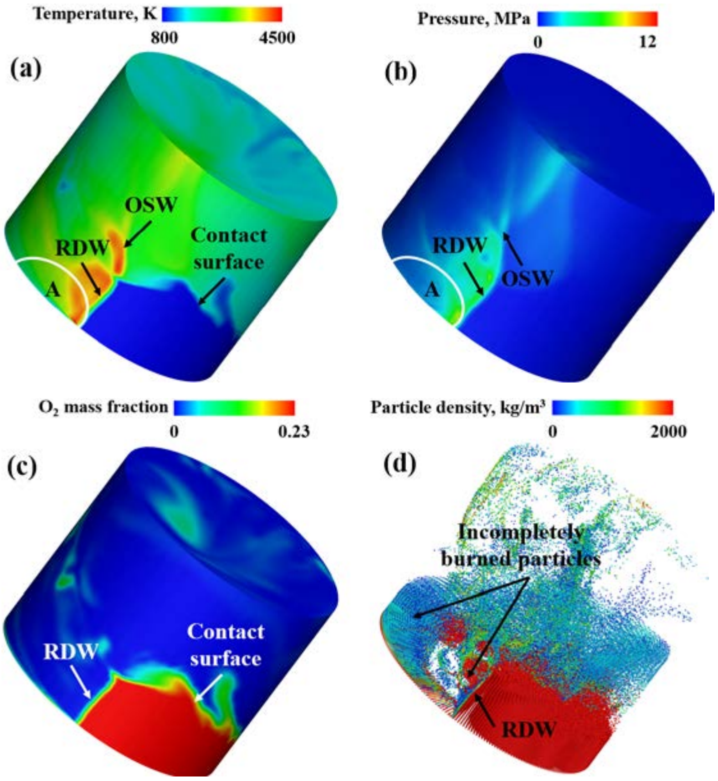

Figure 6: The flow field of the hollow combustor. (a) Temperature contours, (b) Pressure contours, (c) Contours of Mass fraction of O_2 and (d) Particle density.

5 Conclusions

The effect of the inner cylinder on the two-phase flow field of a RDE using carbon and air has been numerically studied. The results are as follows:

(1) The axial velocity in the hollow combustor is higher, resulting in the deteriorated mixing, the increased height and propagation velocity of the RDW and a greater pressure fluctuation.

(2) The local equivalence ratio is higher than the global equivalence ratio for the two-phase flow field because the gas has a higher velocity than the particles. Thus, solid-gas RDEs may operate well in fuel-lean conditions.

(3) Some air in the hollow combustor will flow toward the region near the axis, so the local equivalence ratio before the RDW is higher than that of the annular combustor, and the number of incompletely burned particles is larger. The air above the particle layer deflagrates with the incompletely burned particles in the high-temperature and high-pressure region, making the contact surface uneven and a lack of the LTS.

Acknowledgements

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