Numerical Analysis of 3D-Rotating Detonation Engine Concerning Propagation Mechanism in Combustor Thickness Direction and Effect on its Performance

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1 Introduction

Detonation is complex phenomena with higher thermodynamic efficiency than deflagration. Detonation is used for several aerospace engine systems; pulse detonation engine (PDE), oblique detonation engine (ODE), spin detonation engine (SDE), and rotating detonation engine (RDE). PDE has a simple mechanism and the most developed detonation engine at experimental flight phase. However, PDE must be refilled and initiated every cycle and provides intermittent thrust. On the other hand, RDE is alternative type of a combustion engine where detonation propagates to circumferential direction in annular combustion chamber. RDE's advantages are to initiate once and to inject unreacted gas while detonation wave propagating continuously.

Voitsekhovskii [1] presented the fundamentals of rotating detonation in 1960. Nicholls et al. [2] presented an analysis of the RDE prototype in 1966. However, they only observed the first rotating detonation cycle using a Chapman-Jouget condition and could not observe any additional cycles. Recently RDE sdudies are published by many researches.[3-9]

In this study, 3D program is developed. This paper deals with three-dimensional simulation of RDE propagation mechanism in a combustion chamber with hydrogen-oxygen mixture to observe the phenomena in radial direction in details.

2 Numerical method and condition

For the 3D calculation, the governing equations are compressible Euler equations with 9 species (H_2, O_2, H, O, OH, HO_2, H_2O_2, H_2O and N_2) and 18 elementary reactions. The Strang-type fractional step method is used for time integration, MUSCL Advection Upwind Splitting Method Difference Vector (AUSMDV) scheme is used for convection term, the point implicit method for the source term.

The initial conditions are as follows; the ambient pressure is 0.1 MPa; ambient temperature is 300 K; reservoir pressure is 5 MPa; equivalence ratio is 1.0; inner diameter of conbustion chamber is 0.4mm and outer diameter is 0.45mm.

There are two boundary condition systems for the fuel injection. The supersonic inlet condition is used for most of the experiments because the inlet nozzles for fuel typically have a choked condition at the exits of small nozzles. The subsonic inlet condition is discussed by Zhdan et al. [10].

The computational domain of 3D calculation show in Fig.1. 1D detonation calculation result is attached in the light blue section, H2/O2 mixture is filled in the red section, and air is filled in the blue section. The number of grids are 301 point for axial direction, 51 point for radial direction, and 1201 point for circumference direction, with which the total number of grids is 18,436,551 points. The size of grids are 2μm each directions.

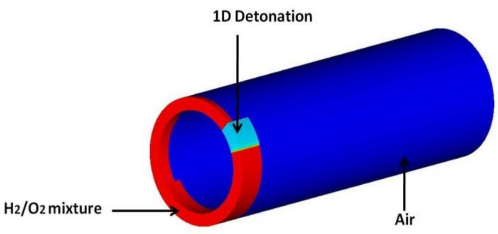

Figure1. 3D computational domain

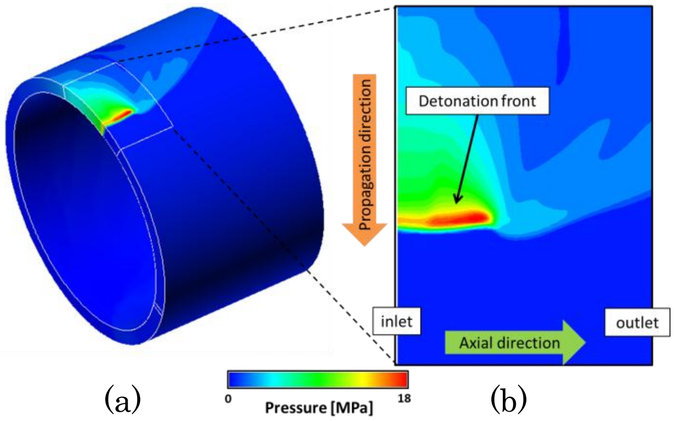

Figure 2. 3D calculation result in RDE ;
(a) the whole view of RDE and (b) a zoomed part of the outer wall

Table 1. Grid condition

Grid number	301x51x1201=18,436,551
Grid size	2μm

3 Results and discussion

3.1 Transverse wave

Figure 2 shows the 3D numerical results on pressure distribution of RDE; the left figure(a) is the whole view of RDE, and the right figure(b) is a zoomed part of the outer wall surface near the detonation front. The orange downward arrow in Fig.2(b) is the detonation propagating direction (circumferential direction) and the green rightward arrow is axial direction.
Figure 3 shows the pressure distribution on outer wall surfaces along the white line. The horizontal axis is the distance from the inlet wall. In Fig.3(2), the pressure rises suddenly at the time of 1.479μs depending on the triple point locations and transverse wave is generated and is propagating from right to left (Fig.3(5) - (7)). This mechanism is similar to the one obtained by 2D calculation for transverse wave. [3]
The structure of detonation front is complex in 3D. In Fig.4, OH distribution describes combustion chamber wall and translucently shown heat release iso-surface is detonation front. Transverse wave reaches the right end of detonation front at inner combustion chamber in Fig.4(a), and propagates to outer wall along the detonation front in Fig.4(b)-(c).

3.2 Unreacted gas pocket

Figure 5 shows OH distribution at the outer wall and the inner wall surface. Unreacted gas pocket was observed in 2D numerical analysis [3] to be generated between detonation front and contact surface. Unreacted gas enters between the detonation front and contact surface in Fig.5(a), and transverse wave propagates to axial direction in Fig.5(b), Unreacted gas shutting by transverse wave and unreacted gas pocket occurs at the inner wall in Fig.5(c). This cycle is repeated and propagates transverse wave continuously.

In Figure 6, combustion chamber wall and detonation front are described by OH distribution, and shock wave is shown by white line as pressure distribution. The oblique shock is generated between detonation front and contact surface, unreacted gas zone is generated between oblique shock and reaction wave. Quickly shutting unreacted gas zone provides an unreacted gas pocket and a micro explosion occurs when transverse wave propagates along the oblique shock, and micro explosion generates transverse wave to the left direction.

Figure 7 shows OH iso-surface and OH distribution. Unreacted gas zone occurs slantingly along the right end of detonation front, depending on the pressure difference between the inner wall and the outer wall, and unreacted gas pocket appeared only near inner wall shown in Fig. 7(e), because unreacted gas zone is too small to generate near outer wall.

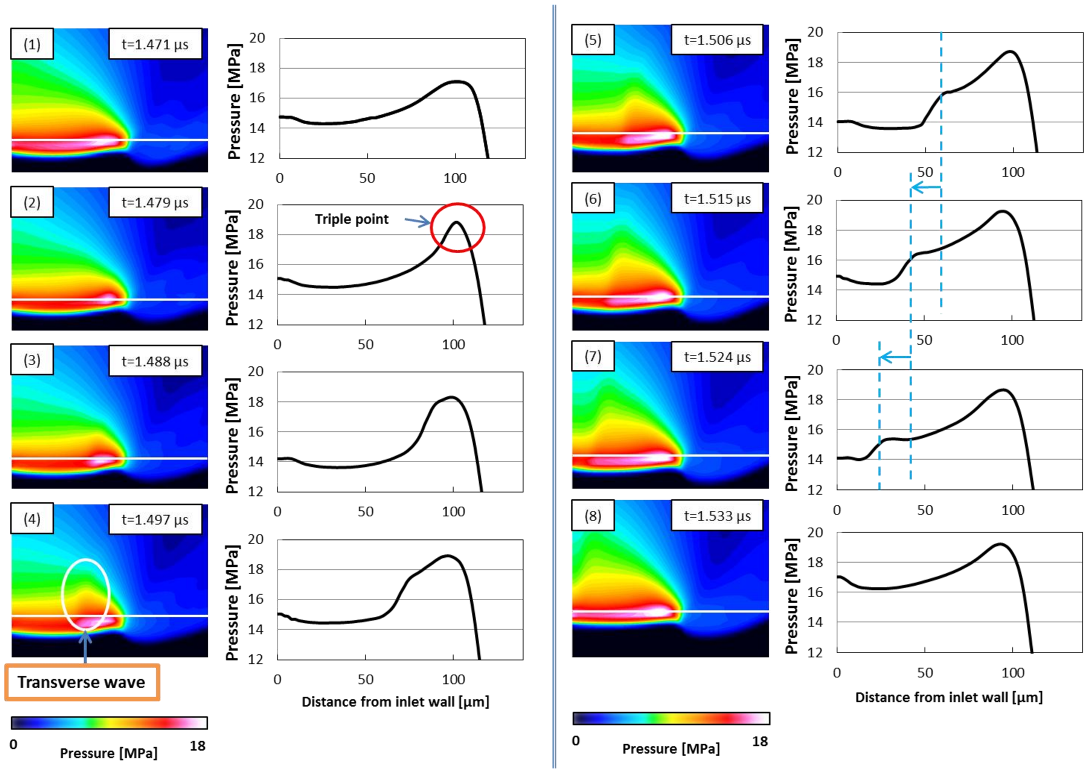

Figure 3. Pressure profiles at the outer wall

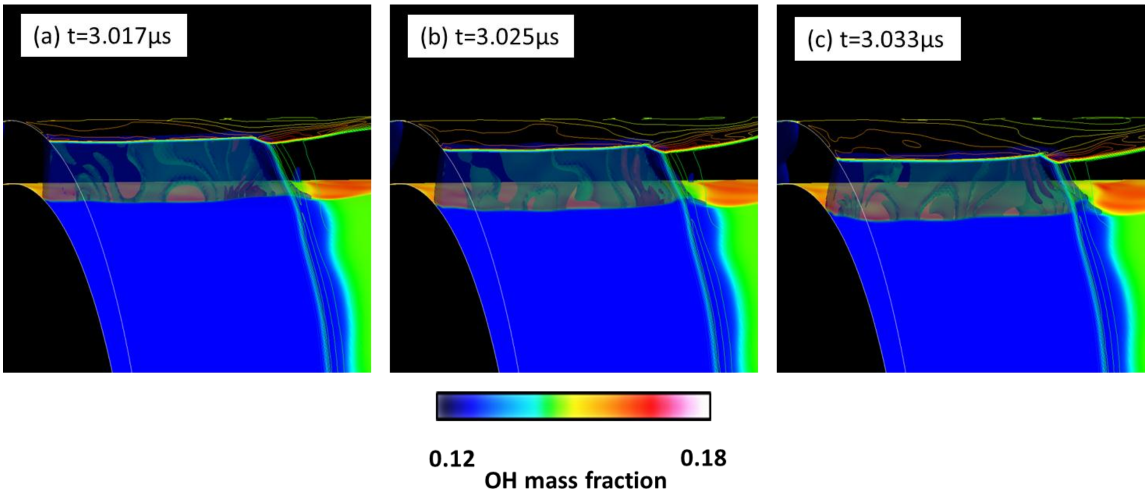

Figure 4. Heat release iso-surface

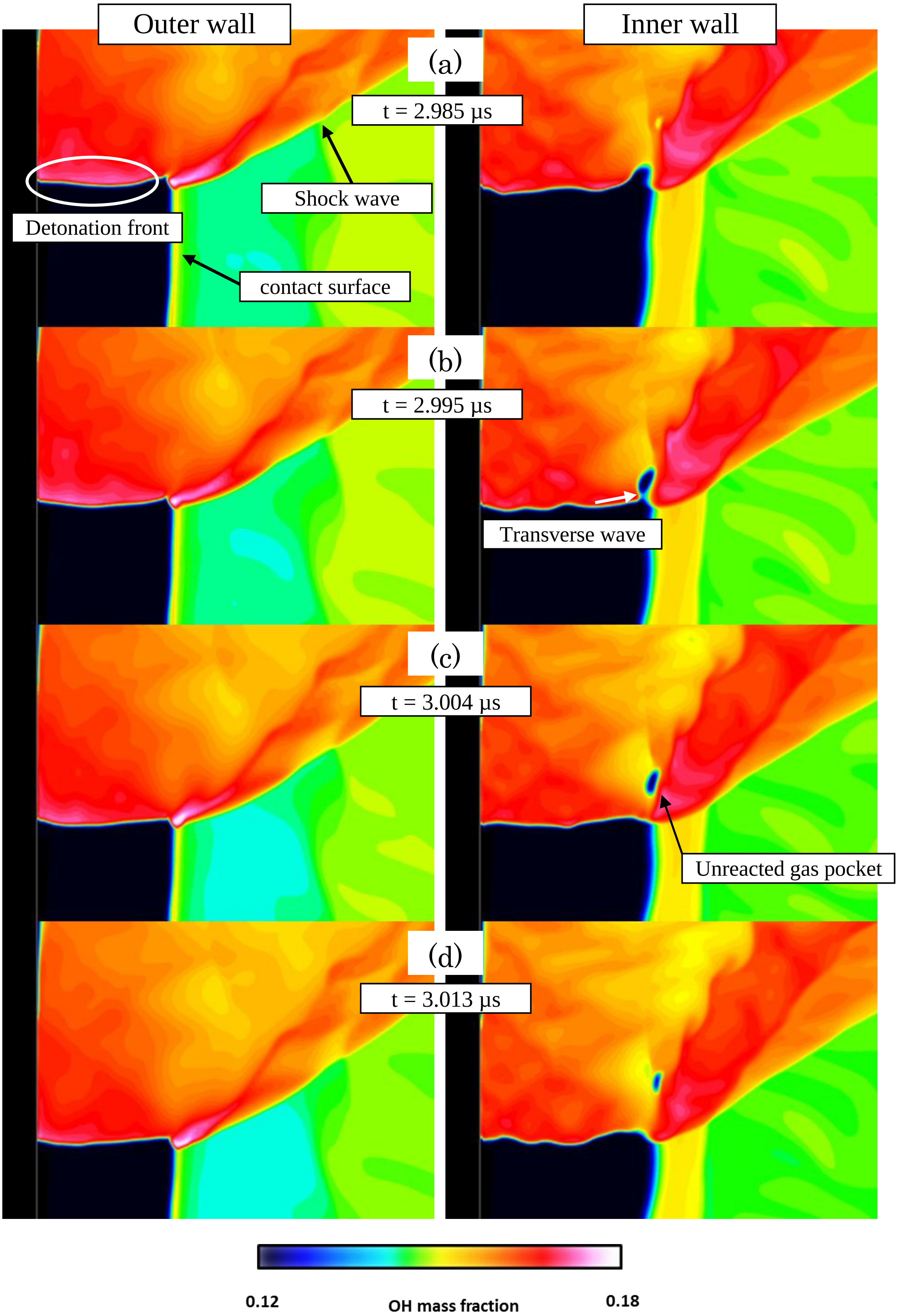

Figure 5. OH distribution at the outer wall and inner wall

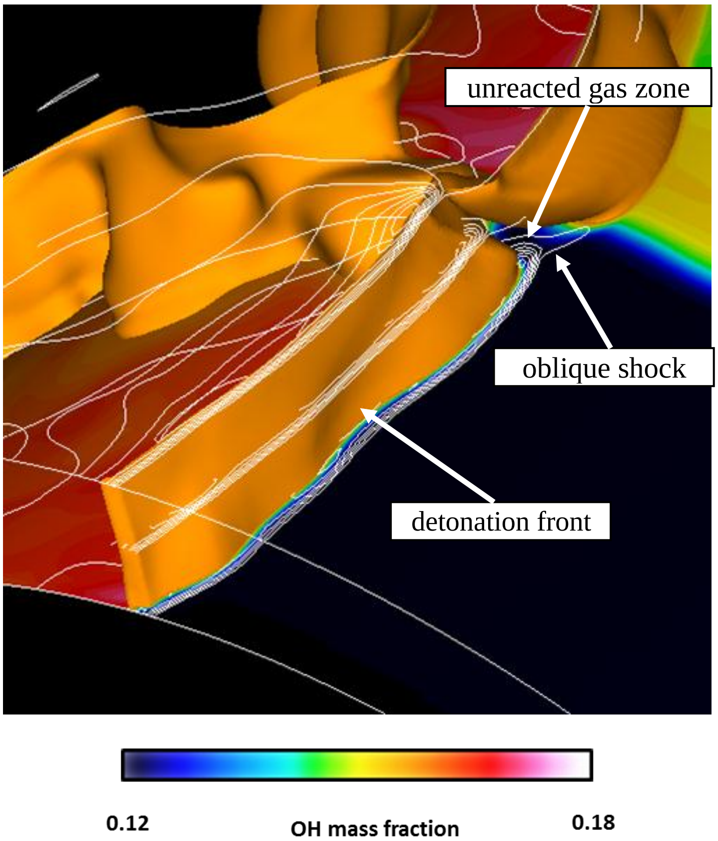

Figure 6. 3D induction zone in OH distribution

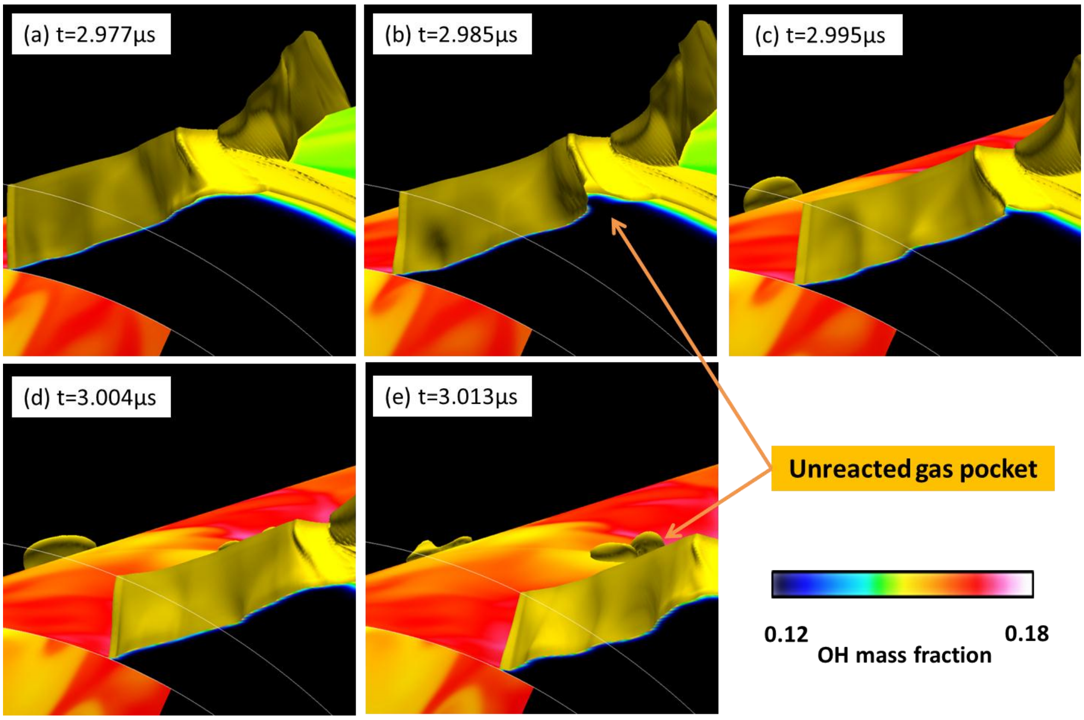

Figure 7. 3D unreacted gas pocket

4 Conclusions

Using 3D numerical code, RDE dynamics was obtained in details. Transverse wave occurs with the closed unreacted gas zone and detonation front appears to propagate toward the axial direction, which is similar to 2D numerical analysis.

The 3D unreacted gas zone exists obliquely to the radial direction along with the detonation front, which seems to affect the occurrence of transverse wave and propagation to the axial direction.

The structure of detonation front and unreacted gas pocket size change at radial direction, especially the unreacted gas pocket shapes conically.

Effects of RDE performance will be shown at the conference.

Acknowledgments

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References

[1] B.V. Voitsekhovskii, Soviet Journal of Applied Mechanics and Technical Physics 129, 6 (1960) 157-164.

[2] J.A. Nicholls, R.E. Cullen, K.W. Ragland, Journal of Spacecraft and Rockets 3, 6 (1966) 893-898.

[3] Y. Uemura, M. Asahara, A.K. Hayashi, N. Tsuboi and E. Yamada, "Transverse wave generation mechanism in rotating detonation" , Proceedings of the Combustion Institute, Volume 34, Issue 2, (2012) 1981-1989.

[4] J. Kindracki, P. Wolanski, Z.Gut, "Experimental Research on the Rotating Detonation in Gaseous Fuels-Oxygen Mixtures" ,Shock Waves, Vol.21, (2011), 75-84

[5] J.P.Wang, T.Shi, Y.Wang, Y.Liu, Y.Li, "Experimental Research on Continuous Detonation Engine", 23rd IVDERS,CD, (2011)

[6] E.M.Braun, N.L.Dunn, and F.K.Lu, "Testing of a continuous Detonation Wave Engine with Swirled Injection", 48th AIAA2010-146,(2010)

[7] P.Wolanski, "Debelopment of the continuous rotating detonation engines", 6th Int, On Pulsed and Continuous Detonations, Moscow,(2008)

[8] M.Hishida, T.Fujiwara, P.Wolanski, "Fundamental of rotating detonations", Shock Waves,Vol.19,(2009),1-10

[9] D.Schwer, K.Kailasanath, "Numerical Investigation of the Physics of Rotating Detonation Engines", Proc. Combust. Inst, Vol.33,(2011)

[10] S.A. Zhdan, A.M. Mardashev, V.V. Mitrofanov, Combustion, Explosion, and Shock Waves 26 (1990) 210-214.