

# Numerical Study of Reinitiation Phenomenon in Continuous Detonation Engine

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## 1 Introduction

Continuous detonations [1] in annular combustion chambers [2] have been tested for short durations, less than a second to a few seconds. The severe heating imposes limitations on a long-term running. Shao and Wang [3] therefore suggested an alternative design concept: a cylindrical combustion chamber (**Fig. 1**). The inner wall is removed from the combustion chamber. Tang *et al.* [4] explored the feasibility of this new design in detail by simulation. They investigated the flow field of continuous detonations in the quasi-steady state and evaluated the engine performance.

The initiation, propagation and stabilization of detonation waves in the continuous detonation engine (CDE) require further investigation, as pointed out by Lu and Braun [5] and other recent review articles [6, 7]. In addition, though the reinitiation of detonations has been observed in the experiment, it has not been discussed in the research on CDEs. In this study, we for the first time carry out a numerical simulation to explore the reinitiation phenomenon in the CDE. Moreover, the possible mechanism underlying this phenomenon is discussed.

## 2 Methodology

The simulation is modelled by the three-dimensional compressible Euler equations:

$$\begin{cases} \rho_t + \nabla \cdot (\rho \mathbf{u}) = 0, \\ (\rho \mathbf{u})_t + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) + \nabla p = 0, \\ (\rho e)_t + \nabla \cdot ((\rho e + p) \mathbf{u}) = 0, \\ (\rho \beta)_t + \nabla \cdot (\rho \mathbf{u} \beta) = \dot{\omega}. \end{cases} \quad (1)$$

The gaseous mixtures are assumed to be perfect and the reaction of the premixed stoichiometric hydrogen-air mixture is calculated by a single-step Arrhenius model:

$$\dot{\omega} = -A\rho\beta\exp\left(-\frac{T_a}{T}\right). \quad (2)$$

The flux terms are integrated by the fifth-order monotonicity-preserving weighted essentially non-oscillatory (MPWENO) scheme and march in time with the third-order total variation diminishing (TVD) Runge-Kutta method. A more detailed description of the modelling and chemical parameters can be found in Ref. [4].

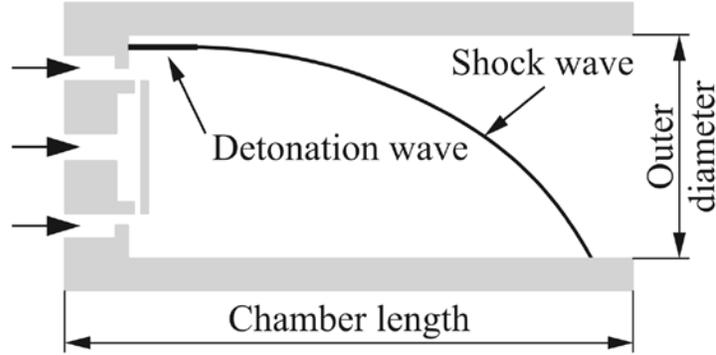


Figure 1. Schematic of a cylindrical CDE combustion chamber.

### 3 Results and Discussion

#### 3.1 Initiation

The ratio of the fuel injection area to the area of the whole surface of the head wall is denoted henceforth as the fuel injection ratio,  $\psi$  [8]. It would directly affect the mass flow rate of fuel injection in the cylindrical combustion chamber. It was found in our previous study that  $\psi$  had effect on the number of detonation waves and the thrust performance of the cylindrical CDE. In our previous work [8],  $\psi$  ranged from 55.6% to 88.9%. In this study, a simulation case with  $\psi = 100\%$  (**Fig. 2**) is considered for the first time.

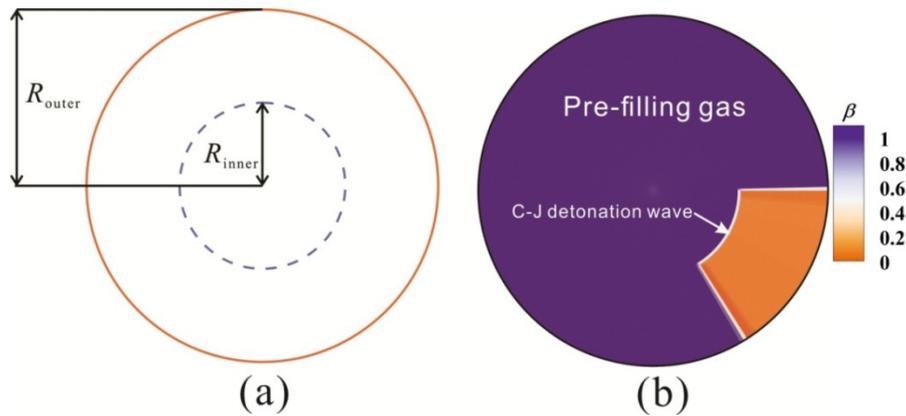


Figure 2. Schematic of (a)  $\psi = (R_{\text{outer}}^2 - R_{\text{inner}}^2)/R_{\text{outer}}^2 = 1 - R_{\text{inner}}^2/R_{\text{outer}}^2$  and (b) initiation.

### 3.2 Reinitiation

During the period of  $t = 1375 \mu\text{s}$  to  $t = 1380 \mu\text{s}$ , a collision between two remaining detonation front snuffs out the detonation flow (**Fig. 3**). The flow maintains the status quo for a period of over  $500 \mu\text{s}$  (**Fig. 4**). At  $t = 1916 \mu\text{s}$ , shock waves are observed gathering in the area circled in **Fig. 5**. And then at  $t = 1918 \mu\text{s}$  a high pressure spot near the outer wall appears, which is captured in the cross section located at  $z = 0.025 \text{ m}$ . This high pressure spot sets off a reinitiation. It could be argued that the reinitiation is caused by the effect of pressure other than temperature. The reasoning behind this postulate is based on the comparison between the pressure and temperature distributions of the flow field in **Fig. 6**. At  $t = 1916 \mu\text{s}$ , burned products are moving downstream and there are many high temperature spots in the flow. But as **Fig. 6** shows, these high temperature spots do not develop into initiation of detonations at  $t = 1918 \mu\text{s}$ . The high pressure spot captured in **Fig. 6** is not the one with the highest temperature in the flow at  $t = 1918 \mu\text{s}$ , but is the one with the highest pressure. It suggests that the reinitiation shown in this study is caused by the sudden and steep increase of pressure. The reason why the high pressure spot appears near the chamber wall is probably due to the effect of concave wall curvature: the compression is most pronounced near the concave wall.

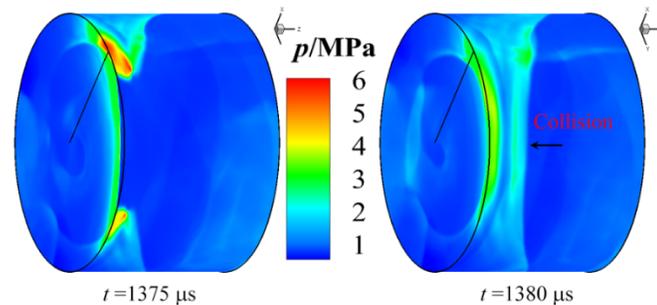


Figure 3. Pressure distributions of the flow - the collision and the subsequent quenching of detonations.

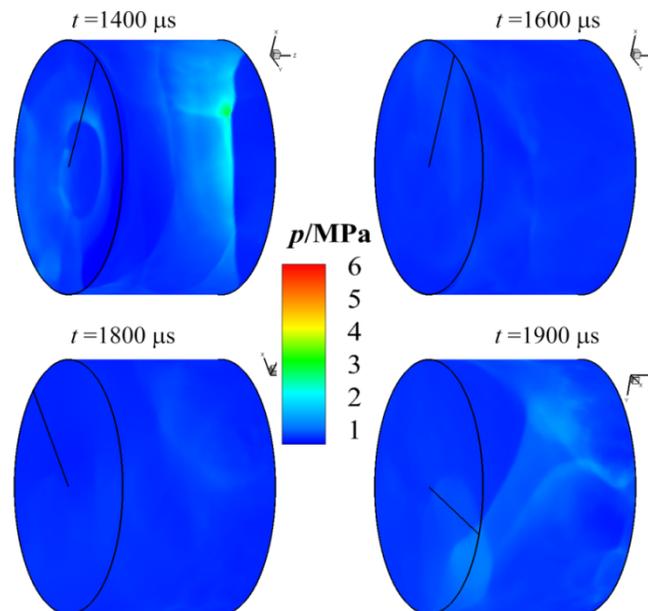


Figure 4. Pressure distributions of the flow - “in the doldrums”.

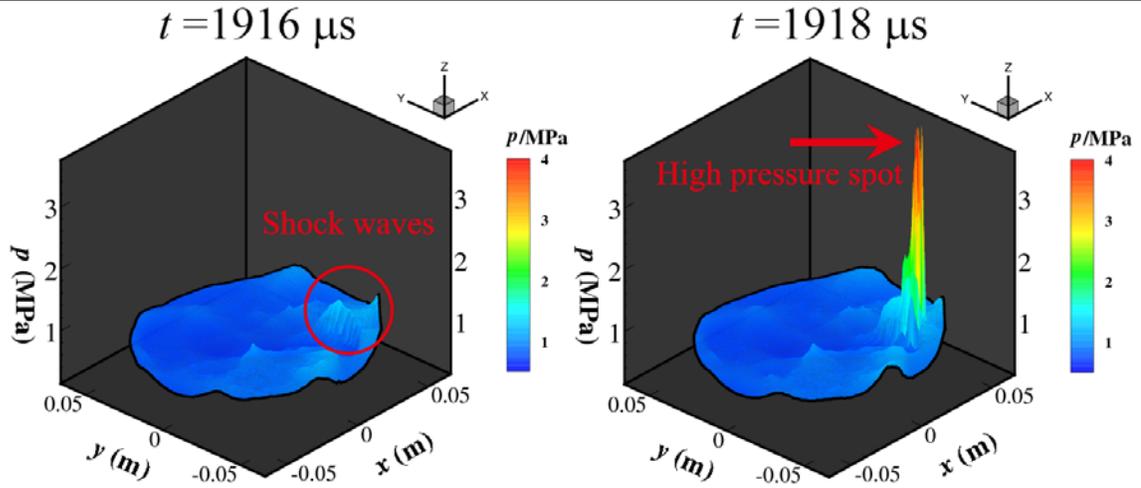


Figure 5. Distribution of pressure over the cross section located at  $z = 0.025$  m. The color scale shows the values of pressure.

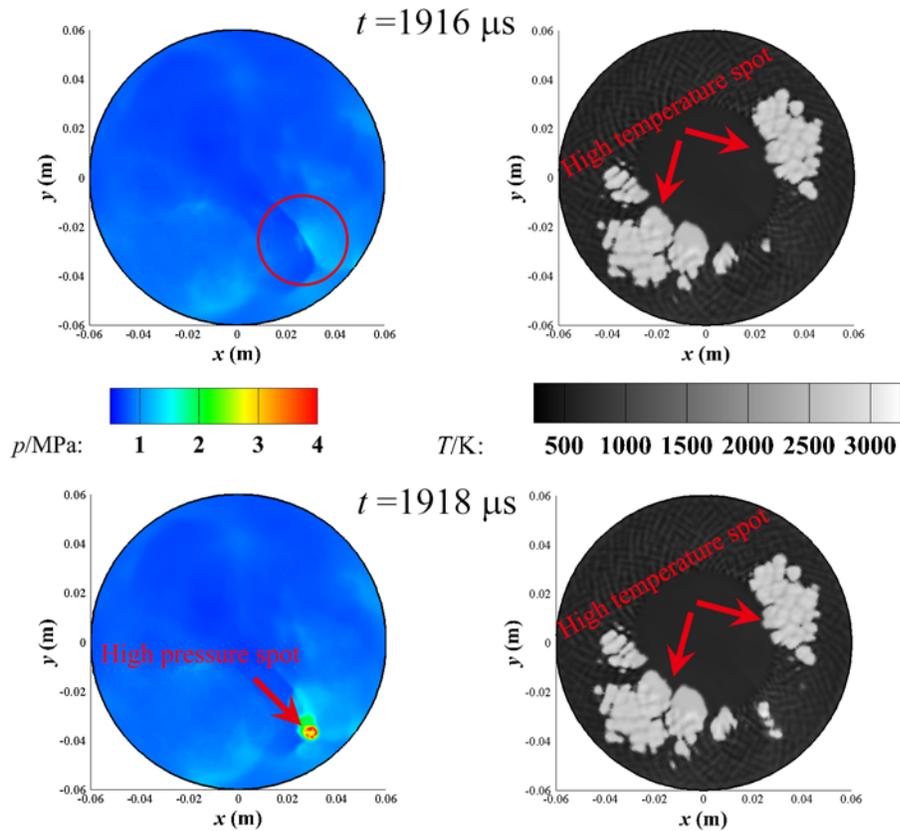


Figure 6. Distribution of pressure and temperature of the flow over the cross section located at  $z = 0.025$  m: the high pressure spot and high temperature spots.

**Figure 7** shows the pressure measurement at a fixed point near the reinitiation spot. The pressure signal presents a pressure rise of  $\Delta p \approx 4$  MPa at  $t = 1916 \mu\text{s}$  when the reinitiation takes place. The development of detonations after the reinitiation is shown in **Fig. 8**. The reinitiation creates a new detonation front C2 which propagates into reactive mixtures and spreads over the entire cross section. Detonation front C2 sweeps at an accelerating speed, which can reach  $U \approx 1950$  m/s, very close to the C-J detonation velocity. Meanwhile, the explosion triggered by the reinitiation collides with the outer wall and the reflected waves bounce back toward the reactive mixture, resulting in the formation of detonation fronts A2 and B2. This is consistent with the experimental observations that strong shock reflection could initiate detonations [9]. Detonation front A2 and B2 start to move along the periphery of the combustion chamber since the reactive mixture surrounding the explosion position is burned out due to the explosion. Therefore, in **Fig. 7**, the oscillations of pressure after  $t = 1916 \mu\text{s}$  are caused by the reflected shock waves.

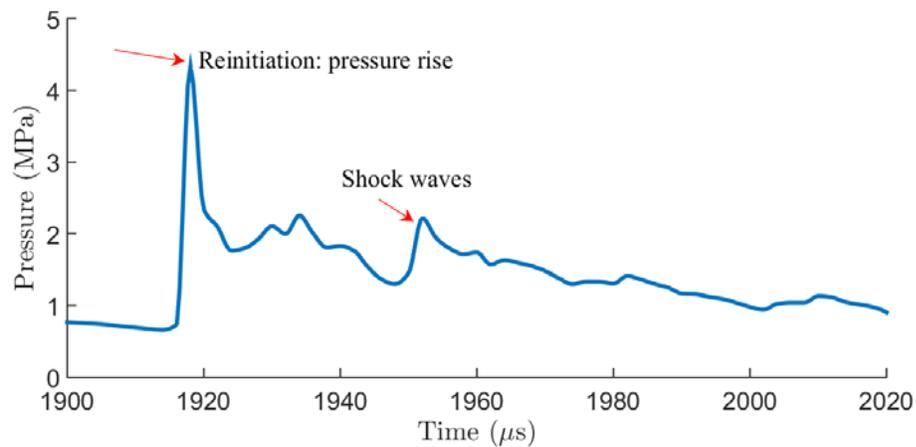


Figure 7. Pressure versus time at the point  $x = 0.03$  m,  $y = -0.04$  m,  $z = 0.025$  m.

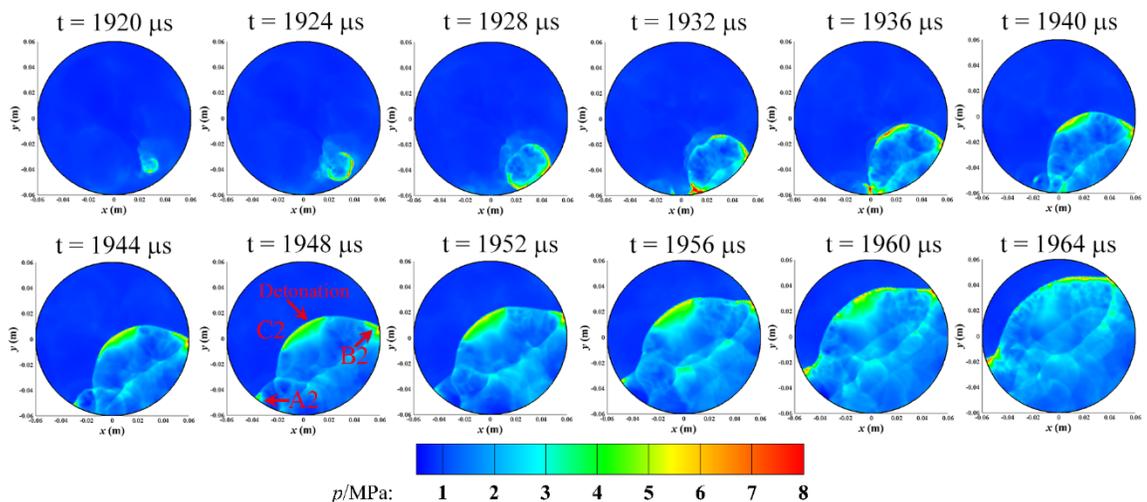


Figure 8. Distribution of pressure and temperature of the flow - development of detonations after reinitiation.

## 4 Conclusions

The present work discusses the phenomenon of reinitiation of detonations in a cylindrical CDE. The simulation shows that detonation waves propagate in more than one direction in the flow after initiation. They will collide with each other and with the outer wall, thus reconstructing the flow intensively. The collision creates explosions which are likely to generate new detonation fronts or quench detonations. In the simulation, a strong head-on collision between two detonation fronts snuffs out the detonation flows. After over 500  $\mu\text{s}$  “in doldrums”, a spontaneous reinitiation is triggered by a high pressure spot near the outer wall of the combustion chamber. The reinitiation sets off a strong explosion that collides with the outer wall and subsequently initiates detonations which spread rapidly into the reactive mixture. It is found that the formation of the reinitiation is closely related to a sharp and sudden increase of pressure.

## Acknowledgments

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## References

- [1] Voitsekhovskii BV. (1959). *Stacionarnaya Dyetonatsiya*. Sov. Doklady Fluid Mech. 129: 1254.
- [2] Bykovskii FA, Zhdan, SA, Vedernikov, EF. (2006). Continuous spin detonations. *J. Propul. Power* 22: 1204.
- [3] Shao Y, Wang J. (2011). Three dimensional simulation of rotating detonation engine without inner wall. 23<sup>rd</sup> ICDERS, Irvine.
- [4] Tang, X, Wang, J, Shao, Y. (2015). Three-dimensional numerical investigations of the rotating detonation engine with a hollow combustor. *Combust. Flame* 162: 997.
- [5] Lu, FK, Braun, EM. (2014). Rotating detonation wave propulsion: experimental challenges, modeling, and engine concepts. *J. Propul. Power* 30: 1125.
- [6] Rankin, BA, Fotia, ML, Naples, AG, Stevens, CA, Hoke, JL, Kaemming, TA, Theuerkauf, SW, Schauer, FR. (2017). Overview of performance, application, and analysis of rotating detonation engine technologies. *J. Propul. Power* 33: 131.
- [7] Kailasanath, K. (2017). Recent developments in the research on rotating-detonation-wave engines. AIAA 2017-0784.
- [8] Yao, S, Tang, X, Luan, M, Wang, J. (2017). Numerical study of hollow rotating detonation engine with different fuel injection area ratios. *Proc. Combust. Inst.* 36: 2649.
- [9] Jones, DA, Sichel, M, Oran, ES. (1995). Reignition of detonations by reflected shocks. *Shock Waves* 5: 47.