Effects of Pre-ignition Conditions on Continuous Detonation Engine

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1 Introduction

The utilization of detonations for propulsion systems has been explored for decades. Recent research has paid much attention to the continuous detonation engine (CDE), which is also called the rotating detonation engine (RDE). The concept of the CDE was attributed to the work of Voitsekhovskii [1]. The feasibility of the CDE has been tested extensively by Bykovskii *et al*. [2].

Experimenting on the CDE requires that the combustion chamber is initially filled with some reactants before initiation. The premixed unburned mixture of fuel and oxidizer will then be consumed by the initial detonation wave introduced by, for instance, the pre-detonator. It seems reasonable to guess that the properties of these pre-ignition gases are unlikely to have a noticeable effect on the initiation process and the final stabilization of the CDE since they will be consumed quickly and then fresh reactants will be supplied continuously. This, however, was proved to be not the case in hindsight. As a matter of fact, interesting phenomena were observed when we varied the properties of pre-ignition gases, e.g., the pressure and temperature and, moreover, the volume of them with which the combustion chamber was initially filled with was also found to have an effect on the stabilization process.

2 Methodology

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

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

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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:

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

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 modeling and chemical parameters can be found in Ref. [3]. In this study, a cylindrical model of the CDE (**Fig. 1**) is considered.

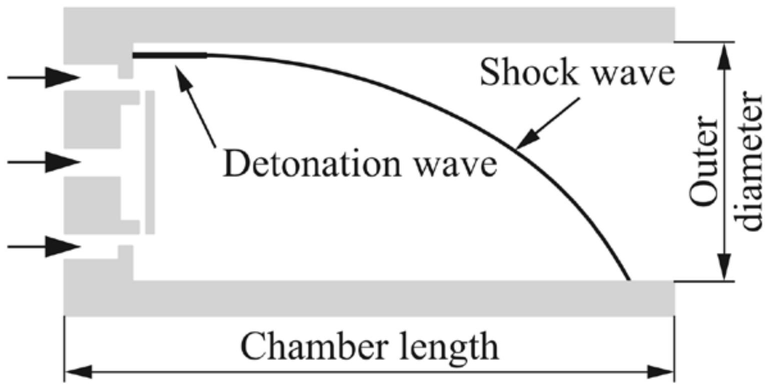

Figure 1. Schematic of a cylindrical CDE combustion chamber.

3 Results and Discussion

3.1 Pre-ignition Gases with Different Pressures and Temperatures

CDEs with various initial conditions were investigated. The combustion chambers were initially filled with unburned gases that have different pressures p^i and temperatures T^i, summarized in **Table 1**, where the variable *N* denotes the number of detonation waves in the stable stage. In cases 1, simulations were conducted by varying the temperatures of the pre-ignition gases while keeping the pressures constant; conversely, the temperatures of cases 2 were keep constant while the pressures vary. It is worth noting that all of the cases have the same fuel injection conditions after initiation: the stagnation pressure and temperature of the premixed fuel mixture were fixed at 3 MPa and 600 K, respectively, supplied by the assumed infinite reservoir.

It was found that although the pre-ignition gases were consumed quickly after initiation, they had a noticeable effect on the final stabilized detonation flow. **Figure 2** shows that case 1-1 and 1-2 were both working in a two-wave mode, whereas case 1-3 in a single-wave mode. Moreover, it was interesting to find that the propagation directions of the two detonation waves in case 1-1 and case 1-2 were opposite. Also, for the first time a cylindrical CDE was found to working in a single-wave mode, e.g., case 1-3. All of the previous simulations and experiments of the cylindrical CDE reported multiple detonation waves during the stable stage. This case will be investigated to a greater extent. Operation of the cylindrical CDE was also found to be sensitive to the pressure of the pre-ignition gases. Case 2-2 is in a three-wave mode, whereas cases 2-1 and 2-3 in a two-wave mode and they have detonation waves propagating in clockwise and anti-clockwise directions, respectively **(Fig. 3**).

These phenomena could be explained by the results of collisions between shocks and detonation waves after initiation in the early stages. Rankin *et al*. [5] clearly illustrated the process of the collision between two detonation waves (**Fig. 4b**) in an optically accessible CDE. The collision of two counter-rotating waves caused an explosion and resulted in new two-wave structures, which they reported to have unique sizes, shapes, and intensities. Similar phenomena were captured in our simulations (**Fig. 4a**). There were frequent collisions between waves and the resultant new structures would not always have unique sizes, shapes, and intensities, which was possibly the reason why different flow structures were observed in these cases.

Table 1: Simulation cases with different initial conditions

Case	p^{i} ($\times10^5$ Pa)	T^{i} (K)	N
1-1	1	273	2
1-2	1	283	2
1-3	1	313	1
2-1	0.8	300	2
2-2	1.0	300	3
2-3	2.0	300	2

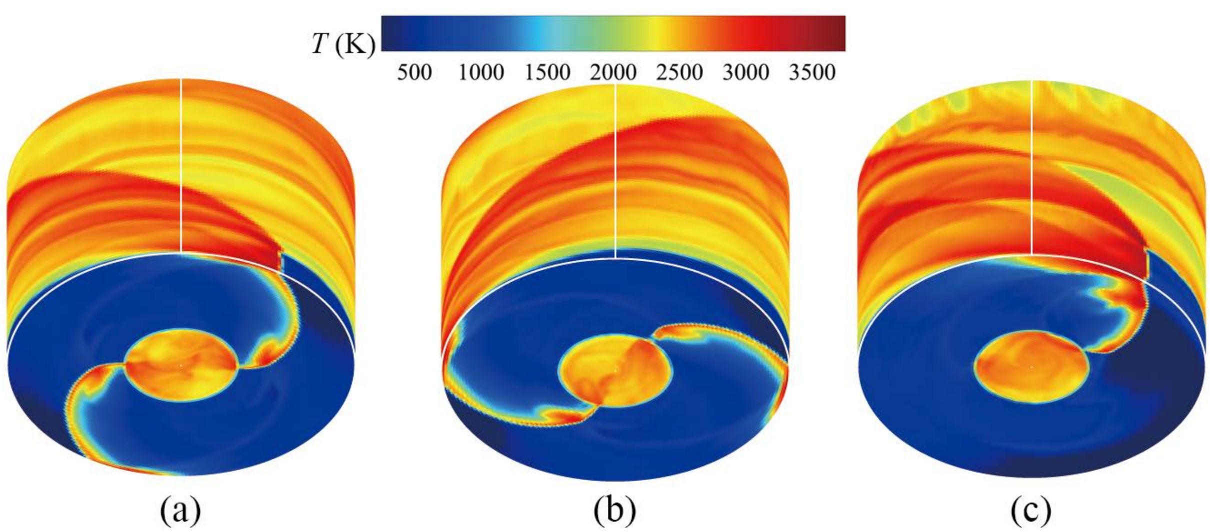

Figure 2. Temperature distribution of the stable detonation flows: (a) case 1-1, (b) case 1-2, and (c) case 1-3.

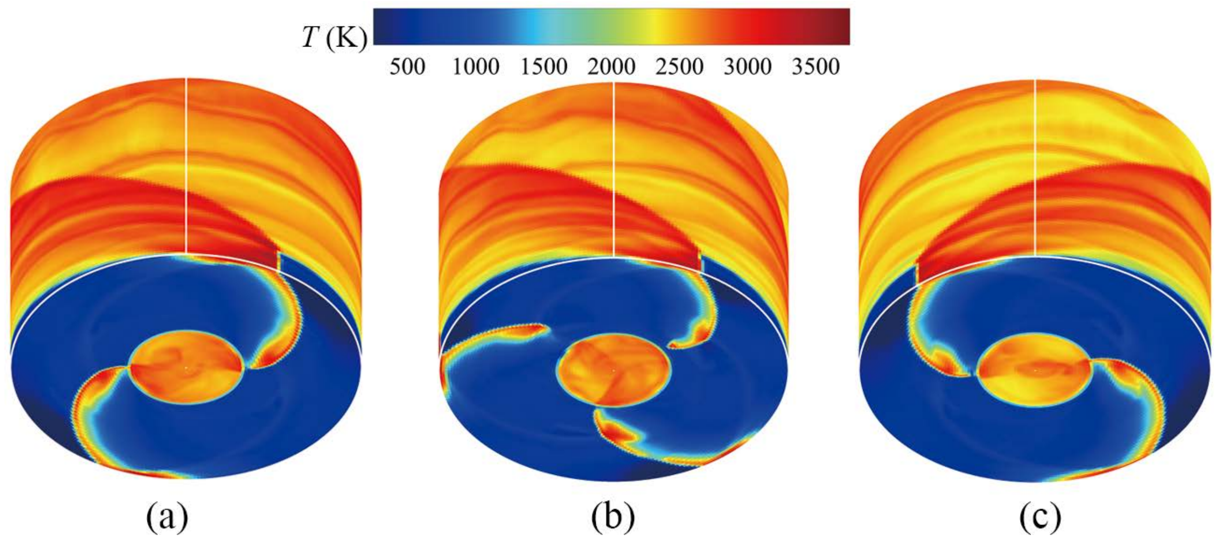

Figure 3. Temperature distribution of the stable detonation flows: (a) case 2-1, (b) case 2-2, and (c) case 2-3.

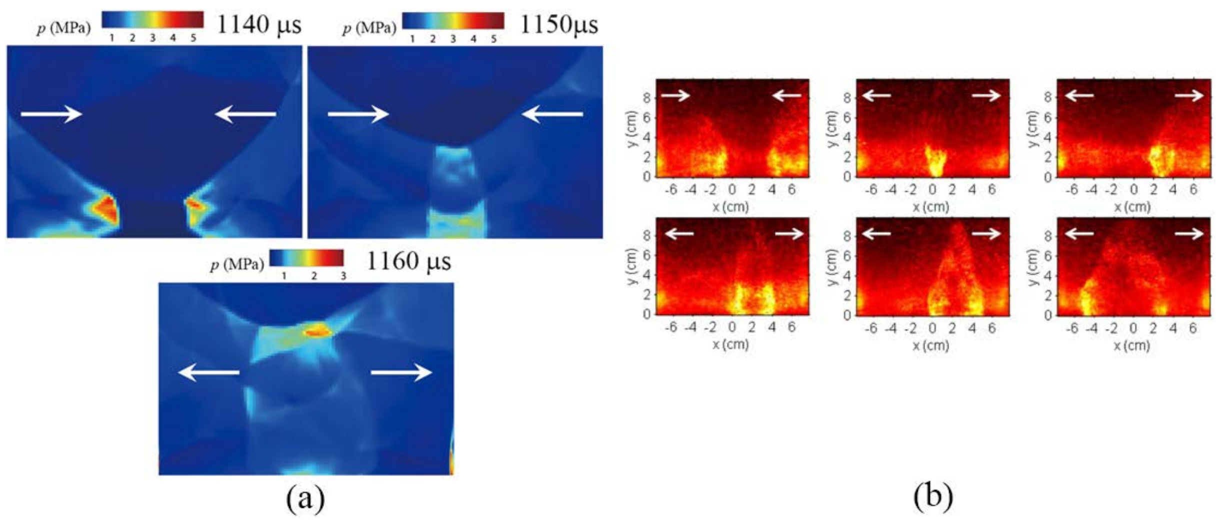

Figure 4. (a) Pressure distribution of the flow field (unwrapped to be two-dimensional) in case 1-3 during t = 1140 – 1150 μs and (b) instantaneous images of the OH* chemiluminescence in an optically accessible CDE [5].

3.2 CDEs with Different Volumes of Pre-ignition Gases

In some other cases, the combustion chamber was initially filled with different volumes of pre-ignitions gases. The ratio of the volume of the pre-ignition gases to the volume of the combustion chamber ϕ ranges from 12.5% to 75.0%.

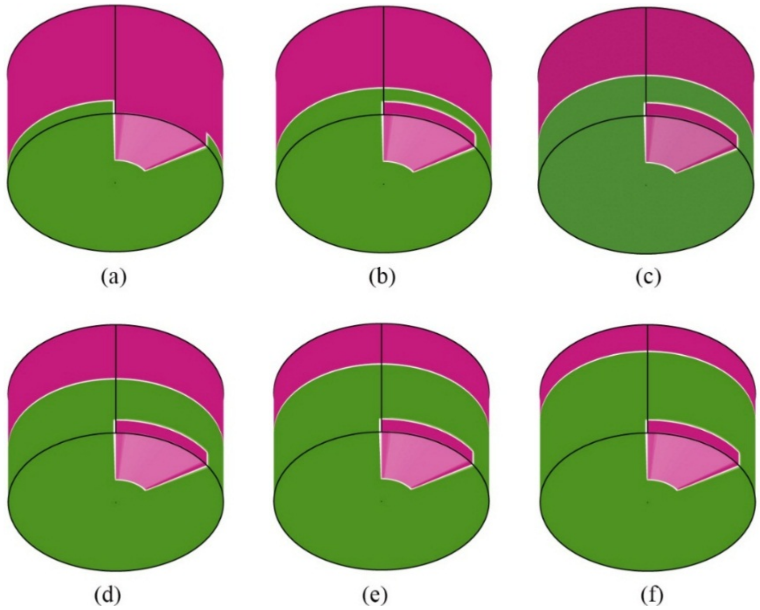

Figure 5. Schematic of the cases with different ϕ: (a) ϕ = 12.5%, (b) ϕ = 25.0%, (c) ϕ = 37.5%, (d) ϕ = 50.0%, (e) ϕ = 62.5%, and (f) 75%.

The stabilization-time t_s is defined in terms of how long the detonation flow takes to reach the stable stage, where there are no collisions between detonation waves. Meanwhile, new detonations waves no longer appear. The stabilization-times of these cases with different ϕ are plotted in **Fig. 6**. It was interesting to find that the continuous detonation had a tendency to stabilize more quickly in those cases with a smaller volume of pre-ignition gases. In other words, if pre-ignition gases were sufficient to support the initial detonation wave, an excess of them was unnecessary or even unfavorable. A possible explanation was offered based on the observation of the stabilization process (**Fig. 7**). If the combustion chamber was initially filled with a larger volume of pre-ignition gases (**Fig. 7b**), which is more than enough to sustain the initial detonation wave, a stronger explosion would be triggered and then led to more fierce and frequent collisions between shock waves, resulting in a more complex flow structure, which needed a longer period of time to stabilize.

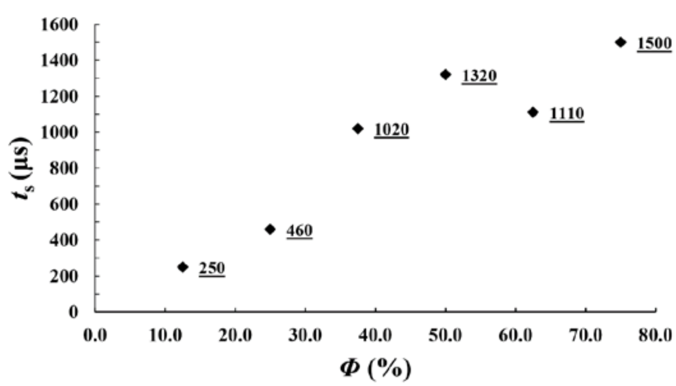

Figure 6. The stabilization-times in different cases.

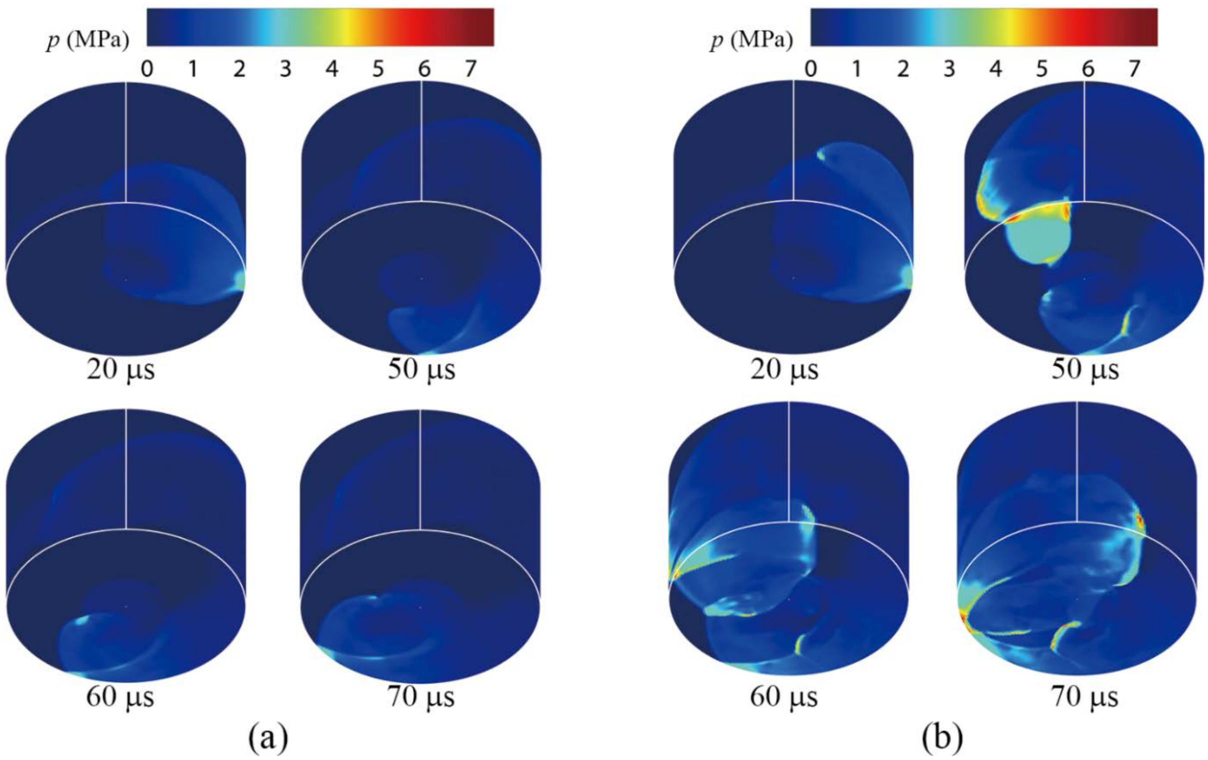

Figure 7. Pressure distribution of the flow field after initiation: (a) ϕ = 12.5% and (b) ϕ = 62.5%.

4 Conclusions

The initiation and stabilization process of a cylindrical CDE was studied, focusing on the effect of pre-ignition gases. It was found that the initial conditions had a noticeable effect on the final stabilized continuous detonation flow. By varying the pressure, temperature, and volume of the pre-ignition gases, the number and the propagation direction of detonation waves in the stable flow changed. Moreover, the volume of the pre-ignition gases was found to influence the length of time for the CDE to obtain a stable state. It was therefore suggested that more attention be paid to the initial conditions of the CDE.

References

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