Adaptive three-dimensional simulations of rotating detonation with cooling walls

Han Peng, Ralf Deiterding
Aerodynamics and Flight Mechanics Group, University of Southampton
Southampton, Hampshire, United Kingdom

1 Introduction

Rotating detonation engines (RDEs) are a type of engine that use one or multiple detonations to compress and burn fuel in a disk- or cylindrical-shaped device. RDEs have been considered as a potential replacement for current aerospace propulsion systems and land-based power generation systems that employ constant pressure combustion [1]. RDEs are of interest since they have the potential to operate more efficiently. Despite these benefits, the rapid heat release associated with RDEs poses challenges for thermal management [2]. Further research is required to optimize the cooling systems of RDEs in preparation for future long-duration tests.

The widely-used 2-D unwrapped model inherently disregards the impact of walls. Most 3-D numerical models of RDEs also assume adiabatic walls for simplicity, despite the fact that RDEs typically operate for only a few seconds in experiments, making the adiabatic wall boundary condition potentially inadequate for simulating real-world processes. Some numerical simulations have been carried out to study the effects of isothermal walls on RDEs. Results showed that, in cases with adiabatic walls, the high wall temperature can cause deflagration, altering the detonation front shape and wave structures [3–5]. In a premixed simulation with continuous injection utilising isothermal walls, the detonation cellular structure vanished [6]. Furthermore, it has been reported that the use of a cooling wall from the start can lead to the subsequent quench of the detonation [7].

In addition to the simulations with continuous premixed injection, the heat loss was estimated in a non-premixed case with discrete injection [8]. The results indicated a significant heat loss that led to a performance reduction in RDEs. While previous studies have primarily focused on the concept of starting with a premixed injection and an isothermal wall, the effect of a cooling wall on stable operation processes remains unknown.

In this work, the annular RDE is simulated with 3-D adaptive meshes. Non-premixed hydrogen and air are injected through discrete holes and a slit, respectively. The simulation starts with adiabatic walls until a stable mode is reached, after which various isothermal wall temperatures are utilized to investigate their effects on detonation propagation.

Correspondence to: h.peng@soton.ac.uk

2 Methodology

2.1 Numerical methods

A recently developed solver is adopted to simulate the RDE problems on a body-fitted adaptive grid. The solver is based on the open-source mesh adaptation framework AMROC (Adaptive Mesh Refinement in Object-oriented C++) [9]. It has been used previously for simulating shock-induced combustion problems [10]. In this work, the 3-D compressible multi-component Navier-Stokes equations are solved as governing equations. The HLLC scheme is employed for evaluating the inviscid flux, and a second-order accurate MUSCL-Hancock scheme with a Minmod limiter is used for reconstruction. The diffusive terms are discretized using a second-order central difference method. The simulation adopts a detailed hydrogen reaction mechanism [11], and Strang splitting is used for the reactive source term. The chemical kinetics are integrated using a fourth-order semi-implicit generalized Runge-Kutta method (GRK4A).

2.2 Numerical configurations

The computational domain of the 3-D annular RDE is depicted in Figure 1. The chamber has an outer diameter of 153.9 mm and a channel width of 7.6 mm, based on one of the experimental configurations in Ref. [12] but with some modifications. For simplicity, the plenum and actual injection schemes are not fully simulated, hence their influences are not studied in this work. The axial height of the chamber is set to 100 mm, and no nozzles are included in the simulation.

The chamber is filled with air at atmospheric pressure and a temperature of 295 K. The presence of nitrogen is assumed as inert and its chemical reactions are neglected. A layer of stoichiometric hydrogen-air mixture is initialised with a height of 10 mm. Patches of pure nitrogen and 1-D ZND solutions are used to artificially generate a single stable detonation wave in the first cycle. The use of pure nitrogen can avoid that the initial burned gas induces detonation in the reverse direction, which may occur in realistic ignition scenarios but is not considered in the present work. Fuel is injected from the head plane through 120 holes with a diameter of 0.89 mm, and air is injected through a 1.6 mm tall slit on the inner wall.

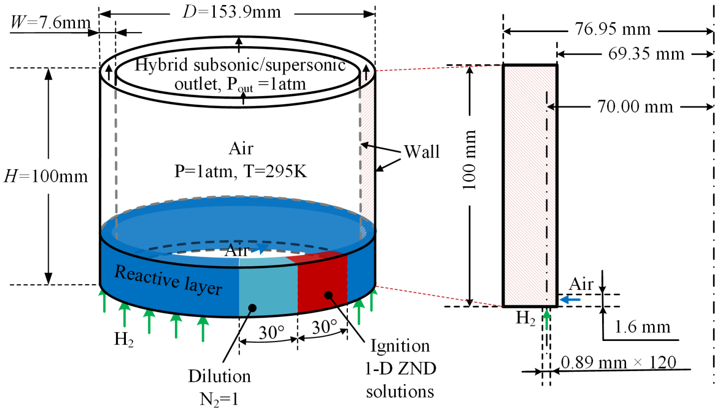


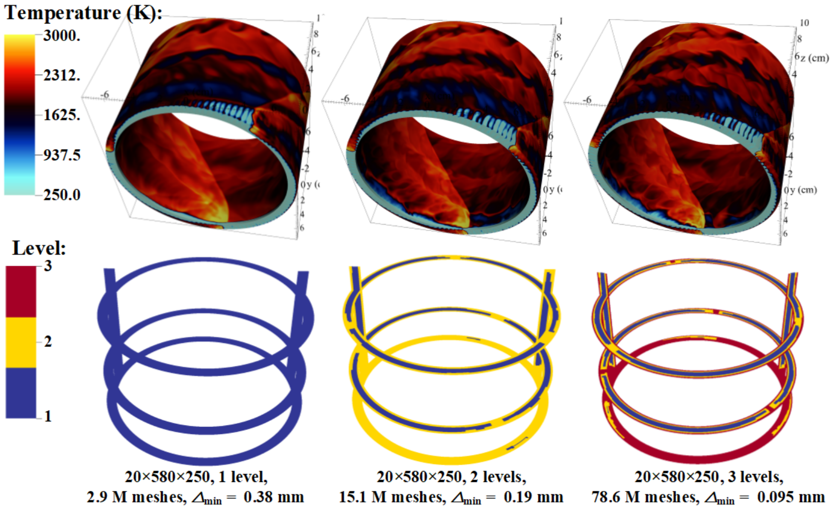
Figure 1: Computational domain of the hydrogen/air annular RDE model.

The 3-D annular model's top side is set as a hybrid subsonic/supersonic outflow with atmospheric pressure as ambient pressure. Outflow variables are extrapolated if the local Mach number is greater than 1, otherwise subsonic outlet is set based on ambient pressure. The mass flow inlet is used for both the hydrogen injection holes and the air slit. The total hydrogen mass flow rate is set to 9.3 g/s and the air mass flow rate is given as 320 g/s, resulting in a globally stoichiometric injection. Other boundaries are considered slip walls, for which either adiabatic wall or isothermal wall boundary conditions are applied in various cases.

The base mesh consists of 20 × 580 × 250 cells and additional refinement levels are applied with a factor of 2 per level. The refinement criteria are given in terms of the temperature, density and pressure scalar gradient: $\varepsilon_T = 500\,\mathrm{K}, \varepsilon_\rho = 0.15\,\mathrm{kg/m^3}$ and $\varepsilon_p = 50\,\mathrm{kPa}$. The first four cells near the walls are always flagged to be refined. The target CFL number is set to 0.8. The following simulations were conducted on the high-performance computing cluster Archer2, where 256 cores (AMD EPYC 7742 2.25 GHz) were used for each case. The total number of the two-level grid is changed dynamically from 10.4 to 15.5 million. Typical run times for the RDE operating time of 1 ms were approximately 4 to 5 days wall-clock time.

3 Result

Three different grids are tested in the adiabatic case to study the effects of mesh dependency as presented in Figure 2. The results demonstrate that the number of waves is independent of the current grids. Despite variations in the flow field when the grid is refined, the two-level grid is considered a suitable balance between computational accuracy and cost. Hence, the following simulations are conducted using this two-level grid.



20×580×250, 1 level, 2.9 M meshes, $\varDelta_{\min}$ = 0.38 mm

20×580×250, 2 levels, 15.1 M meshes, $\varDelta_{\min}$ = 0.19 mm

20×580×250, 3 levels, 78.6 M meshes, $\varDelta_{\min}$ = 0.095 mm

Figure 2: Temperature and refinement levels distribution on different grids.

All the cases start with the adiabatic wall boundary conditions. As shown in Figure 3, a single detonation wave is ignited at the start, followed by multiple unstable cycles and a transition to a three-wave mode. At t=1.8 ms, the wall temperature changes in each case. A phase difference appears when isothermal walls are used. In these cases with cooling walls, the pressure peaks drop to around 0.8 MPa and then recover to 1 MPa at the final stable stage. The wave frequency is estimated from 2.3 ms to 4.4 ms using a fast Fourier transform. The single wave frequency is 4.14 kHz, 4.03 kHz, 4.03 kHz and 4.05 kHz for the cases with adiabatic walls, and isothermal walls at 300 K, 600 K and 900 K, respectively. Compared to the ideal frequency of 4.3 kHz based on a premixed C-J detonation, the average detonation velocity deficit is 3.7% in the adiabatic case and ranges from 5.8% to 6.3% in the cases with isothermal walls.

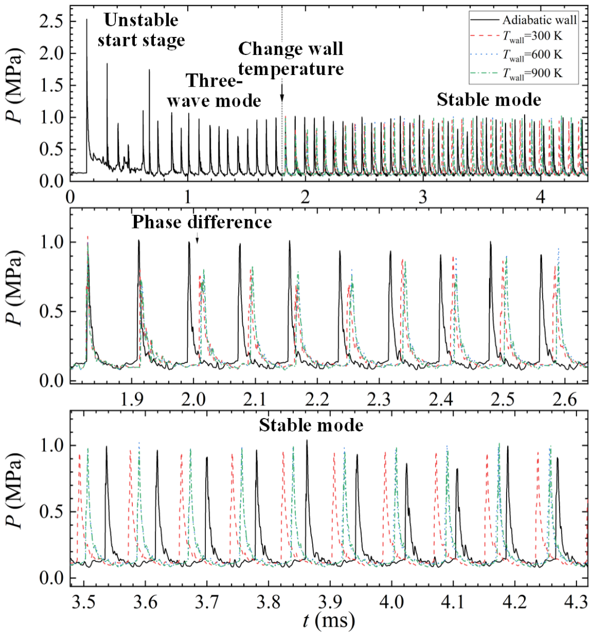


Figure 3: Pressure history in different cases, sensors at $r = 73.15\text{mm}$, $H = 5\text{mm}$ and $\theta = 180°$.

Figure 4 shows the transient temperature distribution and its slice on the head plane when the different cases run in a stable mode. The use of a cooling wall does not change the number of detonation heads in the present simulations. All the cases still operate in a three-wave mode lasting over 2 ms. The isothermal walls rapidly cool the burned gases, limiting high-temperature regions near the wall to only the area where the detonation exists.

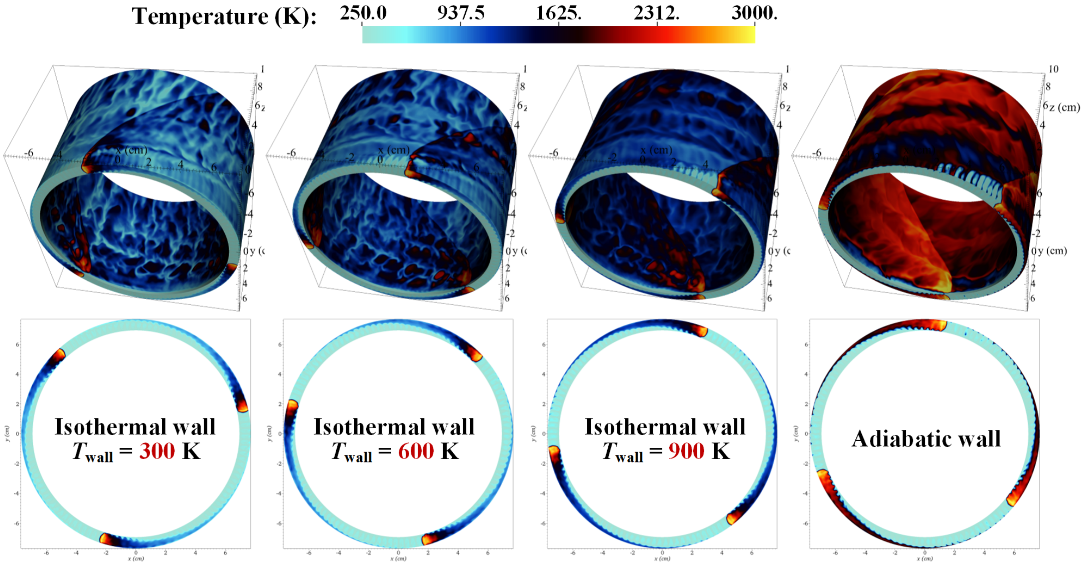


Figure 4: Pseudo-color images of temperature distribution and its slices on the bottom plane.

The left-hand side figures of Figure 5 show the unwrapped slices of the outer wall. In the case using adiabatic walls, the typical rotating detonation structure is observed. The multiple detonation waves are each followed by an oblique shock wave. Irregular slip lines are captured on the contact surface. The fuel-air stratification in the mixture layer is a result of non-premixed injection and incomplete mixing.

As the wall temperature decreases, the temperature behind the detonation wave and oblique shock also decreases, but the detonation still sustains even at a wall temperature of 300 K.

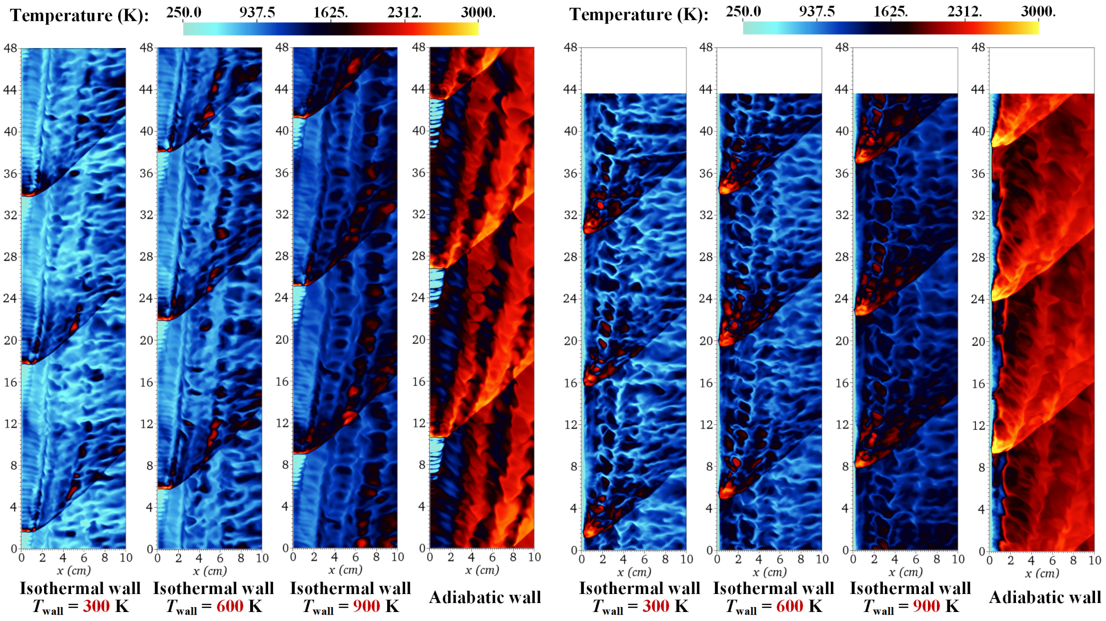


Figure 5: Pseudo-color images of unrolled temperature slices on the wall. Left: Outer wall. Right: Inner wall.

The temperature distribution on the inner wall is depicted in the right-hand side figures of Figure 5. The detonation is observed to be detached from the bottom plane due to the presence of an air slit. The height of the mixture layer is seen to be low on the inner wall. Discrete high-temperature regions are also visible behind the detonation wave in cases with cooling walls. Figure 6 presents a comparison of the temperature in the middle of the channel and shows that parasitic combustion occurs in the mixture layer ahead of the detonation. The differences observed among the varying cases are relatively minor.

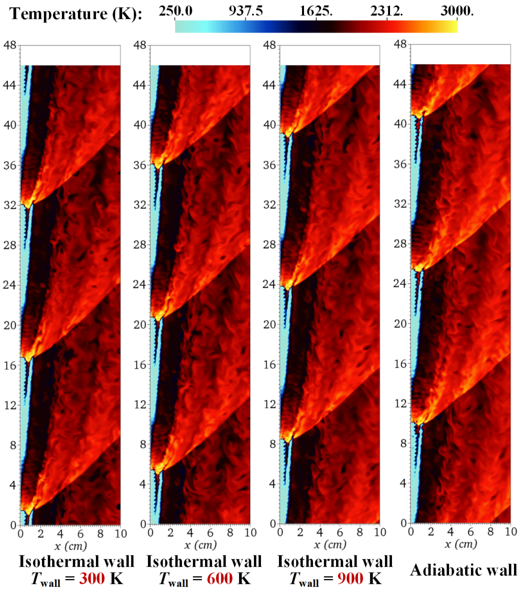


Figure 6: Pseudo-color images of unrolled temperature slices in the middle of the channel.

4 Conclusion

The effects of cooling walls on rotating detonation waves are studied by numerical simulations on 3-D adaptive meshes. Non-premixed hydrogen/air mixtures are injected with a uniform global equivalence ratio. The simulation starts with adiabatic walls until it reaches a stable multiple-wave mode, and then the wall temperature is varied. The results indicate that the number of detonation waves in a stable mode remains unchanged by the wall temperature within a short simulation duration. The average detonation velocity deficit rises from 3.7% to 6.3% when cooling walls are utilized. The phase differences and temperature variations are noticeable, but the wall temperature has a limited effect on the temperature distribution in the middle of the channel. The numerical study demonstrates that wall cooling to enable RDEs with the extended operation will have only limited effects on detonation efficiency.

Acknowledgement

This work used the ARCHER2 UK National Supercomputing Service. H. Peng acknowledges financial support from China Scholarship Council (CSC).

References

[1] Wolański P. (2013). Detonative propulsion. Proc. Combust. Inst. 34: 125-158.

[2] Anand V, Gutmark E. (2019). Rotating detonation combustors and their similarities to rocket instabilities. Prog. Energy Combust. Sci. 73: 182-234.

[3] Wang YH, Wang JP, Qiao WY. (2016). Effects of thermal wall conditions on rotating detonation. Comput. Fluids. 140: 59-71.

[4] Liu PX, Guo QL, Sun D, Li C, Zhang HX. (2020). Wall effect on the flow structures of three-dimensional rotating detonation wave. Int. J. Hydrog. Energy. 45: 29546-29559.

[5] Liu PX, Li C, Sun D, Guo QL, Zhao W. (2021). The effect of wall temperature on three-dimensional rotating detonation wave. J. Phys. Conf. Ser. 1786: 012045.

[6] Cocks PA, Holley AT, Greene CB, Haas M. (2015). Development of a high fidelity RDE simulation capability. 53rd AIAA Aerospace Sciences Meeting No: 1823.

[7] Wu K, Zhang L, Luan MY, Wang JP. (2021). Effects of isothermal wall boundary conditions on rotating detonation engine. Combust. Sci. Technol. 193: 211-224.

[8] Strakey P, Ferguson D, Sisler A, Nix A. (2016). Computationally quantifying loss mechanisms in a rotating detonation engine. 54th AIAA Aerospace sciences meeting No: 0900.

[9] Deiterding R. (2003). Parallel adaptive simulation of multi-dimensional detonation structures. Dissertation.

[10] Peng H, Atkins CW, Deiterding R. (2022). A solver for simulating shock-induced combustion on curvilinear adaptive meshes. Comput. Fluids. 232: 105188.

[11] Burke MP, Chaos M, Ju Y, Dryer FL, Klippenstein SJ. (2012). Comprehensive H2/O2 kinetic model for high-pressure combustion. Int. J. Chem. Kinet. 44: 444-474.

[12] Rankin BA, Richardson DR, Caswell AW, Naples AG, Hoke JL, Schauer FR. (2017). Chemiluminescence imaging of an optically accessible non-premixed rotating detonation engine. Combust. Flame. 176: 12-22.