The effect of wall temperature on three-dimensional rotating detonation wave

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Abstract. The effect of wall temperature on the three-dimensional rotating detonation wave in an annular chamber is investigated by utilizing premixed hydrogen/air as the reactant and the improved delayed detached-eddy simulation method to evaluate the turbulent transportation. Four cases are set with different wall temperature, i.e. adiabatic wall, isothermal wall with 400K, 800K and 1200K. When using isothermal wall, there is no reactant deficit zone which appearing in the case with adiabatic wall. As the wall temperature increasing, the leading oblique shock will form at both side of the detonation front. When comparing the specific impulse with the adiabatic case, all the three isothermal cases have a better performance. And the lowest wall temperature case shows the highest specific impulse.

1. Introduction
As a promising propulsion concept, RDE (Rotating Detonation Engine) has received much interest in recent years. Many experiments and simulations on RDE have been performed [1-4], and many aspects of RDE have been studied, including the fuel and oxidant, the ignition, the injection scheme, the configuration of the combustor, the nozzle, and the flow structure and mechanism. However, most simulations adopted Euler equations, ignoring the viscosity, thermal conductivity and mass diffusion. Such transportation phenomenon and heat flux on the wall may influence the near-wall combustion process, especially in the current commonly used combustor with small radial scale.

Limited literature takes consideration of the transportation phenomenon in RDW (Rotating Detonation Wave) simulation. Zhang et al. [5] found that the wall viscosity caused the detonation front curved and its propagation speed near the wall decreased. Strakey et al. [6] assessed various loss mechanisms in RDE, and the results showed that the heat loss to the wall was significant, while the wall viscosity loss was small. Cocks et al. [7] studied the effect of the wall viscosity and the heat transfer on the 3-D RDW. When using adiabatic wall condition, the near-wall viscosity was found to affect the filling region, increase the level of low-pressure deflagration, and subsequently change the detonation shape. While using the isothermal wall condition, the deformation of detonation front became different, and oblique shock waves were formed ahead the detonation front near the wall. Wang et al. [8] investigated the wall temperature effect on the development of the 2-D detonation wave. It was found that the deflagration caused by the high wall temperature case led the formation of Y-shaped detonation front. In our previous study [9, 10], the wall effect on the flow structures of three-dimensional rotating detonation wave was also studied, and the mechanism of the flow structure alteration was analyzed, and the formation procedure of the reactant deficit zone was proposed. The influence on the propulsion performance was also evaluated. Although some recognitions of the wall...
effect on the propagation of RDW are obtained, the impact of wall temperature on 3-D RDW is still unknown. For the engineering application in the future, RDE may run for a long period, which may encounter the cooling problem of the combustor. Studying the features of RDW under different wall temperature is an important issue for the cooling design.

Targeting at above uncertainties, investigations are performed to estimate the impact of the wall temperature on the propagation properties of the 3-D RDW, emphasizing on the change of flow structures and propulsion performance. Section 2 details the computational model and approach, and section 3 presents the results and discussions. Conclusions are drawn in section 4.

2. Numerical methodology

2.1. Simulation setup

The 3-D annular chamber is adopted as computational model. The inner and outer radii are 4.0 cm and 5.0 cm separately, and the axial length is 10.0 cm. The premixed stoichiometric air/hydrogen mixtures are chosen as the reactants. Reactants are injected into the chamber through the head end, and one or several triangle layers of the reactant are formed thereafter. Detonation wave keeps consuming the combustible mixture and propagating circumferentially. The burnt products are exhausted at the downstream exit.

The inner and outer walls of the combustor adopt no-slip wall boundary with isothermal or adiabatic condition according to different cases. Periodic boundary is used in circumferential direction. For the injection boundary at the head end, premixture assumption is made for simplification, which is adopted in most literatures. And each grid point of the injection inlet is assumed to be the exit of a single virtual micro Laval nozzle. Following Laval nozzle theory, the injection condition can be classified into four situations depending on the local pressure: no injection, subsonic injection, choked subsonic injection, and choked supersonic injection. The details of formulas can be referred to Ref. [9]. The total pressure and temperature of mixture reservoir are 10.0 atm and 300.0 K. The exit employs non-reflecting boundary condition, and the ambient condition is set as 1.0 atm and 300.0 K.

In order to investigate the effect of wall temperature on the 3-D rotating detonation wave, four cases are designed with different wall condition. C1 is with adiabatic wall, while C2-C4 are treated with isothermal wall at different temperatures, i.e. $T_w=400\text{K}$, $800\text{K}$, $1200\text{K}$. A wall temperature of $800\text{K}$ is approximately what the wall temperature would be for a water cooled annulus made of material commonly used in the laboratory [7]. As a comparison, $T_w=400\text{K}$ and $1200\text{K}$ cases are set to investigate the RDW under the better cooling and worse cooling condition. The case setting is summarized in Table 1.

| Case | Wall condition | Wall temperature(K) |
|------|----------------|---------------------|
| C1   | Adiabatic      | --                  |
| C2   | isothermal     | 400                 |
| C3   | isothermal     | 800                 |
| C4   | isothermal     | 1200                |

The initial condition is set as follows. The top section of chamber is filled with the stoichiometric mixtures under the ambient condition, and the other section is with pure air. A one-dimensional Chapman-Jouguet detonation wave is placed into the top mixture section to initiate the detonation. After a period of development, one-wave detonation forms and propagates continuously.

Considering the non-slip wall, the grid is refined near the wall with a resolution of 0.01 mm and stretching with a ratio of 1.2 to a uniform resolution of 0.2 mm. such grid design results in a dimension of $1449 \times 75 \times 501$ (circumferential $\times$ radial $\times$ axial).
2.2. Numerical methods

The governing equations are three-dimensional chemical non-equilibrium Navier-Stokes (N-S) equations with an \( ns \)-species-\( nr \)-reaction model in the generalized body-fitted coordinate. The model with \( ns=7, nr=8 \) for air/hydrogen mixtures [11] is chosen for the present simulation.

Regarding the numerical discretization, a fifth-order WENO-PPM5 scheme [12] is chosen for the inviscid flux, a fourth-order central scheme is for the viscous flux, and a third-order TVD (Total Variation Diminishing) Runge-Kutta scheme [13] is for the temporal discretization. The present simulations take consideration of the turbulent transportation caused by the viscous wall, and the IDDES (Improved Delayed Detached-Eddy Simulation) method [14] is utilized to obtain the eddy viscosity coefficients. More details about the numerical procedures can be referred to Ref. [9].

3. Results and discussions

3.1. Flow structures

After a few cycles, one-wave detonation forms and propagates successively. The instantaneous temperature counters of different cases are shown in Figure 1. As shown by middle radial slice in C2, the main flow structures are captured, as reported in previous experiments and literatures [1-4]. The basic structures include detonation wave front A, oblique shock wave B due to the expansion of product downstream, a triangular layer of combustible premixture C accumulated by the continuous injection, the slip line D in the burnt gas between A and B due to different gas states, and the interface E between premixture and product.

From Figure 1 (a), the temperature distribution in adiabatic case is very different from those in isothermal cases. In adiabatic case, the origin of oblique wave near the wall is far ahead the detonation front and there is a high temperature area denoted by a black ellipse. The formation of such a high-temperature area is due to the stagnation effect on the viscous wall. While in isothermal cases, the high temperature zone is only limited to the detonation front, which is ascribed to the heat conductivity with the isothermal wall.

![Figure 1. Instantaneous temperature contours.](image)
The shape of the detonation front and the filling region of the reactant are shown in Figure 2 through the iso-surfaces of the hydrogen fraction coloured by the temperature. In adiabatic case, the boundary of deflagration is extended. And the depletion of reactants ahead the detonation front leads to the formation of valleys in the filling region, which is denoted as 'reactant deficit' (as indicated by the black ellipses in adiabatic case in Figure 2). Some unburnt gas pockets generate from the conjunction of detonation front and oblique wave, because the detonation front becomes narrow at the unbounded side and cannot burn all the reactants in time. Such mechanism is explained in detail in Ref. [9]. When considering the isothermal wall, there is no reactant deficit formed. And in the case with $T_w=1200K$, the heat conductivity makes the deflagration occur near the wall, and the deformation takes place in the conjunction between the detonation front and the wall (as indicated by the black ellipses in $T_w=1200K$ case in figure 2). Such phenomenon is consistent with the results in Ref. [7].

Back to Figure 1 (b), it can be seen that there is a low-temperature area marked by a black ellipse in the adiabatic case. This is caused by the fast expansion of the heterogeneous burnt products at the unbounded side [9]. In the $T_w=400K$ and $800K$ cases, there is no reactant deficit zone, and the products behind the detonation front are relatively homogeneous, so the low-temperature area almost disappears. While in the $T_w=1200K$ case, such low-temperature zone becomes larger and extends upstream toward the injection head. The combustion is weakened by the deflagration near the wall, and the wave expansion and reflection will lead to such phenomenon. The temperature and pressure contours in the chosen axial slices in Figure 5 (d) can help explain this process.

![Figure 2. Iso-surfaces of the hydrogen fraction ($f(H2)=0.01$) colored by the temperature.](image)

In order to explain the mechanism of such alteration of flow structures caused by the wall temperature, the flow details near the detonation front are checked. Two specific slices are chosen, as shown by the $T_w=400K$ case in Figure 3. The circumferential slice is located just ahead the detonation front, and the axial slice is $z=1.0cm$.

![Figure 3. Temperature contour at chosen slices for C2.](image)

![Figure 4. Temperature contours in the chosen circumferential slice.](image)
The temperature contours in the chosen circumferential slice are shown in Figure 4. As mentioned before, the large high temperature area extended upstream is due to the ‘reactant deficit’ in adiabatic case. With the wall temperature increasing in C2-C4, the range of deflagration in the boundary layer extends further along the upstream direction.

Figure 5 compares the temperature distributions in the chosen axial slice. When $T_w=400K$, the wall temperature is relatively low, there is no deflagration ahead the detonation front, which is similar with the adiabatic case at this axial position. When $T_w=800K$, the deflagration occurs only in the very limited area near the wall, the small-scaled oblique shock appears. When $T_w=1200K$, the range of deflagration becomes more extensive, the scale of oblique shock becomes larger, as shown by the red ellipse in Figure 5 (d). In the 2-D RDW in the annual ring by Wang et al. [8], they also found that the oblique shock would appear once the deflagration occurred ahead the detonation front near the wall. The pressure of the detonation product in the middle is much higher than that of the deflagration product near the wall. Thus the expansion and the reflection lead to the emergence of the low-temperature area and the second lift, as shown in the right of Figure 1 (b).

The mechanism for no formation of ‘reactant deficit’ in isothermal cased can be explained as follows. Comparing the adiabatic case, the isothermal wall in present simulation serves as cooled wall, because all the three chosen temperature is lower than that in the deflagration product near the wall. So it will weaken the combustion through heat conductivity, and narrow the range of deflagration. Then the strength and the scale of the leading oblique shock is also attenuated, which in turn weakens the deflagration. The cooling effects inhibit the appearance of ‘reactant deficit’. When the wall temperature reaches to a specific value, the heat conductivity makes the deflagration occur near the wall. Because the shock wave propagates faster in the burnt products than in the fresh reactants, the leading oblique shock wave appears near the wall.
3.2. Propagation speed and propulsion performance

In order to obtain the propagation cycle period, a monitor is placed at the position \((r=4.5\text{cm}, \theta=5.92, z=0.4\text{cm})\) to record the temporal variation of the monitored pressure. Then the propagation speed can be calculated. The propagation speed along the circumferential direction, the mass flux at the injection plane, the thrust and the specific impulse based on the H\(_2\) species are listed in Table 2. All these parameters are averaged through about five cycles.

From Table 2, there is no significant difference in the propagation speed, and the biggest discrepancy is about 3.77%. The injection condition is affected by the combustion process, so the mass fluxes exist a little difference. The existence of ‘reactant deficit’ in adiabatic case indicates that more reactants are consumed by deflagration than those in isothermal case, which will decrease the overall combustion efficiency of RDW. So the thrust and the specific impulse of C1 is the smallest among the four cases. As to C2-C4, these two parameters are decreasing as the wall temperature is increasing. This trend is also caused by the amount of deflagration consumption.

| Case   | Speed (m/s) | Mass flux (kg/s) | Thrust (N)  | Specific impulse (/s) |
|--------|-------------|------------------|-------------|-----------------------|
| C1 (adiabatic) | 1857.71     | 1.127            | 1336.25     | 4407.90               |
| C2 \((T_w=400\text{K})\) | 1812.46     | 1.062            | 1502.59     | 5286.27               |
| C3 \((T_w=800\text{K})\) | 1787.25     | 1.094            | 1411.09     | 4813.81               |
| C4 \((T_w=1200\text{K})\) | 1848.00     | 1.109            | 1383.14     | 4675.27               |

4. Conclusions

Using hydrogen/air mixture as reactants, four 3-D cases of rotating detonation simulation are performed with different wall conditions to investigate the effect of wall temperature on the flow structures and propulsion performances. After the detailed analyses and comparisons, the following conclusions are drawn:

1. Wall temperature has notable effect on the flow structures in 3-D RDW. The three chosen isothermal walls cool the burnt products, and inhibit the formation of ‘reactant deficit’ existing in adiabatic case. As the wall temperature reaches a certain value, the leading oblique shock will appear at the both side of detonation front.

2. The wall temperature shows little influence on the propagation speed of the detonation front, and the biggest discrepancy is about 3.77%. All the three chosen isothermal cases have better thrust and specific impulse performance than the adiabatic case. The deflagration consumption leads to the decreasing of propulsion performance with increasing the wall temperature.

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