Simulation Study on Detonation Propagation Driven by Piston

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1 Introduction

Detonation propagation and structure has been studied using high precision numerical method for several decades, and many mechanisms of detonation initiation and propagation have been studied comprehensively[1-2]. For the consideration of time-consumption computation of the multi-dimension problems, many researches studied the detonation structure in supersonic incoming flow try to fix the detonation front almost static, using the pressure outlet as boundary layer behind the detonation front[3-5]. Actually such treatment method ignite all the effect of conditions behind the detonation on the detonation propagation, while the conditions behind the detonation may have an significant effect on the detonation structure and detonation pattern sometimes, that is say it is maybe CJ detonation or overdriven detonation.

Recently, more and more attentions are focused on the application of ODE and RDE. The detailed flow field in the engine is very complex, but there are some common mechanisms such as detonation propagate in high-speed/supersonic combustible mixtures and the flow field behind the detonation may effect the detonation propagation, even turn into overdriven[4-6].

In this paper, the above complex problems are reduced to a one-dimension problem with piston-moving behind detonation. Firstly, the verification of relative motion of piston and incoming flow is implemented. Then the CJ velocity is used as that of incoming flow after we find that in quiet mixture flow for the real chemistry reaction. We can obtain the different conditions behind the detonation by using the different velocity of piston, and then the different propagation model, such as CJ detonation and overdriven detonation, will be found. At the same time the overdrive degree of detonation propagation can also be achieved.

2 Numerical method

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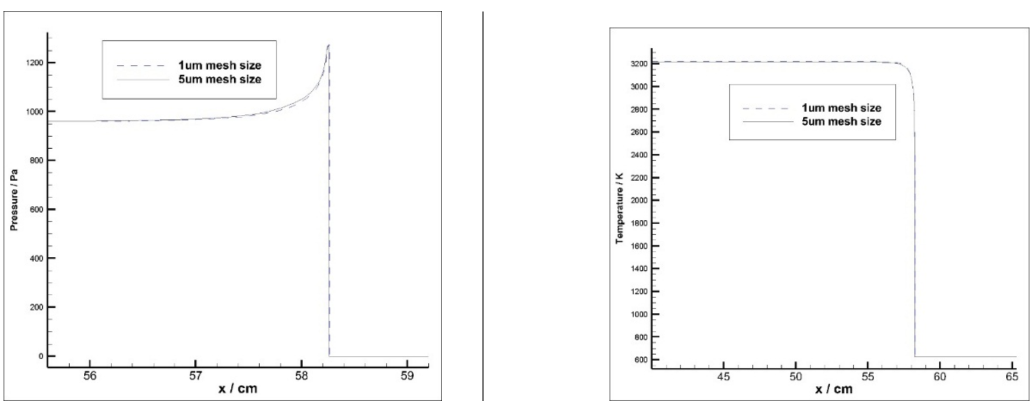
The One-dimensional reactive Euler equations with the detailed reaction model are used as the governing equations. The second-order accurate MUSCL-TVD finite volume method (FVM) is adopted for the convective flux discretization. The second-order Strang splitting was used for the process of reactive source term [9]. The standard one-dimensional Roe-type Riemann solver is applied. The Van Albada limiter adopted with the MUSCL reconstruction to structure a second-order accurate TVD-type method. The second order accurate MUSCL-Hancock technique [10] is used for temporal iteration. The dynamic adaptive time step with the constant CFL number 0.9 is used for the time iteration. The high-order shock-capturing finite volume method is adopted on rectangular Cartesian grids . The Ghost Fluid Method (GFM) is used to simulate the moving wall , which uses some finite volume cells as ghost cells.

3 Results and Discussion

The mixture and incoming flow parameters are the same in this paper. The mixture mole fraction ratio is H2:O2:Ar=2:1:7, pressure and temperature are 36679.65Pa and 624K respectively. We can calculate the CJ detonation velocity D_{cj}=1621m/s using Chemkin.

For verifying the mesh size enough for the resolution of the detonation simulation, two mesh sizes are tested, that is 5um and 1um of the smallest size of mesh. A piston with velocity 960m/s moving forward in the quiet mixture to produce a detonation. The pressure and temperature profile are taken at the same time for two size mesh case, which are shown in the Fig.1(a) an Fig.1(b) .



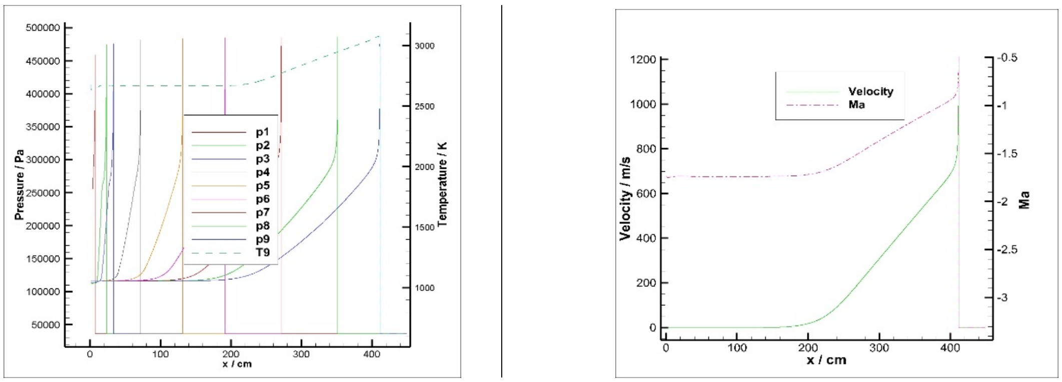
(a) (b)

Fig.1 comparison of pressure and temperature for different mesh size of 5um and 1um, corresponding to Fig.1(a) and Fig.1(b),respectively

From the result shown above, it can be found that the two profile almost overlap together, which means the two mesh size are all available for current detonation simulation. The 5um smallest mesh are used for reducing the computing consumption in current simulation.

For obtaining the steady CJ detonation velocity , a 4.5merters-long tube with one-end wall is used for detonation propagation, which is initiation by ZND structure corresponding to the theory D_{cj}=1621m/s. It can be found from Fig.2(a), at the beginning of initiation, the pressure p1 is a little smaller. At the next time p2 becomes larger significantly, and then the pressure are almost the constant, which means the steady detonation is a little stronger than the initial detonation. We can also calculate the velocity of steady detonation by the two position of detonation at different times, which is nearly 1660m/s. It shows the really detonation velocity calculation by detailed chemistry is a litter larger than the one from CJ theory for our currently problem.

Ma number profile relatively to detonation front can also be obtained shown in Fig.2(b). We can also find the flow velocity at the sonic point is about 630m/s, which is 25.6cm after the detonation front. So it says any disturbance after that point maybe doesn't influent the detonation propagation.



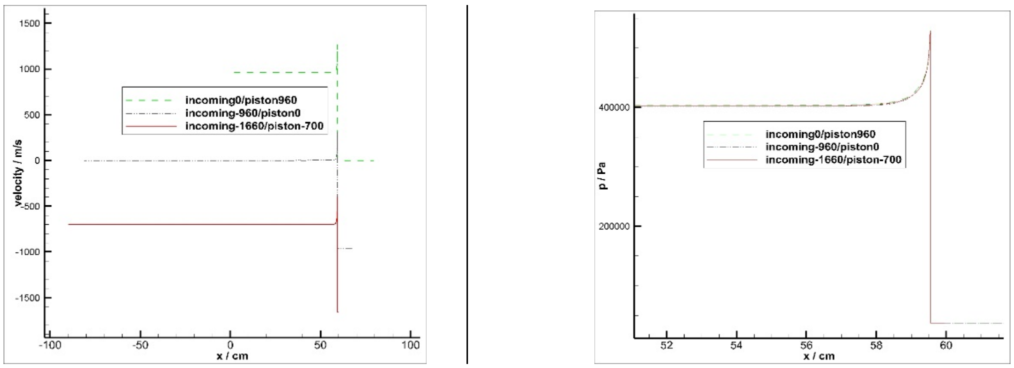
(a) (b)

Fig.2 detonation propagation in quiet combustible mixture initiated using znd profile of 1621m/s

Aim to further analyze the effect of rear condition on the detonation propagation, we use the piston moving with different velocity to product the different pressure and velocity behind the detonation. Firstly, it is necessary to analyze the validity of relative motion between piston and incoming flow. For this reasons, three cases are compared, that is (1) piston moves forward in 960m/s in quiet mixture, (2)piston is quiet while incoming flow velocity is -960m/s, towards the piston, (3) piston moves backward in velocity of -700m/s, and incoming velocity is 1660m/s towards piston. So for these three cases, the relative velocity between the piston and incoming flow is 960m/s, which is shown in Fig.3(a). Fig.3(b) shows the pressure profile of three cases, which seems that detonation structures are almost the same when the relative velocity is same. Then we can just set the incoming velocity equal to detonation velocity, the detonation front will be fixed relative to the lab coordinate. From the above analysis it seems the reality steady CJ detonation velocity is 1660m/s, so the incoming velocity of all the cases below are 1660m/s.

One of the above cases that detonation propagate in quiet mixture with one-end wall boundary condition is corresponding with the case that incoming velocity -1660m/s with piston moving backward in -1660m/s, which is definite CJ detonation. So we adds the velocity of piston gradually to find a critical value below which the detonation velocity will not change a little, which means the CJ detonation. At last we found when the critical value of the relative velocity of piston and incoming velocity is about 700m/s, which is a little larger than 630m/s corresponding to sonic point. It's shown from fig.4 that all the pressure profile overlapping each other after the initiation stage, which means the detonation have become steady detonation and the velocity is equal to 1660m/s. The relative velocity between the piston and incoming flow is 700m/s.

Base on the final result of the case above, the piston is set behind close to detonation front again, and move at the velocity changed from -960 m/s to 900m/s. It can be found that the detonation begins to move ahead at 5.91m/s. So the detonation velocity D_{cj} is about 1665.9m/s, which is a little overdriven. The relative velocity between the piston and incoming flow is 760m/s.



(a) (b)

Fig.3 comparison of of three cases with the same relative velocity of piston and incoming flow

After that, the piston velocity was increased from -900 to -980, where the relative velocity is 680m/s. It's shown that at the first stage when the piston velocity changes, the detonation propagate ahead a litter and the velocity decelerate quickly. After propagating for 5ms at 0.0202653s, all of the profiles almost overlap together. So at this time, the detonation become static. The detonation velocity is decrease to 1660m/s, which corresponding to CJ detonation.

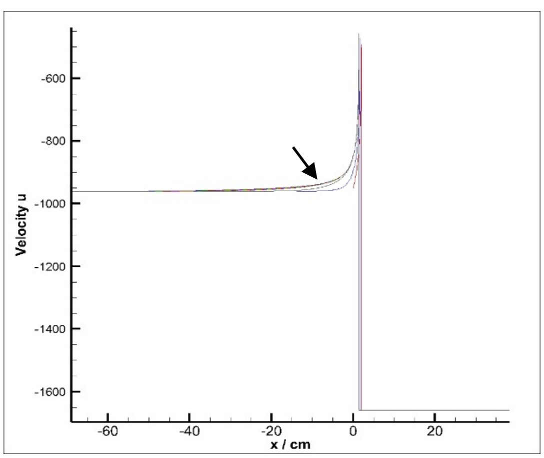


Fig.4 pressure profile of case of incoming -1660m/s with piston moving back -960m/s. Detonation become static in supersonic flow 1660m/s. So the velocity is 1660m/s too.

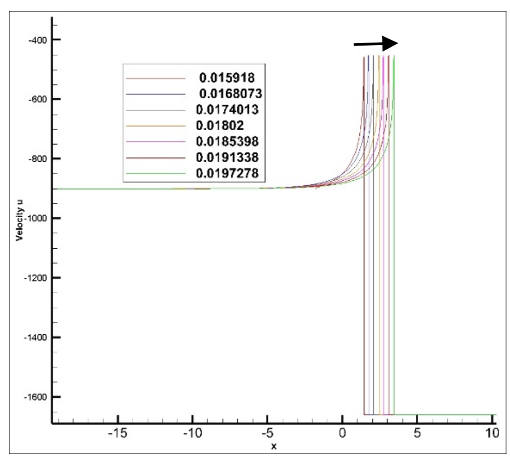


Fig.5 velocity profile varying with the time when the piston velocity changing from -960 m/s to -900m/s in incoming velocity -1660m/s mixture.

We can also get the velocity profile and Ma number relative to detonation front for the case of piston velocity -990m/s and incoming velocity -1660m/s mixture, which shown is Fig.7. It found that the flow field behind the front is subsonic totally, while the CJ detonation for this case isn't effected significant. It says the detonation can resist the disturbance behind it in some range. But the detonation will become overdriven if the piston move in smaller velocity backward the detonation. But what's the mechanism leading to overdriven and what's the exact relationship of velocity or Ma number with the mixture above which will lead to overdriven hasn't been revealed.

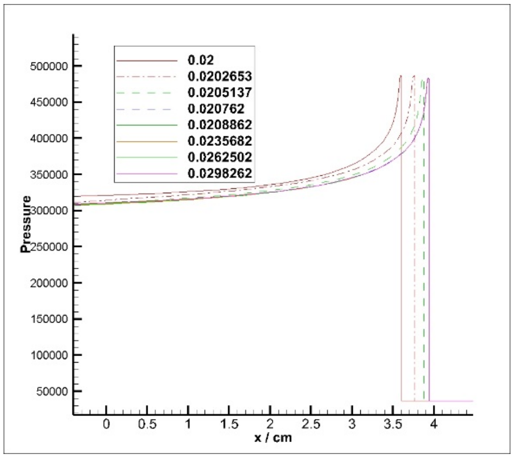


Fig.6 pressure profile varying with the time when the piston velocity changing from -900 m/s to -990m/s in incoming velocity -1660m/s mixture.

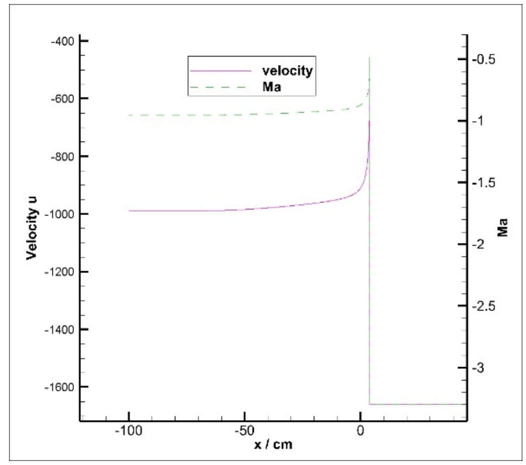


Fig.7 velocity profile and Ma number profile relative to detonation front with piston velocity -990m/s in incoming velocity -1660m/s mixture.

4 Conclusions

It's found that there is significant deviation of detonation velocity obtained using real chemistry with that from CJ theory. When the piston move back fast enough relative to the incoming flow, the detonation will always be CJ detonation. It is about 700m/s of piston relative to flow velocity for the current mixture. When the piston velocity toward the detonation larger than that, the detonation will be overdriven. For the CJ detonation, the flow behind the detonation can also become subsonic, which means the detonation can resist the disturbance in some range. But the real mechanisms lead to this phenomenon hasn't been revealed.

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