Detonation Wave Propagation in Annular Channels

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1 Introductions

The enhancement of detonation initiation has been a key issue in the development of the pulse detonation engine (PDE) to enhance the PDE operation frequency since the higher operation frequency is a desperate performance parameter that makes the PDE useful. As a mean of enhancing the detonation initiation, Frolov et al, employed the coil shape tube and U-bend tubes.[1,2] As a alternative way of using detonation wave for aerospace propulsion, continuous detonation wave propagation in a annular channel has been considered recently by adopting the old concepts suggested by Nicholls et al.[3,4] and Voitsekhovskii et al.[5,6] in 1960's. Daniau et al.[7,8] considered it for the rocket applications with name of CDWRE(continuous detonation wave rocket engine). A numerical study is going on for this application.[9] Milanowski et al.[11] also considered nearly same idea for airbreathing application with name of RDE(rotating detonation engine). These concepts have same flow feature of detonation wave propagation in tubes or channels with large curvature. It is surprising enough that little work has been done on the deflagration-todetonation transition (DDT) or shock-to-detonation and detonation diffraction in such elements, as Frolov mentioned.[1] Therefore, the main purpose of present paper is the systematic study on the effect of curvature on the detonation wave propagation.

2 Numerical formulations

The computation code used for multi-dimensional detonation wave propagation studies[12,13] has been extended to the present study with OpenMP parallelization for multi-core SMP machines. For the simplicity of study in two-dimensional configuration, annual channels with different radii of curvature were considered by normalizing the radius of curvature, R by the channel width H. The normalized radius of curvature was considered as unique geometric parameter changing varying from 1.5 to 9.0. The computation was carried out by using a fixed computational domain of arc length 50.0 along the center line of the annular channel. The computational domain is covered by 5,001×101 uniform grid, of which the grid resolution has been proven as being sufficient to capture the cell structures for the thermo-chemical parameters considered.[12] The parameters are as follows; specific heat ration of the unburned and burned gases are 1.602 and 1.288, respectively, dimensionless heat release is 24.2, and dimensionless activation energy normalized by gas constant and von Neumann temperature is 5.2. The reference value of the pre-exponential factor is set to 5,000 to have a multiple cells within the channel width, but is varied to find the dependency on it. The detonation regime for this condition corresponds to the weakly unstable detonation condition.[13] The ZND structure was calculated prior to the CFD analysis, which was imbedded at one end part of the computation as an initial condition with an inclined distribution for initial perturbation. The marching window, (MW) technique was used in the present study to reduce the computing time, i.e., only the region of interest is computed whereas the rest parts are unsolved.[13] 0.1H ahead of the detonation front was selected as front boundary of the MW, and the location where Chapman-Jouguet, (C-J) condition is satisfied is selected as the exit boundary of the computational domain. The size of the MW is variable, but is maintained at the size about 100~150×101 depending on situation. Therefore the computational cost for the MW is about 1/30~1/50 that of the entire computational domain, and it is nearly same to that for the simulation with wave stationary computing system. The inflow boundary of the MW is set to the initial value of the computational domain, but the C-J boundary condition was applied at the exit. Slip wall boundary condition was applied at the inner and outer wall of the annular channel.

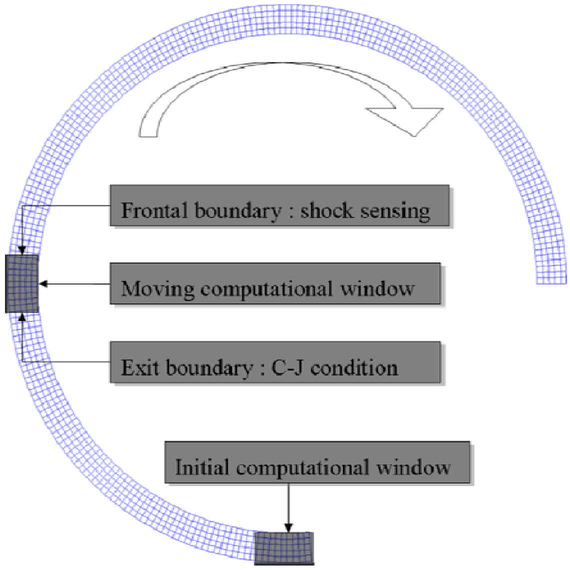

Figure 1 Grid system & Computational domain

As an initial condition of the simulation of detonation wave propagation, the results of the ZND structures calculations were used by setting the ZND solutions along the every grid line in longitudinal direction. For the initiation of unstable motion, the solutions were set inclined in transverse direction. Fixed stationary inflow boundary condition was used. Extrapolation was used at exit if flow speed ahead is supersonic, but speed of sound is used with C-J pressure if the flow is subsonic. Both walls were assumed be slip wall and adiabatic. Smoked-foil record is simulated numerically by recording the peak pressure behind the shock wave across the width of the computational domain.

The flow features such as cell structures and pressure variations are investigated for different regimes of detonation with respect to the radius of curvature. The pre-exponential factor, *k* considered are 1,000, 2,000, 5,000, 10,000, 20,000, 100,000, 200,000, and 400,000

3 Results and Discussions

Figure 2 shows variation of reaction rate and shock wave accompany with variation of radius at weakly unstable detonation with k=5,000. In cases of of R=1.5 and 3.0, there is wide reaction zone around triple point. This is a point of difference with ZND structure analysis of general weakly detonation. If radius is done beyond 4.5, variation of reaction zone is not difference. Shock wave is irregular at beyond 4.5. This shows multiple triple points exist.

Figure 4 shows max pressure of weakly unstable detonation wave from *k*=5,000 and R=6.0 inside of channel. Outer surface of channel pressure is higher than inner surface of channel pressure. Figure 5 shows outer surface of channel pressure with variation of radius. In cases of R=6.0, 7.5 and 9.0, outer surface of channel max pressure is not difference. Max pressure shows regular cycle. At weakly unstable detonation, pressure decreases in proportion to the increase of radius. But, at moderately and highly unstable detonation, pressure increases in proportion to the increase of radius. All of cases, inner and outer pressure gap becomes smaller in proportion to the increase of radius. Here, effect of curvature becomes smaller in proportion to the increase of radius. So, the results are similar in result of straight channel.

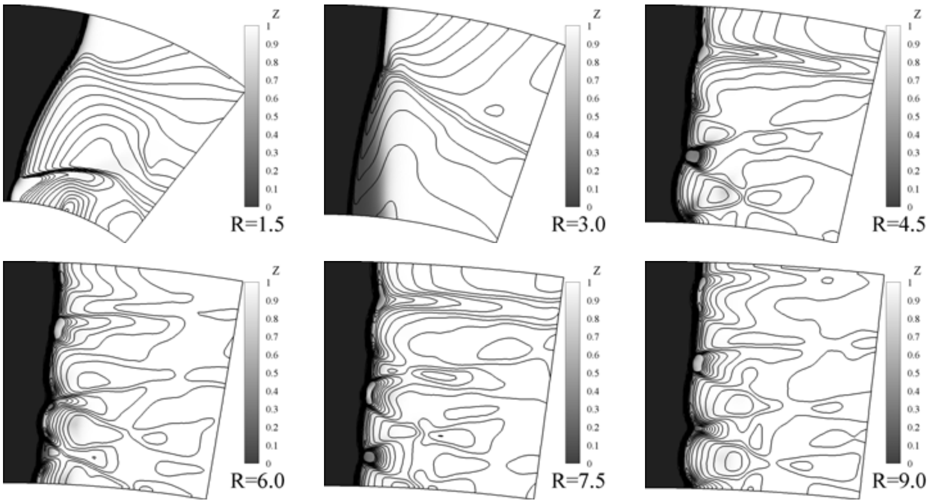

Figure 2. Front structures of weakly unstable detonation wave from k=5,000(Δy=0.01)

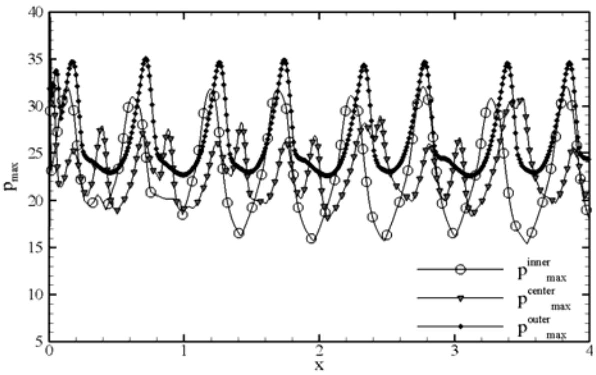

Figure 3. P_{max} of weakly unstable detonation wave from *k*=5,000 and R=6.0

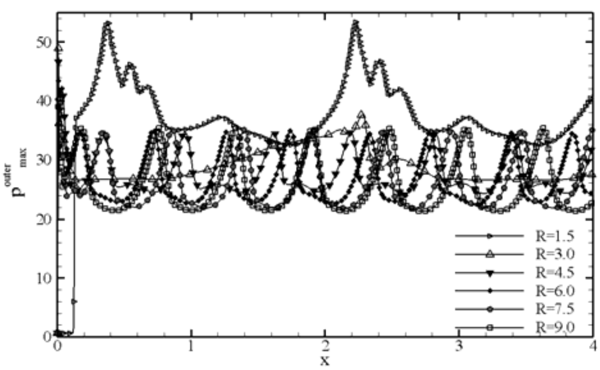

Figure 4. P_{max} at the outer surface of channel from *k*=5,000

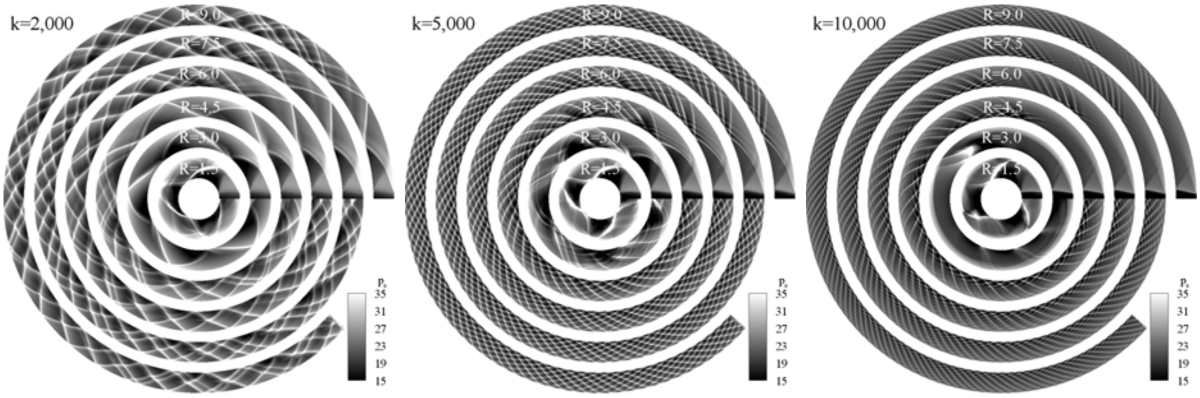

Figure 1. Smoked-foil records for different radii of curvature with different pre-exponential factor, *k*.

Figure 4 shows smoked-foil record accompany with variation of pre-exponential factor at weakly unstable detonation. Cell grid distance becomes smaller in proportion to the increase of pre-exponential factor. But, cell capture is not to easy in proportion to the increase of pre-exponential factor with increase of reaction sensitive. Differently expectation, outer cell size is as large as inner cell size. Cell structure capture results are similar in straight channel. If radius is done beyond 4.5, effect of radius is small.

4 Conclusions

Numerical studies were carried out to identify the effects of curvature on the detonation wave propagation in annular channels. It is shown that there is a critical radius of curvature where the regular cell structure could be maintained. Where the radius of curvature is smaller than the critical radius, the detonation wave propagates unstably something like spinning detonation or galloping detonation. The pressure trace exhibits much higher pressure than the C-J pressure at the outer surface in these cases. Where the radius of curvature is greater than the critical radius, the detonation wave propagates regularly while maintaining nearly the cell structures and cell sizes with respect to the detonation wave propagation in a straight channel. In overall, the major effect of the radius of curvature is considered as the flow compression around the choking point. Thus, the detonation speed is maintained around the C-J detonation speed though the detonation wave is further accelerated at the outer region whereas decelerated at the inner region. As a result, pressure at the outer surface exhibits the higher pressure than the center line while the lower pressure at the inner side. The critical radius where the regular cell structure could be maintained is 4.5 among the case considered in this study. It is considered that present study will serve as a basis for further studies on detonation wave propagation in tubes with curvature especially for propulsion applications.

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