Effect of Curvature on the Detonation Wave Propagation Characteristics in Annular Channels

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Abstract

Present study examines the detonation wave propagation characteristics in annular channel. A normalized value of channel width to the annular radius was considered as a geometric parameter. Numerical approaches used in the previous studies of detonation wave propagation were extended to the present study with OpenMP parallelization for multi-core SMP machines. The major effect of the curved geometry on the detonation wave propagation seems to be a flow compression effect, regardless of the detonation regimes. The flow compression behind the detonation wave by the curved geometry of the circular channel pushes the detonation wave front and results in the overdriven detonation waves with increased detonation speed beyond the Chapmann-Jouguet speed. This effect gets stronger as the normalized radius smaller, as expected. The effect seems to be negligible beyond the normalized radius of 10.

Introduction

There were a lot of studies on the detonation propagations for the variety of applications. During the last decade the research efforts pulse detonation engine (PDE) has lead the activities of detonation studies. For the development of the PDE, acceleration of detonation initiation has been a key issue 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.[10] 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 DDT, SDT, 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. For the simplicity of study in two-dimensional configuration, annual channels with different curvature were considered with the radius of curvature as a unique geometric parameter normalized by the channel width. The flow features such as cell structures and pressure variations are investigated for different regimes of detonation with respect to the radius of curvature. Methodologies used for two- and three-dimensional detonation wave propagation studies has been extended to the present study with OpenMP parallelization for multi-core SMP machines.

Numerical Approach

Governing Equations and Numerical Analysis Methods

When compressible inviscid flow, two-dimensional Euler's equation and pressure are presented Eq.(1) and (2). Steady 1-dimensional ZND structure analysis about detonation wave was done. This is basic analysis in detonation wave study. For computational fluid dynamics analysis of detonation wave cell structure, Eq.(1) is discreated by limited volume cell point scheme. Numerical fluxes in cell boundary were formulated using Roe's Riemann solver, MUSCL-type TVD scheme and 4th order accurate Runge-Kutta time integration scheme. These are basic and important matter in detonation wave study. A Newton sub-iteration method was also used to preserve the time accuracy and solution stability.

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\\ \rho Z\end{bmatrix}+\frac{\partial}{\partial x}\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho e+p)u\\ \rho Zu\end{bmatrix}+\frac{\partial}{\partial y}\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho e+p)v\\ \rho Zv\end{bmatrix}=\begin{bmatrix}0\\ 0\\ 0\\ 0\\ \rho w\end{bmatrix} \quad (1)$$

$$p=(\gamma-1)\rho\left\{e-\frac{1}{2}\left(u^2+v^2\right)+Zq\right\} \quad (2)$$

Analysis Condition

Numerical requirement was considered with unstable state condition. For cell structure analysis, nondimensional activation energy $(\theta = E/RT_{VN})$ which is VN states temperature and unburned and burned gas rate were determined. ZND structure analysis result was derived by classification reaction specific length with inducement length(L_{ind}), heater length(L_{HR}), and half reaction length($L_{1/2}$). Weakly unstable detonation has not inducement length. Moderately unstable detonation has a little inducement length and several times long heater length. But highly unstable detonation has long inducement length and short heater length.

Known for various radius effects in annular channel, each radius length R has 1.5, 3.0, 4.5, 6.0, 7.5, and 9.0. Known for reaction constant sensitivity, each pre-exponential factor *k* has 1,000, 2,000, 5,000, 10,000, 20,000, 100,000, 200,000, and 400,000. Grid resolutions are 5,001×101and 5001×201.

Table 1. Summary of computational cases

Weakly unstable detonation		
$\theta = 5.2$	k=1,000 ~ 10,000	R=1.5 ~ 9.0
Moderately unstable detonation		
$\theta = 6.9$	k=1,000 ~ 20,000	R=1.5 ~ 9.0
Highly unstable detonation		
$\theta = 12.7$	k=100,000 ~ 400,000	R=1.5 ~ 9.0

Computational Domain, Initial and Boundary Conditions, and Smoked-foil Record

Fixed grid system was used in this study. Because optimum grid resolution search in all conditions is very difficult. Width grid number of annular channel is fixed in 2-dimensional detonation wave propagation of numerical analysis computational domain. Length computational domain is regular and using grid number is 1and 2 times. Width length is 150 times as long as Δy.

Table 2. Summary of computational grid

Grid system	Minimum spacing	Channel width
5,001×101	$\Delta y = 0.01$	1.0
5,001×201	$\Delta y = 0.005$	1.0

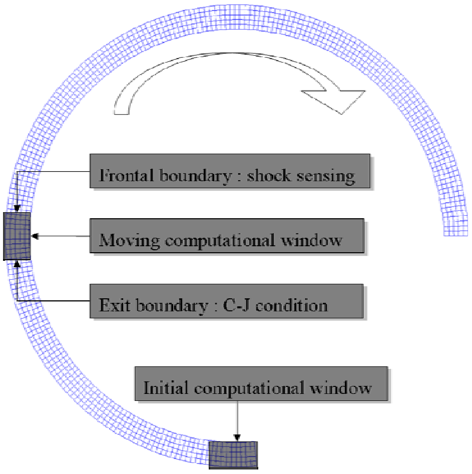


Fig. 1. Grid system & Computational domain

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 incoming boundary condition was used with C-J detonation speed as incoming flow speed. Extrapolation was used at exit if flow speed ahead is supersonic but speed of sound is given as flow speed 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 physical mechanism of smoked-foil inscription is known as a shear stress around the triple point, but the peak pressure has been widely used for numerical reproduction for its simplicity.

Result and Discussion

Effect of Curvature

Detonation wave propagation characteristic was investigated by variation of curvature. Fig. 2 shows variation of reaction rate and shock wave accompany with variation of radius at weakly unstable detonation with k=5,000 and Δy=0.01. On occasion 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.

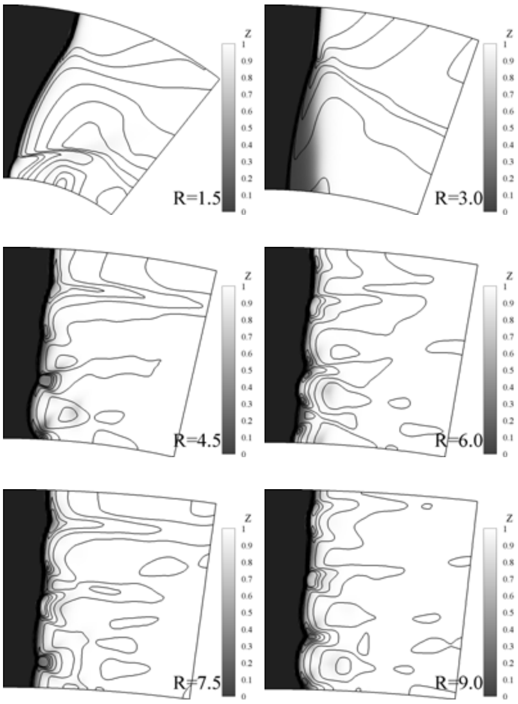


Fig. 2. Front structures of weakly unstable detonation wave from k=5,000(Δy=0.01)

Figure 3 shows smoked-foil record accompany with variation of pre-exponential factor at weakly unstable detonation with $\Delta y=0.01$. 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.

Figure 4 shows smoked-foil record accompany with infinity radius(=straight) channel at k=2,000 and 5,000. Cell number of k=5,000 increases three times what it did k=2,000. At R=1.5, 3.0, effect of radius is large. So, cell configuration is shown up and down channel wall.

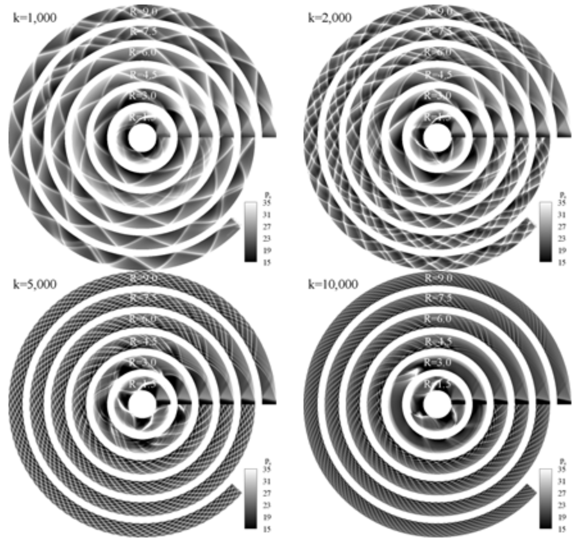
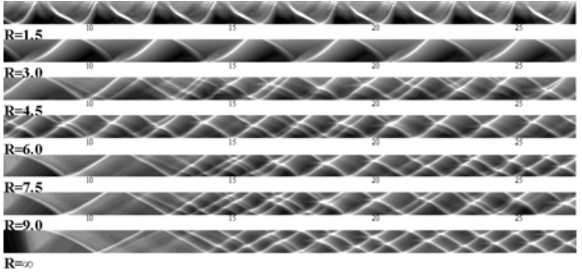


Fig. 2. Numerical smoked -foil record on weakly unstable detonation wave by variation of pre-exponential factor(*k*)

k=2,000



k=5,000

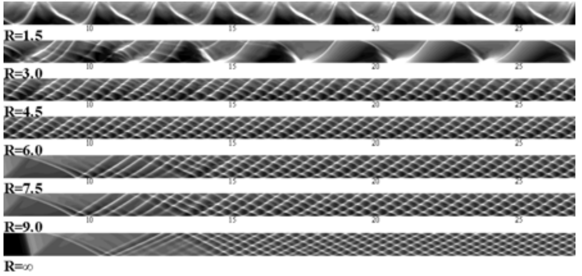


Fig. 3. Numerical smoked-foil record on weakly unstable detonation wave by variation of pre-exponential factor, k

Figure 5 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 6 is shown that detonation velocity is compared with pressure where k=5,000 and R=6.0. Figure 7 shows outer surface of channel pressure with variation of radius. On occasion of R=6.0, 7.5 and 9.0, outer surface of channel max pressure is not difference. Max pressure shows regular cycle. Figure 8~10 show average pressure inside of channel at weakly, moderately, and highly unstable detonation with variation of radius. 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.

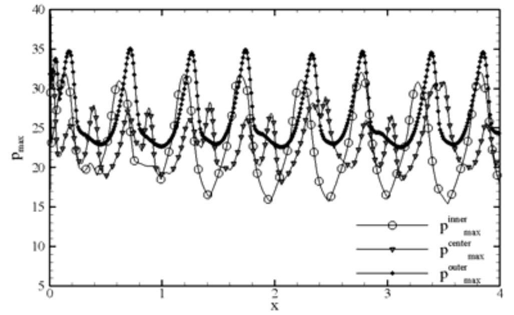


Fig. 5. P_{max} of weakly unstable detonation wave from *k*=5,000 and R=6.0

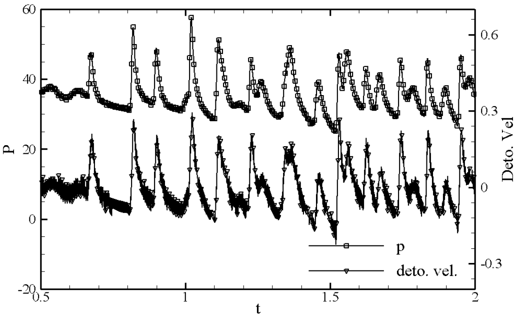


Fig. 6. Comparison of detonation velocity and pressure

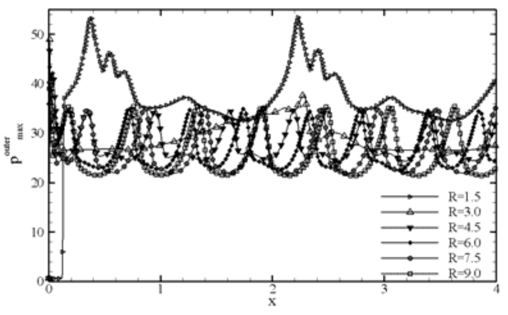


Fig. 7. P_{max} at the outer surface of channel from *k*=5,000

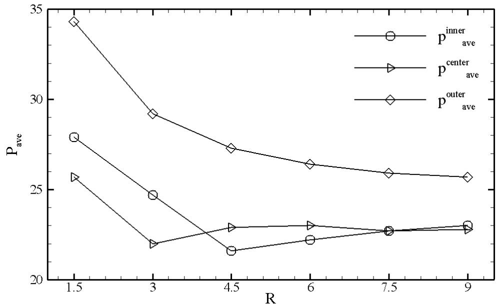


Fig. 8. $P_{average}$ weakly unstable detonation wave from k=5,000

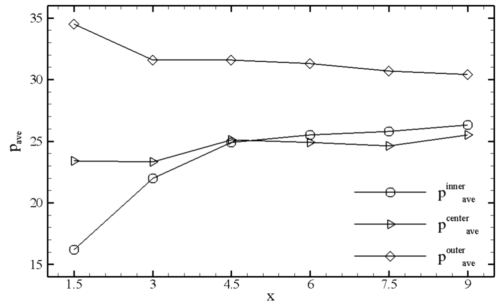


Fig. 9. $P_{average}$ moderately unstable detonation wave from k=5,000

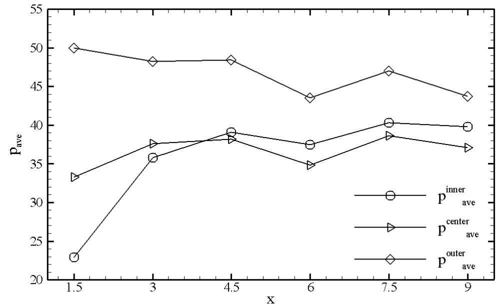


Fig. 10. $P_{average}$ highly unstable detonation wave from k=5,000

Effect of Grid Resolution

Figure 11 shows reaction rate and pressure following variation of pre-exponential factor *k* in weakly unstable detonation using Δy =0.01 grid. When *k* is increased, reaction is done rapidly. So, reaction region is smaller than before and more triple points are showed. Figure 12 shows smoked-foil records each case. When *k* is increased, cell space is narrowed. Cell configuration is regularly when *k* =5,000. Cell configuration is captured dimly when *k* =10,000.

Using Δy =0.005 grid, reaction region is increased and more triple points are showed. It is because the grid resolution is increased and the reaction region is captured easily. Figure 14 is the resulting smoked-foil records the cases. In case of *k*=1,000, detonation wave is not fully settled down and blows out of the computational domain. Due to the enhanced grid resolution the detailed structure are observed at fine scale, and smoked-foil records for the case of *k*=10,000 can be obtained clearly. It is easy that the cell structure capturing when the grid resolution is rised. It is shown that the number of cells is getting increased with the reaction constant.

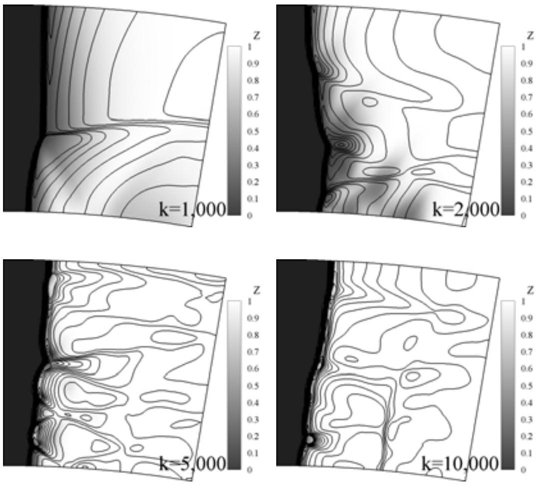


Fig. 11. Front structures of weakly unstable detonation wave from Δy=0.01 grid with R=6.0

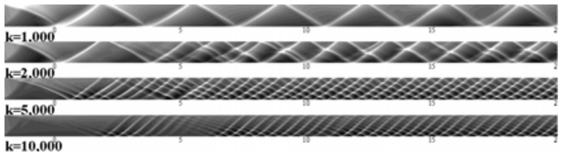


Fig. 12. Smoked-foil records of weakly unstable detonation wave from Δy=0.01 grid with R=6.0

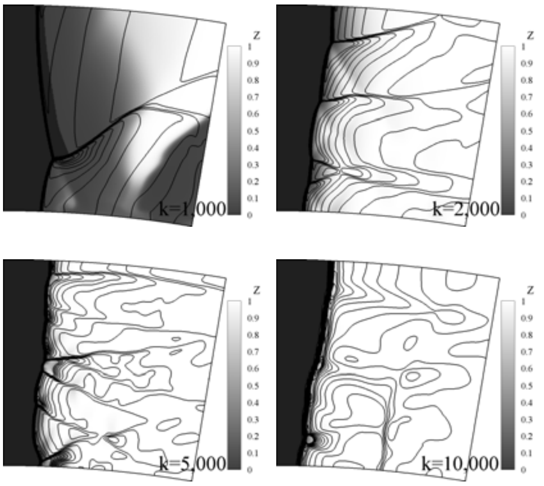


Fig. 13. Front structures of weakly unstable detonation wave from Δy=0.005 grid with R=6.0

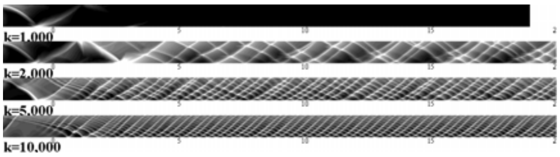


Fig. 14. Smoked-foil records of weakly unstable detonation wave from Δy=0.005 grid with R=6.0

Summary and Conclusion

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.

Acknowledgment

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References

1) Frolov, S.M., Aksenov, V.S., and Shamshin, I.O., "Shock wave and detonation propagation through U-bend tubes," Proceedings of the Combustion Institute 31 (2007), pp.2421- 2428.
2) Frolov, S.M., and Aksenov, V.S., "Deflagration-to-Detonation Transition in Kerosene Air Mixtures," 21st ICDERS, July 23-27, 2007, Poitiers.
3) Nicholls, J.A., Dabora, E.K., and Gealler, R.A., "Studies in Connection with stabilized Gaseous Detonations waves" in the 11th Symposium (International) on Combustion and Detonation, London, 1959, pp. 766-772.
4) Nicholls, J.A., Cullen, R.E. and Raglano, K.W., "Feasibility Studies of a Rotating Detonation Wave Rocket Motor," Journal of Spacecraft, Vol. 3, No. 6, June 1966, Pp.893-898.
5) Voitsekhovskii, B.V., Mitrofanov, V.V., and Topchiyan, M.E., "Structure of a detonation front in gases". SiberianBranch of the USSR Academy Sci., Novosibirsk, 1963.
6) Voitsekhovskii, B.V., "Stationary spin detonation", in Sov. J. of Applied Mechanics and Technical Physics. 1960. No3. pp. 157-164.
7) Daniau, E., Falempin, F., Bykovskii, F.A., and Zhdan, S., "Pulsed and Rotating Detonation Propulsion System : First Step Toward Operational Engines", AIAA 2005-3233.
8) Daniau, E., Falempin, F., Getin, N., Bykovskii, F.A., and Zhdan, S., "Design of a Continuous Detonation Wave Engine for Space Application," AIAA 2006-4794, 42nd AIAA/ASME/SAE /ASEE Joint Propulsion Conference & Exhibit, 9 - 12 July 2006, Sacramento, California.
9) Davidenko, D.M., Kudryavtsev, A.N., and Gökalp, I., "Numerical Simulation of H_2/O_2 Continuous Spin Detonation with a Detailed Chemical Mechanism," 21st ICDERS, July 23-27, 2007, Poitiers.
10) Milanowski, K., Kindracki, J., Kobiera, A., Wolanski, P., and Fujiwara, T., "Numerical Simulation of Rotating Detonation in Cylindrical Channel," 21st ICDERS, July 23-27, 2007, Poitiers.
11) Choi, J.-Y., Ma, F., and Yang, V., "Numerical Simulation of Cellular Structure of Two-Dimensional Detonation Waves," AIAA Paper 2005-1174, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Jan. 10-13, 2005. Also, Choi, J.-Y., Ma, F., and Yang, V., "Numerical Simulation of Cellular Structure of Two-Dimensional Detonation Waves," Combustion Explosion and Shock Waves, be submitted, Sep. 2007.
12) Cho, D.-R., Won, S.-H., Choi, J.-Y., Ma, F., and Yang, V., "Three-dimensional Unstable Detonation Wave Structures in Pipes," AIAA 2006-0957, 44th AIAA Aerospace and Science Meeting and Exhibit, Jan. 9-12, 2006, Reno, NV.