# Numerical and Experimental Study on Single Spinning Detonation in a Square Tube

**Nobuyuki Tsuboi[1], Makoto Asahara[2], Shota Kitano[2], and A.Koichi Hayashi[2]**

[1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Yoshinodai 3-1-1, Sagamihara, Kanagawa 229-8510, Japan

[2]Department of Mechanical Engineering, Aoyama Gakuin University, Fuchinobe 5-10-1, Sagamihara, Kanagawa 229-8558, Japan

Numerical and experimental research for unsteady three-dimensional detonations in a square tube are presented in order to reveal characteristics of single spin mode. The numerical results show a feature of a single spinning detonation which has a transverse detonation rotating along the wall. Experimental research is now carried out to obtain a single spinning detonation for a stoichiometric hydrogen/air and hydrogen/oxygen diluted with Ar.

## 1 Introduction

Spinning detonation in a square tube have been observed in a few past experiments and have been studied in order to reveal its shock structure for over eighty years. The spinning detonation in a square tube, which propagates with a helical track on the wall and rotates around the tube axis, has a similar shock structure with that in a circular tube. Campbell and Woodhead first observed as the reproducible striations produced on high-speed photographic records of detonations in stoichiometric mixture of carbon monoxide and oxygen in 1926 [1, 2, 3]. They obtained spinning detonation in not only a circular tube but also non-circular tube such as a square tube. Oppenheim presented a smoke-film record of the spinning detonation in a square cross section tube[4].

Recent computational fluid dynamics (CFD) has yielded remarkable insight in these problems. Three-dimensional simulations have been performed by Williams et al., who studied the rectangular mode in a square tube [5, 6], and by the present authors[7, 8, 9].

There exists two modes for the three-dimensional detonation in a square tube; namely a rectangular mode and a diagonal mode. Furthermore, there are two types in the rectangular mode; in phase and partially out of phase. These rectangular modes consist of two two-dimensional waves. The three-dimensional cell length for these rectangular modes is approximately the same as the two-dimensional cell length. The diagonal mode shows a three-dimensional diagonal motion of the triple point lines and cannot be simulated by two-dimensional calculations. The single spinning detonation in a square tube, which also has a three-dimensional shock structure, has not been simulated, successfully simulated by some of the authors to find the unstable three-dimensional shock structure[10, 11]. Some researchers experimentally tried to find the dependence of the initial pressure and composition of gas mixture on the detonation structure, however, it is not enough to understand the dependence of them on its structure.

In this paper, we presented simulation and experiment of a single spinning detonations in a square tube in order to reveal a three-dimensional shock structure and effect of the initial pressure and composition of gas mixture.

## 2 Numerical Method

The governing equations are the Euler equations with 9 species ($H_2, O_2, H, O, OH, HO_2, H_2O_2, H_2O$, and $N_2$) and 18 elementary reactions and they are explicitly integrated by the Strang type fractional step method. The chemical reaction source term is treated in a linearly point-implicit manner. A Harten-Yee non-MUSCL type TVD scheme is used for the numerical flux [12]. The Petersen and Hanson model is used for chemical kinetics to solve detonation problems. This model was proposed by Petersen and Hanson [13] as a new detailed chemical reaction model.

The computational mesh is a cylindrical system with 1201x101x101 (atmospheric pressure:$p_0$=0.1 MPa) and 601x101x101 (low pressure:$p_0$=0.01 MPa) grid points. The grid sizes are 5$\mu$m in the propagating direction 10$\mu$m in the other directions for atmospheric pressure, respectively. Five micrometer corresponds to a resolution of 32 grid points in the theoretical half reaction length which equals $1.6 \times 10^{-4}$m for $H_2$. Therefore, computational domains are 3mm in length and 1mm in width. For initial pressure of 0.01 MPa, all scales are multiplied by ten. The present computed domain is small in order to maintain high resolution, however, the three-dimensional propagating structure can be revealed in such a small scale.

The boundary conditions are as follows: the upstream conditions are at pressure of 0.1 MPa or 0.01 MPa and temperature of 300K, and the inflow gas is stoichiometric with $H_2$/air gas mixture; the wall boundary conditions are adiabatic, slip, and non-catalytic; and the downstream condition is the non-reflected boundary proposed by Gamezo et al.[14].

The initial conditions for the one-dimensional simulations are given in two computational domains with high pressure in the vicinity of a closed end wall and low pressure. In the three-dimensional calculation the results from the one-dimensional simulations are used as an initial condition, and sheets of unburned gas mixture behind the detonation front are artificially created. Present simulations requires about 300 hours for $p_0$=0.1 MPa or 150 MPa for $p_0$=0.01 MPa on 8 processors of a NEC SX-6 to obtain a steady detonation.

## 3 Experimental Method

Experiments are carried out in the detonation tube with a 40x40 mm typical rectangular cross section. The detonation tube of about 3000 mm long is filled with stoichiometric oxyhydrogen mixtures diluted with argon and the length of the pre-detonation tube filled with oxyhydrogen mixtures is 250 mm. A typical commercial ignition plug is used to ignite the mixture with a standard ignition coil. A Shchelkin spiral wire is used in the pre-detonation tube. Four PCB type pressure transducers (PT) and two ion gauges (IG) are used to measure the pressure of gases and the flame position, respectively. An oscilloscope is used to measure signals from those sensors to send them to PC with the LabVIEW system which controls the whole experiment procedure sequentially and processes the data.

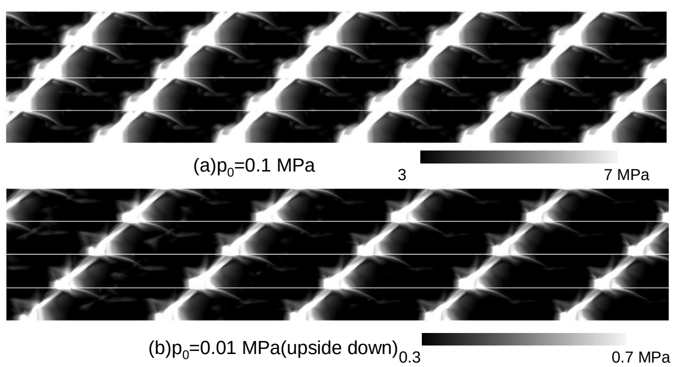


Figure 1: Maximum pressure history on the tube wall. Detonation propagates from left to right.

## 4 Results and Discussions

Figure 1 shows a comparison of maximum pressure histories on the wall. A spinning detonation pattern which is observed experimentally resembles a "ribbon" wrapped in a loose spiral for both cases. The calculated track angle is 48 deg. for $p_0 = 0.1$ MPa and 44.5 deg. for $p_0 = 0.01$ MPa, respectively. The track angle for $p_0 = 0.01$ MPa is smaller than the experimental data which are appriximately 49 deg. The effects of the initial pressure are also observed in the band width.

Figure 2 presents instantaneous detonation front shapes viewed from the front side at various times. The orthogonal triple lines are always observed on the detonation front. Three Mach stems and one

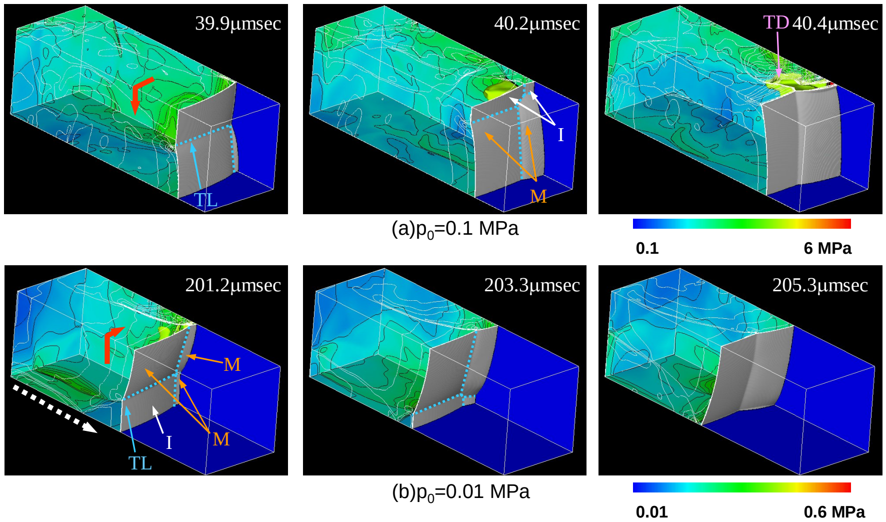


Figure 2: Comparison of instantaneous pressure space isosurfaces and contours in the tube at various times. The lime green space isosurface is pressure of 4 MPa($p_0 = 0.1MPa$) or 0.4 MPa($p_0 = 0.01MPa$). The gray space isosurface denotes the detonation front. The white broken arrow denotes the propagating direction of the detonation front, and the red arrow near the detonation front denotes the rotating direction. I - incident shock side, M - Mach stem side, TD - transverse detonation, and TL - triple line, respectively.

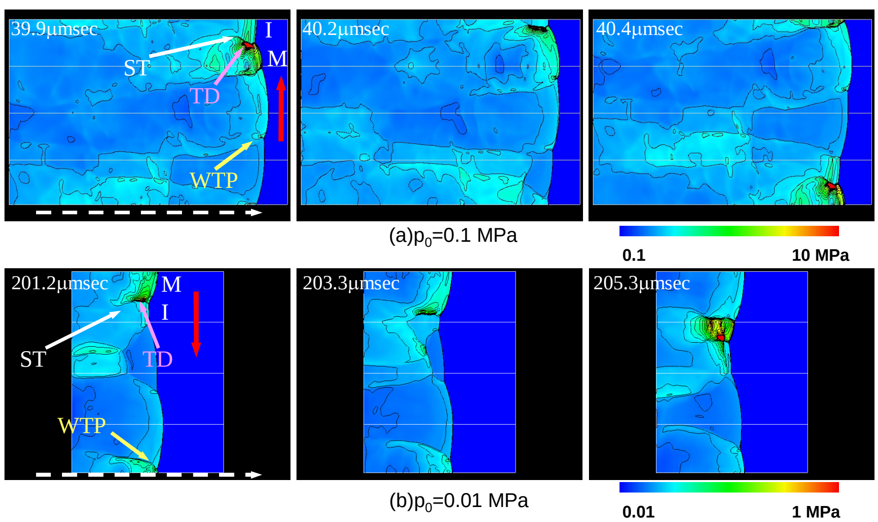


Figure 3: Comparison of instantaneous pressure contours on the wall. The white broken arrow denotes the propagating direction of the detonation front, and the red arrow near the detonation front denotes the rotating direction. I - incident shock side, M - Mach stem side, TD - transverse detonation, ST - short pressure trail, and WTP - weak triple point, respectively.

incident shock are separated by the triple lines. The vertical and the horizontal triple lines move partially out of phase, therefore the present spinning mode is the rectangular mode partially out of phase. These triple lines in the diagonal mode and the rectangular mode in phase move in phase in our past simulations[7], which differ from the present results. The overall shock structures for both cases have a similar pattern.

Figure 3 shows instantaneous pressure contours on the wall. A transverse detonation is observed for both cases. Furthermore, a weak triple point which is reflected from the orthogonal wall also propagates along the wall for both cases.

# 5 Conclusions

Unsteady three-dimensional simulations with a detailed reaction model were performed for hydrogen/air mixtures in the square tube in order to reveal the effects of initial pressure on the structure of detonation. The instantaneous shock structures in both cases have similar pattern, however, the track angle and band width on the maximum pressure history on the wall are dependent on the initial pressure.

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