Numerical Simulation of Blast Waves in a Closed Space

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Abstract
An experiment for an explosion of natural gas pipeline is planned. A pipe of 20m long is placed in a 8m×8m×40m facility and exploded to investigate the extension of the crack on the pipe. In the experiment, the blast waves travel in the box and interact with the walls. In the present study, the behavior of the blast wave in a closed space, which is a simplified model of this experimental facility, is examined. Two-dimensional simulations show that the maximum pressure is observed at the bottom corner of the box by the second attack of the blast wave. Also shown is the effectiveness of the holes placed at the bottom corner. Three-dimensional simulations are also performed and strong two-dimensionality of the flow around the middle of the pipe is concluded.

1. Introduction

Natural gas is a promising alternative to oil in this century. Nowadays, there are projects to construct natural gas pipelines that transport gases in higher pressure than conventional ones. The pressure inside is so high that an accidental eruption of gas due to a crack in the pipe may cause serious damage on the whole pipeline system. An experiment is planned where a pipe of 20m long containing high-pressure gas is exploded in a 40m × 8m × 8m box. Figure 1 illustrates the experimental facility. The pipe is filled with 350atm, 10 percent air and 90 percent water. The length of pipe is 20m. Although the main purpose of this experiment is to observe the travel of the crack, the behavior of the blast waves in the box is another interest because the estimation of the blast wave strength at s practically important for the construction of the experimental facility. In the present study, the blast wave behavior is only focused on. The pipe is simplified to be an energy core. The interactions of blast waves and walls are mainly discussed with a variety of the box configurations.

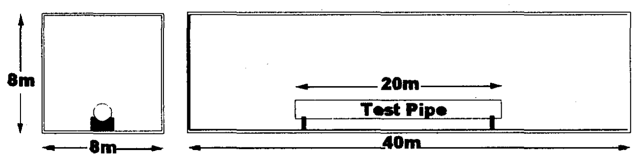


Fig. 1 Experimental facility

2. Two-dimensional model

Figure 2 illustrates the two-dimensional model. To simplify the problem, the pipe is assumed to be filled with 35atm, 100 percent air. In this condition, the internal energy in the pipe is almost the same as that in the experiment. The standard air is set outside of the pipe. The radius of the pipe is 1.2m and the pipe is placed 1.2m above the ground and in the center of two sidewalls. The pipe is infinitely thin. The box is an 8m×8m cross section. Initial velocities are zero. Temperature is 288[K] as the standard condition. All walls are treated as slip walls. The governing equations are the Euler equations, which are discretized with Harten-Yee's upwind TVD scheme.[1] A regular spacing Cartesian grid is used in order to uniformly capture the traveling blast waves.

As the Cartesian grid is used, the boundary of the pipe does not fit with the grid lines. When the grid points are not sufficient around the pipe, the initial energy given in the pipe might be inaccurate and the strength of the blast wave might differ with the grid spacing. In order to overcome this problem, the initial pressure around the boundary of the pipe is modified so that the amount of the energy be close enough to the ideal value. Figure 3 illustrates the procedure. The grid cells on the boundary of the pipe are subdivided into 16 subcells. The number of the subcells, which are located in the pipe, is counted and this is used as a weight factor. For example, the filled circles in the grid cell A are 12, then the initial pressure at A is calculated as $12/16\times35+4/16\times1$[atm].

At the beginning of the simulation, the infinitely thin pipe tube disappears instantly.

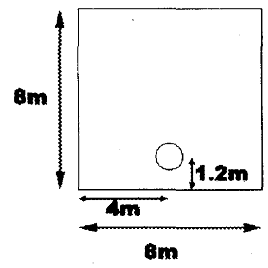


Fig2. Two-dimensional model

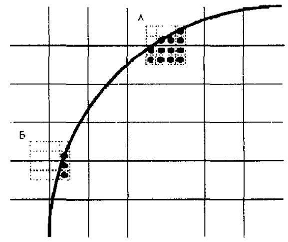
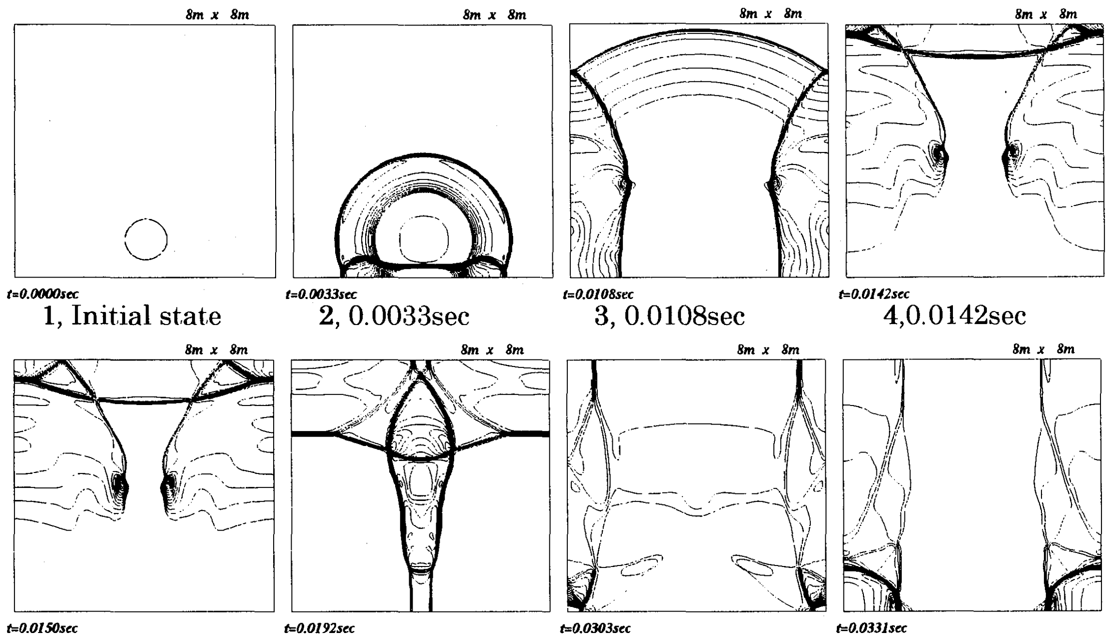


Fig.3 Initial pressure value near the edge of the pipe



1, Initial state 2, 0.0033sec 3, 0.0108sec 4,0.0142sec

5,0.0150sec 6, 0.0192sec 7,0.0303sec 8, 0.0331sec

Fig.4 Flowfield in the closed space

The grid convergence test is executed with a series of grids. The number of grid points ranges from 41×41 to 601×601. From these results, 201 × 201 grid points are concluded to be necessary to resolve this particular flowfield

3.The result of two-dimensional simulations

Figure 4 shows the time sequence of the flowfield. The lines are pressure contour lines. The number of grid points is 201×201. After the pipe tube disappears, the blast wave reaches at the ground first, then reflects, reaches at the sidewalls and reflects. Our interest is the pressure rise on the walls (side or top) and not on the ground. Hence the pressure on the three walls is recorded and it is found that the maximum pressure rise is observed at the bottom corner of the sidewalls. Some periodical pressure rises are observed at this corner. Figure 5 is the time history of the pressure at the bottom corner. The first pressure peak was recorded about 10[atm] at 0.006[sec]. The second one was recorded about 12[atm] at 0.03[sec]. The second peak pressure is a result of two waves interaction, i.e. one reflecting the opposite side wall and the other reflecting the top of the wall. Due to this concentration of energy, the second pressure peak is stronger than the first one.

In order to relieve the pressure on the wall, the silencers are planned to be placed on the wall in the experiment. Instead of the silencers, small holes are placed in the present simulation. The locations of the holes are determined to be the bottom corners where the maximum pressure value is observed. The height of the holes is 0.2m. In this case, one more grid shown in Fig. 6 as Grid2 is prepared for the hole and the outer region. The curve of top boundary in Grid2 is given as a sine curve. From the previous results, the flow symmetry is assumed and computational domain is a half of the box. The two zones (the half of the box and the outer region) are solved by Fortified Solution Algorithm (FSA) approach.[2] The interface procedure using FSA is explained as follows. In Fig. 7 the points ● of Grid1 is given the value which is solved on Grid2 in previous time step. Then, the points ▲ of Grid2 is given the value which is solved on Grid1 in previous time step. The linear interpolation is used at the grid points that do not coincide with the point of the other grid. In Grid1, all walls and the ground are treated as slip walls. In the region of Grid2, the walls of top and ground are slip walls and all variables are extrapolated at the boundary of opposite side from Grid1. Initial conditions are the same as the case without a hole. The maximum pressure is recorded on the sidewall just above the hole. Figure 8 is the time history of the pressure at the point. The value of the first pressure peak is almost the same as the case without the holes, but the second peak is reduced by half. Figure 9 shows two snapshots of the flowfield with small holes. The lines are pressure contour lines. The pressure distributions at the moments of the first peak and of the second peak are depicted in Fig. 9(a) and Fig. 9(b). The gas spouts out from the box in both moments. However, due to the concentration of the blast waves at the bottom corner, the gas spouts out more effectively in the latter moment. This practically prevents the fatigue of the wall against the repeating blast wave attacks.

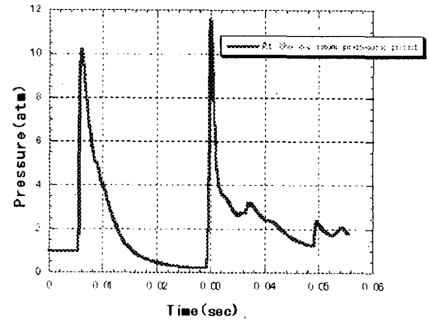


Fig.5 Time history of pressure at the maximum pressure point

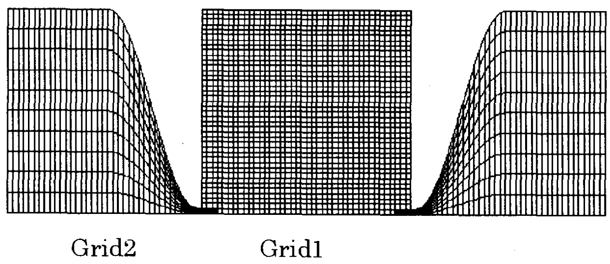


Fig.6 Grid2 is prepared for the hole and outer region

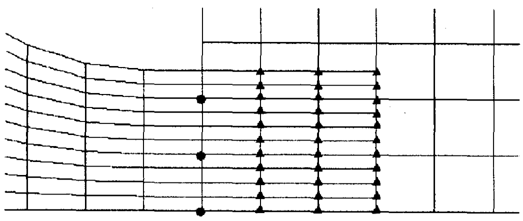


Fig.7 Extended joint part

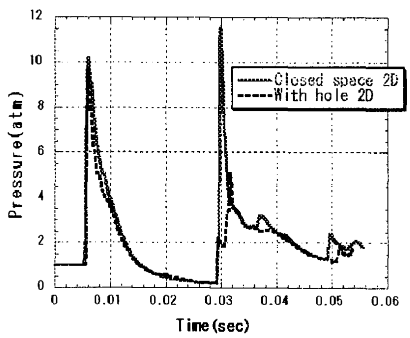
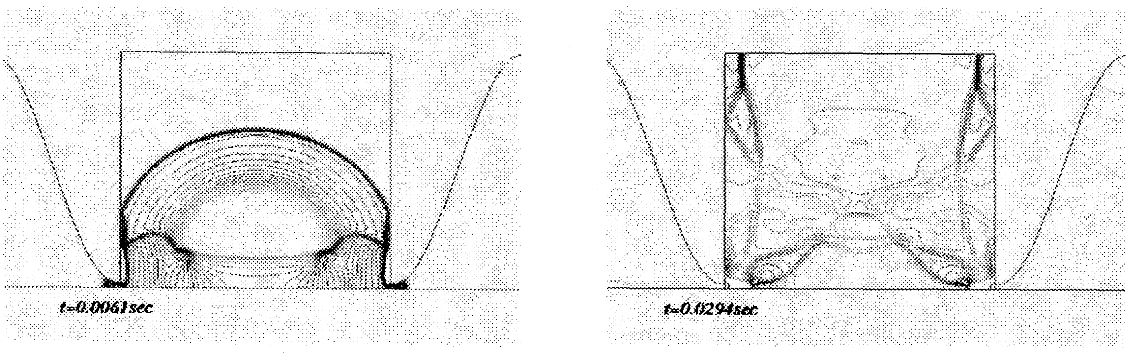


Fig.8 Time histories of pressure with and without holes



(a)0.0061 sec (first peak) (b)0.0294 sec (second peak)

Fig.9 Flowfield in the closed space with holes

4. Three-dimensional models

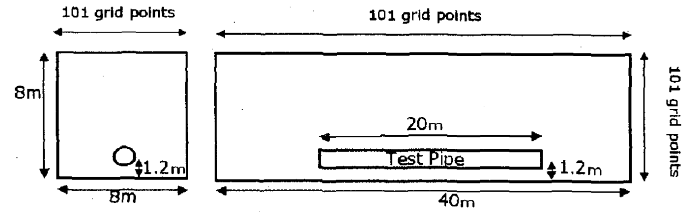


Fig. 10 Three-dimensional model

In the experiment, the length of the pipe is half of the box and it may cause the three-dimensional effect. The three-dimensional flowfield is now simulated for the estimation of the three-dimensional effect. The three-dimensional model is illustrated in Fig. 10. The cross section is the same as the two-dimensional case. The pipe is placed in the middle of the box in the longitudinal direction. Initial and boundary conditions are the same as the two-dimensional case. From the two-dimensional results, flow symmetry is assumed and the computational domain is a quarter of the box. The grid points in the cross section is 53 x 101 and in the longitudinal direction is 53 points for this quarter area. Thus, this grid corresponds to the grid which has 101×101×101 grid points for full domain. Firstly, the three-dimensional flow field in a closed space is simulated. Figure 11 shows the initial condition of pressure in the half domain in the longitudinal direction. The maximum pressure rise is observed at the bottom corner of the sidewalls in the middle of the box in the longitudinal direction. The corner is labeled as point A in Fig. 11 and the intervals from A to F are constant. Figure 12 shows the pressure distribution at the moment when the first peak of pressure is observed. The pressure isosurfaces are plotted. Figure 13 shows the time histories of at A to F. Due to the insufficiency of the grid points in the cross section, compared with two-dimensional cases, the second peak of pressure is rather hebetated. Thus we limit the following discussions within the qualitative aspects. The time histories of the pressure on the A, B and C are almost the same. In Fig. 14, the time history of pressure at A and the one of the two-dimensional flowfield with 101×101 grid points are plotted. The two time histories of pressure are almost the same. This result shows that the flowfield around the middle of the box in longitudinal direction is almost two-dimensional. This two-dimensionality is explained by the observation that the blast wave, which is reflected at the end wall in longitudinal direction, does not come until the blast waves in the middle region of the box decay, because the end wall in the longitudinal direction is rather far.

The second case is a closed space with seven discrete holes (Fig. 15). The intervals of the seven holes are constant. The size of these holes is 0.2m x 0.48m. Figure 16 is the pressure distribution at the moment when the maximum pressure rise is observed. Figure 17 is also the pressure distribution on the sidewall at the same moment. The black areas correspond to the holes. The pressure load between the holes is high. Figure 18 is the time history of pressure at the maximum pressure point in the cross section (i) and (ii), which are indicated by the line (i) and (ii) in Fig. 17 respectively. While the second peak in the cross section (ii) is reduced, the pressure in the cross section (i) is not reduced. Figure 19 is the time history of pressure in the cross section (i) together with the two-dimensional case without holes. Both the time histories in Fig. 19 are almost the same. Actually, comparing the time sequences of pressure distribution in the cross section (i) with two-dimensional case without holes, both of them are almost the same. The influence of placing the several discrete holes does not reach to the cross section (i). The influence of the holes is limited because of the strong two-dimensionality of the flowfield.

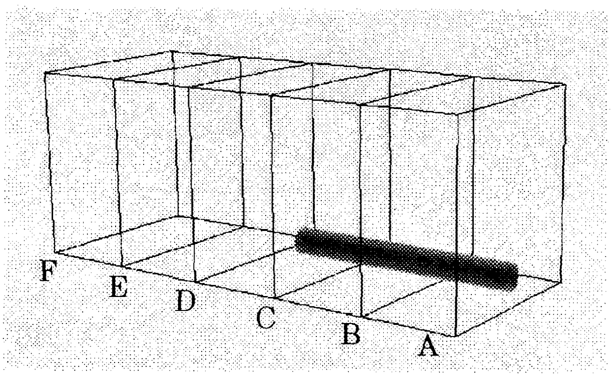


Fig. 11 Initial condition

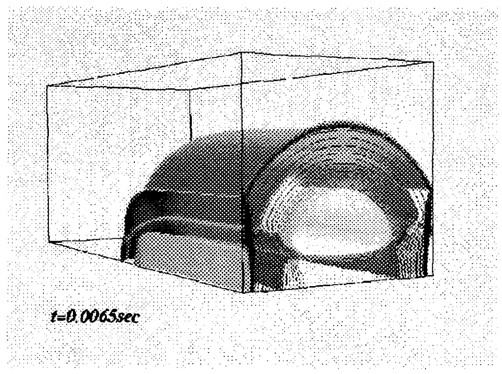


Fig. 12 Pressure distribution in a closed space

5. Conclusions

The behavior of blast waves in the closed space is investigated in this study. The followings are concluded.

In two-dimensional flow simulations,

- The blast waves cause the strong pressure rise at the bottom corner of the box by repeating the reflection at the walls, and the ground. The pressure rise repeats several times.
- The maximum pressure rise is observed at the second peak at the bottom corner of the box.
- This second peak of pressure is reduced by half by placing the holes at the bottom corner of the box.

In three-dimensional flow simulations,

- The behavior of the blast waves in the box has strong two-dimensional nature, especially around the middle of the box in longitudinal direction.
- The influence caused by placing discrete holes is limited.

References

1)Yee.H , "Upwind and Symmetric Shock-Capturing Schemes", NASA TM 89464, May,(1987)

2)Fujii.K, "Unified Zonal Method Based on the Fortified Solution Algorithm," Journal of Computational Physics 118 , pp.92-pp.108 (1995)

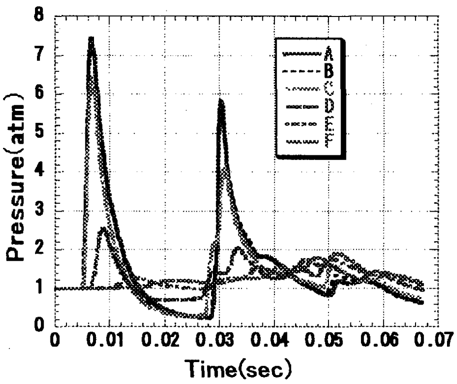


Fig. 13 Time history of pressure at from A to F

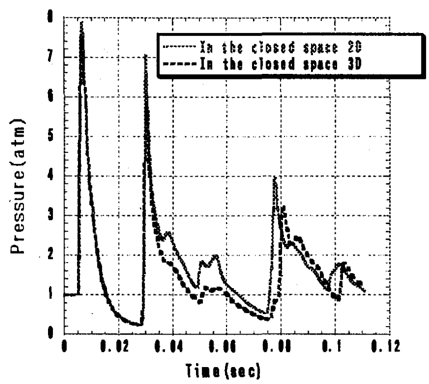


Fig. 14 Time history of the pressure compared with the two-dimensional case

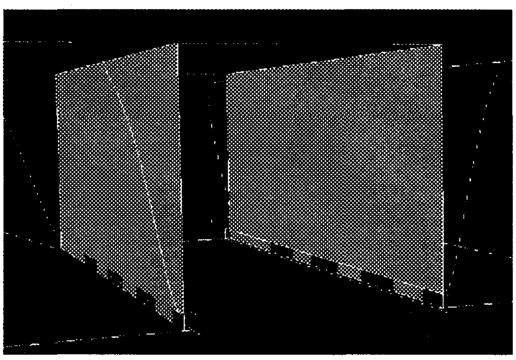


Fig. 15 With discrete holes

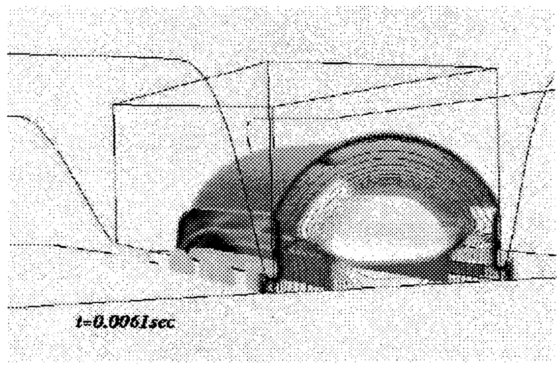


Fig. 16 Pressure distribution in a closed space with discrete holes

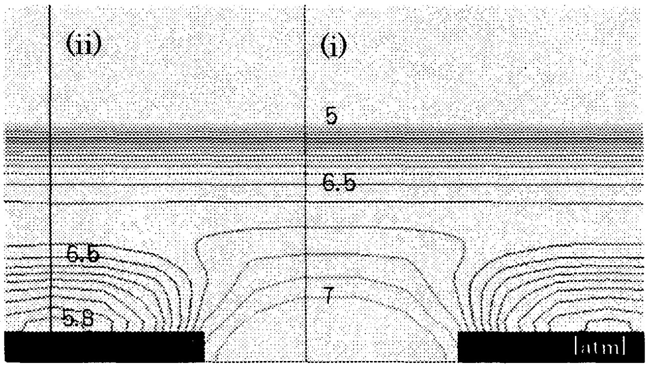


Fig. 17 Pressure distribution on the sidewall

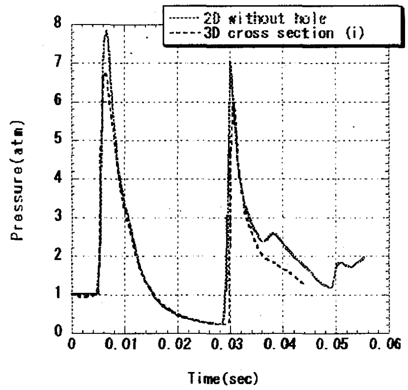


Fig. 18 Time history of pressure in the cross section (i) and (ii)

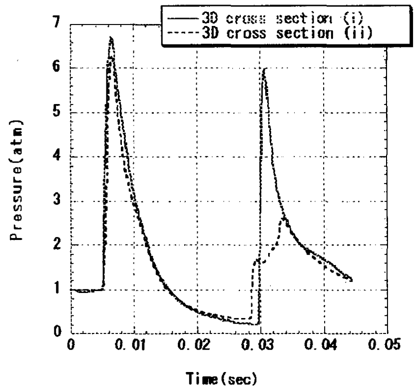


Fig. 19 Time history of pressure in the cross section(ii) compared with the two-dimensional case without holes