Numerical simulation of a shock wave experiment apparatus based on the air cannon

Wei Bin SONG\textsuperscript{1,2} Yu Ning SUN\textsuperscript{1}

\textsuperscript{1}School of Energy Science Engineer, Henan Polytechnic University, Jiaozuo, Henan 454000, China;
\textsuperscript{2}Henan Key Laboratory for Green and Efficient Mining & Comprehensive Utilization of Mineral Resources, Henan Polytechnic University, Jiaozuo, Henan 454000, China
weebin@126.com

Abstract. According to main problems in the development of the shock wave experiment apparatus used for the model test research of explosion doors, a series of CFD simulations were performed to look for approaches of improving of the apparatus. The results of simulation of the non-diaphragm mode show that the strength of shock waves generated by the apparatus can be improved to different extent with a variety of ways, such as increasing the operating pressure of the air cannon, decreasing the diameter of the driven section and increasing the diameter of the blow pipe, and that the most feasible approach to increase the strength of shock waves is adopting the two methods of increasing the diameter of the blow pipe and decreasing the diameter of the driven section together. The results of simulation of the diaphragm mode show that the forming of the shock wave is a result of the overlap of two pressure waves. These research results plays a important role in promoting and improving the apparatus, and are very valuable to study issues relevant to air cannons.

1. Introduction
In the mine ventilation system, as an attachment of the main fan, the explosion door has an important role in providing protection for the main fan against air blast. In order to carry out the model test research of explosion doors, an experiment apparatus based on the air cannon was developed. The apparatus consisted of a 300-liter industrial air cannon for powder declogging, pipe sections (DN300 iron pipes), a compressed air system, a data acquisition system for pressure, etc.(see Figure 1). The apparatus could be routinely run in diaphragm mode and non-diaphragm mode\textsuperscript{[1-3]}\textsuperscript{[4-7]}. When the apparatus was run in non-diaphragm mode, it worked as a non-diaphragm type shock tube, and could excite shock waves with an over-pressure peak value of 0.045MPa(gauge pressure, similarly hereinafter). When the apparatus was used under diaphragm mode, it could be regarded as a special shock tube\textsuperscript{[4-7]}, and could generate shock waves with an over-pressure peak value of 0.077MPa. The practical application showed that the apparatus could basically meet the technique requirements of experiment study of explosion doors, and the apparatus was stable and reliable. However, since the apparatus development mainly depended on experience and rough estimates, it still had some problems in practice, for example, the shock wave was relatively weak. For the purpose of revealing the internal mechanism of the apparatus and optimizing design parameters, CFD simulations were performed.
2. CFD modeling

The full-size 3D numerical model was established by using ANSYS WORKBENCH software. Taking advantage of the symmetry, the full model could be replaced by a quarter/half part of it to save computation time. As shown in Figure 2, the apparatus model consisted of the air cannon, the driver section and the driven section (in non-diaphragm mode, the driver section would be a part of the driven section). The inner structure of air cannon model was reasonably simplified, more specifically, the quick release piston valve or the triggering mechanism was removed from the cannon model. The fluid mechanics volume mesh was generated using ANSYS Meshing application. A mixture of tetrahedral and hexahedral elements was adopted in the grid dividing. The maximum element size was 40 mm\(^8, 9\).

![Figure 2 Geometry model of the testing apparatus](image)

The simulations were carried out with the FLUENT software. The 3D single-precision solver was used for computations, which was proved sufficiently accurate for cases investigated in the paper. The density-based solver/method was applied because fluid is compressible. The analysis type was set to transient. The viscous model selected for computations was the SST k-omega model, and the energy equation was used. Air listed in materials database was selected as the single fluid material. The air density was defined using the ideal gas law, and the air viscosity was defined using Sutherland's viscosity law. Implicit formulation was used because it is more stable than the explicit formulation. AUSM schemes were adopted as the flux splitting schemes. The spatial discretization schemes were set to second-order upwind for all items. Some surface monitors were defined to monitor variables (pressure, density, velocity, etc.) at locations corresponding to those at which the apparatus's sensors were installed. The hybrid initialization method was selected as the solution initialization method. The model was patched to define the initial pressure of the air cannon body. The time step size was usually set to 1e-5s. When the mesh quality was relatively poor, the time step size might need to be shorten to 1e-6s or less according to residual monitoring\(^10\).
Boundary conditions were defined in the model as follows. The wall boundary conditions applied to the walls of the cannon body and the pipe sections were set by default. Interfaces of adjacent model parts were defined as interior conditions. The model had only an outlet and no inlets. The outlet or exit were assigned an pressure-outlet boundary condition.

3. Results and discussion

3.1. Simulation of non-diaphragm mode

On the basis of analysis of contours of solution variables (pressure, density, mach number, etc.), the process of the formation and development of the shock wave in the apparatus model can be clearly illustrated. First, the compressed air with a pressure 0.69MPa expands explosively, the shock wave with Mach number of 1.65 is formed rapidly in the air cannon’s blow pipe/exhaust pipe (see Figure 3a). Next, when the shock wave front arrives at the interface of the blow pipe and the driven section, with a sudden change in cross section, the shock wave dissipates immediately (see Figure 3b). Then, a new shock wave takes shape in the driven section (see Figure 3c). After that, the shock wave travels along the driven section. Finally, the shock wave discharges from the exit of the driven section, in the meantime, an expansion wave is reflected on free surface which propagates back into the driven section.

![Figure 3 Density contour plots during the forming process of shock wave](image)

The propagation rules and characteristics of the shock wave in the apparatus model is obtained by means of analyzing Pressure-Time (P-T, same as below) curves of monitors. As Figure 4 shows, the P-T curves of monitor M3, M5, M6 and M7 is plotted in the same coordinate system. The numbers after dashes in the legends of Figure 4 stands for the distance between a monitor position and the left side of the driven section. It is obvious from Figure 4 that the shock wave characterized by an abrupt change in pressure has been formed before it reaches the monitor M3 position. As shown in Figure 4, during the propagation of the shock wave, its peak pressure decreases gradually at first (from monitor M3 to M5), then levels off at about 0.043MPa (after monitor M5). For each monitor or P-T curve in Figure 4, with the arrival of the shock wave, the pressure has a sharp jump and then falls and levels out at around 0.035MPa. As the expansion wave reaches, the pressure falls again and then turns negative. It is apparent from Figure 4 that the positive phase duration of the shock wave depends mainly on the monitor position in the driven section.

By comparing the results obtained from numerical simulations and physical tests, some interesting facts are uncovered. The numerical simulation model is established on the basis of the physical test, so its test conditions are nearly the same as the physical test. Figure 5 shows two P-T curves. One is plotted from the data of monitor M6 defined in numerical simulation model, another is plotted from
the data recorded by the sensor S6 installed on the apparatus. It is obvious from Figure 5 that two P-T curves are roughly similar in shape, and that there is very little difference in the peak values of two curves (0.043MPa and 0.045MPa). This comparison result shows that the numerical simulation model is relatively reliable. Furthermore, it is also obvious from Figure 5 that there is a significant difference in the rise time (or steepness) of shock waves formed in the numerical simulation and the physical test. The shock rise time of the numerical simulation is less than two milliseconds, and is about 1/5 that of the physical test. The main reason for this difference is that the air cannon structure is simplified in the simulation model, such as the removal of the quick release valve, and that the opening process of the quick release valve is not taken into account in the simulation model at all.

![Figure 4 Pressure-Time curves of monitor M3, M5, M6 and M7](image)

![Figure 5 Pressure-Time curves of numerical simulation and physical test](image)

When the apparatus is run in non-diaphragm mode, shock waves formed in the apparatus are not ideal shock wave characterized by a nearly discontinuous change in the flow parameters. Since the key characteristic of shock waves is not obvious, it is very difficult to analyze test data collected by sensors, for example, it is hard to calculate the velocity or Mach number of shock waves whose discontinuity location cannot be identified in P-T diagram. Now a beneficial implication for the improvement of the apparatus can be obtained from the simulation results. If the opening time of the quick release valve can be significantly shorten, the shock rise time may be accordingly shorten to some extent.

3.2. Simulation of non-diaphragm mode with different initial pressures

When the apparatus is run in non-diaphragm mode, as section 3.1 show, the shock waves produced by the apparatus are relatively weak, which make it difficult to meet the need for the model test research of explosion doors. In order to look for ways of improve the strength of the shock waves formed in the apparatus, many simulations with different conditions were carried out. This section mainly focuses on the relation of the air cannon’s operating pressure and the shock wave strength.

Using the same simulation model as above, a series of simulations were carried out under various conditions of operating pressure. In these simulations, the operating pressure of the air cannon model is increased gradually from 0.4MPa to 1.2MPa (in 0.1MPa increments). The shock wave’s pressure peak value of each simulation test that is detected at monitor M6 is plotted in Figure 6.

It is obvious from Figure 6 that the shock wave’s pressure peak value increases linearly with the operating pressure of the air cannon model. Even if the operating pressure is increased to the maximum of 1.2MPa, the pressure peak value of shock waves is only 0.067MPa, which is less than the desired value of 0.1MPa. By using a linear regression curve fit, the relation equation is obtained easily: $y=0.042x+0.0157$, where $y$ is the pressure peak value of shock waves and $x$ is the operating pressure of air cannons. According to the regression equation, if the pressure peak value of shock waves reaches 0.1MPa as expected, the operating pressure needs to be more than 2.35MPa.
It is well known that the safe bearing capacity of most commercial and industrial air cannons is about 0.8MPa, and that most air compressors are designed to operate at around 0.6-0.7MPa. It may be not practical to increase the operating pressure of air cannons to more than 0.7MPa, so it may be not feasible to obtain stronger shock waves by increasing the operating pressure of air cannons.

3.3. Simulation of non-diaphragm mode with different diameter sizes of driven sections

It may be feasible to increase the strength of stock waves strength by reducing the diameter of the driven section. In order to make clear the relationship between the strength of stock waves and the diameter of the driven section, a series of simulations was performed.

In this series of simulations, the diameter(inner diameter, similarly hereinafter) of the driven section replaced with the letter "D" is set to 1.0Dₙ, 1.2Dₙ,...,3Dₙ, respectively(in 0.2Dₙ increments). The symbol Dₙ here represents the diameter of the exhaust pipe of the air cannon model. The value of the symbol Dₙ is 97 millimeters. If the diameter of the driven section equals 1.0Dₙ, the diameter of the driven section is the same as that of the exhaust pipe; if D=3Dₙ, the diameter of the driven section is close to that of the initial model(300mm). All operating pressure values of the air cannon models is set to 0.7MPa in this series of simulations. The shock wave’s pressure peak value of each simulation recorded at monitor M6 is plotted in Figure 7.

As Figure 7 shows, with increase of the diameter of the driven section, the shock wave’s peak pressure decreases in an approximate negative exponential fashion. According to Figure 7, if the diameter of the driven section is less than or equal to 1.6Dₙ, the peak pressure of the shock wave formed in the simulation model is greater than or equal to 0.11MPa, which can reach and surpass the desired pressure level. However, it may be not reasonable to reduce the diameter of the driven section to 1.6Dₙ or less. In consideration of the size of the physical test models, the suitable diameter of the driven section is within the range of 2.4Dₙ to 3.0Dₙ. In this size range, the maximum pressure peak is 0.062MPa, which cannot meet the requirement for pressure(0.1MPa).

3.4. Simulation of non-diaphragm mode with different diameter sizes of the blow pipe

This section is focused on the relationship between the strength of stock waves and the diameter of the blow pipe. In this series of simulations, the diameter of the blow pipe was set to 1.0Dₙ, 1.1Dₙ,...,1.5Dₙ, respectively(in 0.1Dₙ increments). The value of Dₙ was the same as that of the above section(97mm). The operating pressure of the air cannon in the model was set to 0.7MPa. Other conditions remained the same as those of the model established in Section 3.1.

See Table 1, the strength of shock waves increases significantly with the increase of the diameter of
the blow pipe. When the diameter of the blow pipe is 1.5D₀, the shock wave’s peak pressure is almost twice that of the diameter of 1.0D₀. If the diameter of the blow pipe is further increased, the shock wave’s peak pressure will certainly reach the desired value of 0.1MPa. The maximum diameter of the blow pipe in air cannons available on the market is 125mm (about 1.3D₀). However, the diameter of the blow pipe must be limited, and is too large to be practical.

Table 1  Shock waves’ peak pressures monitored by M6 under the different diameter conditions of the blow pipe

| Diameter of the blow pipe | 1.0D₀ | 1.1D₀ | 1.2D₀ | 1.3D₀ | 1.4D₀ | 1.5D₀ |
|---------------------------|-------|-------|-------|-------|-------|-------|
| Peak pressure,MPa         | 0.044 | 0.054 | 0.060 | 0.067 | 0.074 | 0.080 |

According to the results of the above sections, it may be a more efficient way to get more strong shock waves by means of increasing the diameter of the blow pipe and decreasing the diameter of the driven section simultaneously. Figure 8 shows that the strength of the shock wave can be increased to more than 0.12MPa when the diameter of the blow pipe is 1.5D₀ and the diameter of the driven section is 2.6D₀, and that the strength of the shock wave is more than 0.08MPa with the combination of 1.3D₀ (blow pipe) and 2.6D₀ (driven section).

![Figure 8](image)

3.5. Simulation of diaphragm mode

There are two main problems in the physical tests: (1) the strength of shock waves is relatively weak, and (2) the strong discontinuity characteristic of shock waves is not obvious. In order to solve these problems, a diaphragm (aluminium diaphragm or kraft paper) was introduced to improve the improvement of the apparatus. The diaphragm was placed between the first segment and the second pipe segment, which divided the pipe segments two parts: a driver section and a driven section like a diaphragm type shock tube. The improved apparatus could excite a shock wave with a pressure peak of 0.077MPa. For the investigation on the mechanism of the apparatus run in diaphragm mode, some simulations were carried out.

The simulation model was based on the model established in the section 3.1. Before the simulation begins to run, the boundary condition of the interface between the driver section and the driven section is set to type ‘wall’ at first, thus the ‘diaphragm’ has been defined in the model. In the process of calculation, once the pressure monitored in the driver section rise to the burst pressure (around 0.15MPa), the calculation is manually stopped. Then the boundary condition of the ‘diaphragm’ is
changed to type ‘interior’, which means the ‘diaphragm’ ruptures or disappears. Afterwards, the calculation was resumed. Until the calculation is finished, there is no more manual intervention.

As Figure 9 shows, the strength of the shock wave formed in diaphragm mode is nearly twice that excited in non-diaphragm mode. In diaphragm mode, there is obviously two pressure peaks, one is 0.066MPa, the other is 0.082MPa. The first peak pressure is formed mainly due to a result of the diaphragm rupture, and the forming of the second peak pressure is a result of the overlap of pressure wave.

As shown in Figure 10, there are two shock waves in the driven section, named shock wave A and shock wave B. Shock wave A is generated at the diaphragm rupture, and shock wave B is driven by the blast of the air cannon. Shock wave B travels faster than shock wave A, and will catch up with shock wave A finally if the driven section is long enough. Due to the overlapping effects of pressure waves, the shock wave excited in diaphragm mode is stronger than that in non-diaphragm mode.

![Figure 10 Contour plots of pressure and temperature during the forming process of shock wave](image)

4. Conclusion

According to main problems in the development of the apparatus used for the research of explosion doors, a series of CFD simulations were performed. In the non-diaphragm mode, the results of simulation show that the most feasible way to increase the strength of shock waves formed in the apparatus is that two methods of increasing the diameter of the blow pipe and decreasing the diameter of the driven section are adopted together. In the diaphragm mode, the results of simulation indicate that the forming of the shock wave is a result of the overlap of two pressure waves.

References

[1] McCormack Rhys W. Development of a diaphragmless, miniature, liquid-piston shock tube, Grapevine, TX, United states, 2017[C]. American Institute of Aeronautics and Astronautics Inc., 2017.

[2] Lynch P. T. Note: An improved solenoid driver valve for miniature shock tubes[J]. Review of Scientific Instruments, 2016,87(5).

[3] Kashitani Masashi, Yamaguchi Yutaka, Oki Genkai, et al. Preliminary study on diaphragmless shock tube for transonic airfoil testing with PDI, Orlando, FL, United states, 2010[C]. American Institute of Aeronautics and Astronautics Inc., 2010.

[4] Colombo M., di Prisco M., Martinelli P. A New Shock Tube Facility for Tunnel Safety[J]. Experimental Mechanics, 2011,51(7): 1143-1154.

[5] Aune Vegard, Fagerholt Egil, Langseth Magnus, et al. A shock tube facility to generate blast loading on structures[J]. International Journal of Protective Structures, 2016,7(3): 340-366.

[6] Andreotti Riccardo, Colombo Matteo, Guardone Alberto, et al. Performance of a shock tube facility for impact response of structures[J]. International Journal of Non-Linear Mechanics, 2015,72: 53-66.

[7] Ghate Gururaj, Saify Saiffuddin. Shock tube simulation in LS-DYNA for material failure characterization, Detroit, MI, United states, 2014[C]. SAE International, 2014.

[8] Xu Jian, Chen Hai Sheng, Tan Chun Qing, et al. Numerical and experimental investigations for an air cannon optimization[J]. Science China Technological Sciences, 2011,54(2): 345-351.

[9] Jin Yong-Fei, Zhao Xian-Ke, Li Hai-Tao. Numerical simulation study on the key parameters of
air cannon busting in cleaning coal bunker blocking[J]. International Journal of Earth Sciences and Engineering, 2014, 7(5): 1793-1798.

[10] Zhang Guang, Setoguchi Toshiaki, Kim Heuy Dong. Numerical simulation of flow characteristics in micro shock tubes[J]. Journal of Thermal Science, 2015, 24(3): 246-253.