Shock Wave Attenuation by Means of Built-in Baffles in a Tube

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Abstract

The transient phenomena of incident shock waves during its passage through an orifice, a diverging nozzle, and a conical disk as baffles in a tube are numerically simulated. The influence of geometrical configurations of the baffles on shock attenuation is investigated. The results show that the conical disk was most effective configuration to weaken the strength of transmitted shock waves, since the pressure close to the inlet of the cone does not increase significantly while the transmitted shock wave is passing downstream in the cone.

Keywords: shock wave, compressible fluid dynamics, beamline

1 Introduction

Investigations on the interaction of incident shock wave with baffles in a tube are important from the viewpoint of industrial applications. Since the obstacles provide significant attenuation of oncoming shock waves, they are suitably used for protection against shock wave hazards. An orifice, a conical disk or a cone are used as typical obstacles for an air ventilation system of public shelters, and scientific facilities such as a system of synchrotron radiation beamlines that is
basically composed of many long pipelines and vacuum pumps. Each pipeline of the system has an acoustic delay line, a fast-closing valve and a photon shutter to maintain the facility at low pressure. When a part of the pipeline is destroyed by an abrupt accident, air surrounding the pipeline flows into a tube to generate shock wave as well as contact discontinuity. In practice, one should plumb to investigate this problem in the field of rarefied gas dynamics, since the initial pressure in every beamline is extremely low. However it is worthy to investigate the general feature of shock wave propagation and reflection in the range of continuum mechanics \[8, 9\]. Even if the pressure jump across the shock front is small, in general, various optical devices and pressure gauges mounted inside the tube may be damaged by the shock wave, during the impingement of pressure and density discontinuities on the devices \[10\].

In order to protect the facilities from such damages, various kinds of the obstacle like an orifice, a conical baffle or a diverging nozzle are set in the tube. The strength of transmitted shock wave may be attenuated due to the interaction between the shock front and the obstacle.

In the past decade, several types of the obstacles with various configurations were proposed to investigate the effective baffle-geometry called an acoustic delay line to attenuate incident shock waves. Although few model experiments for the acoustic delay line have been made, there are several discrepancies among various gases used in the experiments. In many cases, a number of performance tests to maintain the beamlines under high-vacuum conditions were temporarily examined for each acoustic delay line, before shipping it from a factory\[1-5\]. Hitherto, systematic inspections were rarely performed to evaluate the attenuation of incident shocks by means of baffle obstacles in a tube except for an experimental investigation by Takiya et al\[7\]. They clearly explained about the geometrical effect of the orifice, the conical baffle and the nozzle on the shock attenuation.

In the present analysis, numerical computations were performed to analyze the problem on shock speed and arrival time at specified locations by solving compressible fluid equations. The results can be compared to the experimental ones obtained by the above mentioned work to confirm the validity of the present analysis.

2 Numerical computation

The basic equations are the unsteady 2D Euler equations written in a generalized coordinate system,

\[
\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{F}_1}{\partial \xi} + \frac{\partial \mathbf{F}_2}{\partial \eta} = 0
\]

(1),

Each vector element in Eq.(1) can be expressed by a matrix form as:
\[
\mathbf{Q} = \frac{1}{J} \begin{bmatrix}
\rho \\
\rho u_1 \\
\rho u_2 \\
e
\end{bmatrix}, \quad \mathbf{F}_1 = \frac{1}{J} \begin{bmatrix}
\rho U_1 \\
\rho u_1 U_1 + \xi_1 \eta_1 p \\
\rho u_2 U_1 + \xi_1 \eta_2 p \\
(e+p)U_1
\end{bmatrix}, \quad \mathbf{F}_2 = \frac{1}{J} \begin{bmatrix}
\rho U_2 \\
\rho u_1 U_2 + \xi_2 \eta_2 p \\
\rho u_2 U_2 + \xi_2 \eta_2 p \\
(e+p)U_2
\end{bmatrix}
\]

(2)

Here, \( J \) is Jacobian, \( \rho \) the density, \( p \) the pressure, \( e \) the total energy per unit volume, \( u_1 \) and \( u_2 \) the velocities for the \( x \) and the \( y \) directions, \( U_1 \) and \( U_2 \) the covariant velocities, \( \xi_x, \xi_y, \eta_x, \eta_y \) the metrics for a generalized coordinate system. The spatial discretization for the inviscid flux is executed by the Chakravarthy-Osher TVD scheme. The convective terms are discretized by the flux difference splitting method by Roe, and a high-order accuracy term is supplemented to a limiter function.

Simulations were performed for a two dimensional tube with 40mm height as shown in Fig. 1. Three kinds of model obstacles with 8mm opening inlet were set in the tube as shown in Fig. 1. They are referred to as (a) an orifice, (b) a diverging nozzle, and (c) a conical baffle in the followings. The incident shock Mach number is set to be \( M=1.25 \) just in front of the baffle-obstacles.

![Fig.1 Three types of model configurations used in the 2D computations](image)

In the case of axi-symmetrical computations, the following compensation term is added to modify the vector term in the corresponding discrete equation as [11]
\[
\frac{d}{dt} \hat{q}_{i,j} = \hat{f}_{i(2),j} - \hat{f}_{i(2),j} - \hat{f}_{i,j(2)} + \hat{f}_{i,j(2)} + d\hat{f}_{i,j}
\]

Here, \(\hat{q}_{i,j}\) and \(\hat{f}_{i,j}\) are the factors used for the vectors \(\hat{Q}\) and \(\hat{F}\) respectively. The last term \(d\hat{f}_{i,j}\), called in general, pressure compensation term, is necessary due to the difference in the circumference direction in the axi-symmetrical coordinate.

The geometrical models used for the axi-symmetrical computation are shown as Fig. 2. These configurations are the same geometry as the ones used in the previous experiment [7]. The initial position as well as shock strength was given at 50mm upstream from the baffle entrance. Furthermore, the pressure changes with time were observed at 500mm downstream from the baffle entrance, in order to evaluate the shock wave attenuation by the obstacles. Initial conditions for incident shock waves are given in front of the obstacles. The incident shock Mach number is taken as \(M_s=2.0\), and the initial pressure and temperature are 13kPa and 293K, respectively.

Fig.2  Three models of the baffle obstacles set in the axi-symmetrical tube

3 Transition phenomena of shock waves

Density contours during the shock wave front passing through the orifice at various instances are shown in Fig. 3. These figures show sequential simulation patterns of the instance of the shock front arrival at the orifice plate in Fig. 3(a), and the beginning of shock expansion from the orifice due to the rapid increase of the cross section in Fig. 3(b). One can observe that a part of the shock front passes through the orifice to produce a refracted shock wave from the edge of the orifice and the rest of the shock front is reflected from the orifice plate. In this case the flow induced behind the transmitting shock front generates a free vortex during the flow issuing from the orifice. The transmitting wave front further expands towards the tube wall and reflects on the tube wall as shown Figs.3(c) and 3(d). While the vortex in Fig.3 (b) continuously grows until it interacts with the tube. The flow density close to the axis of symmetry behind the transmitting
Shock wave attenuation

Shock decreases suddenly due to shock expansion. The transmitting shock propagates further downstream to expand until the wave front hits on the tube wall, as in Fig. 3(d). The incidence angle of the transmitting shock front to the wall is small enough at this stage that the reflection pattern of the shock is a normal reflection. Thereafter two reflected shock fronts from both walls, i.e. the upper and the down sides in this figure, approach to collide one another. During this process, both shock fronts compress the fluid surrounded by the shocks and the orifice plate and the density in this region, especially close to the center axis of the tube, increases abruptly. At the same time, the vortices leave downstream away from the orifice.

Fig.3  Sequential density contours during shock wave interaction with an orifice

Two shock fronts reflected from the upper and the lower sides of the tube in this figure come to collide each other on the center axis of the tube. The density being caught between the two reflected shock fronts may increase until the two shocks collide each other as shown in Figs. 3(d) to 3(g).

A gas core in high pressure and density is formed between the reflected shock front and the orifice plate in Fig. 3(d). The high enthalpy gas thus produced behind the reflected shock front may flow out from the orifice into the flow behind the shock as a jet. The jet interacts with the reflected shock front from the tube wall to form complicated flow patterns as in Figs. 3(d) to 3(h). During the interaction between the jet and the reflected shock front from the tube wall, the high enthalpy core may further expand to the downstream along the tube axis.

The sequential density profiles during the interaction of a propagating shock with the diverging nozzle are shown in Figs. 4(a) to 4(h). Figure 4(a) shows the instance of the shock arrival at the entrance of the diverging nozzle. The high density gas caused behind the reflected shock front from the nozzle follows the transmitted shock front in Fig. 4(b). The transmitted shock is accelerated by the jet in Figs. 4(c), (d), as in the orifice case. The shock front as well as the jet,
however, cannot freely expand in the nozzle. The jet generates weak shocks that interact with the nozzle wall behind the transmitted shock in Figs. 4(d) to 4(f). Such the shocks construct the x-type shock in Fig. 4(f) and catch up with the transmitted shock to interact each other in Fig. 4(g) and 4(h).

![Fig.4 Sequential density contours during shock wave interaction with a diverging nozzle](image)

The upstream flow from the nozzle entrance generates a jet similar to the case of the orifice flow as in Fig. 4(d). The jet may flow out towards downstream and induces vortices close to the wall around the nozzle entrance. While the main jet flow is accelerated along the nozzle axis and causes pseudo-shocks, so that the flow density behind the shock waves in the tube wall slightly increases as in Figs. 4(e) and 4(f). The interaction of the transmitted shock front with the pseudo shocks can be seen in Figs. 4(f) to 4(h).

In the case of both baffles of the orifice and the nozzle shown in Figs. 3 and 4, the formation of high density region behind the reflected shock has an important role to generate the strong jet that accelerate the transmitted shock front. From these numerical simulations, one can expect that the strength of the transmitting shock may attenuate by changing the configuration of the baffle, if the density at the nozzle entrance can be decreased.

Figures 5(a) to 5(h) show sequential density contours behind transmitted shock waves passing through the conical baffle. Figure 5(a) shows that the instance of shock arrival at the inlet of the conical baffle. The incident shock front is cut by the cone-edge. A part of the shock front transmits inside the cone and the rest of the shock front propagates outside the cone. The high-density gas between the cone and the tube behind the shock flows into the cone after the time elapse. Although the gas outside the inlet of the cone and behind the reflected shock is not so high in comparison to the orifice and the nozzle cases, it should turn around the periphery of the cone to flow inside the cone. As a result, strong
vortices are generated around the periphery of the inlet. The vortex thus generated around the inlet seems to be more conspicuous than that in the case of the orifice or the diverging nozzle. In this case, the effect of the jet flowing into the cone may not be remarkable, since the pressure and the density to generate the jet are not sufficiently high different from the case in the nozzle flow in Fig. 4. It means that the jet does not work significantly to accelerate the transmitted shock wave. Although one observes x-type shock wave behind the transmitted shock wave in Fig. 4(f), this kind of shock waves cannot be found in the cone. In the outside of the cone, the incident shock front initially propagating downstream may converge and then be reflected from the boundary between the cone and the tube. When the reflected shock passes through the inlet region of the cone, after reflecting from the blocked region between the cone and the tube, the pressure behind the reflected shock close to the inlet increases again. Then a part of the high-pressure gas expands to the inside of the cone. However, the jet flowing into the cone is not so strong to generate the x-type shock. The vortex generated around the inlet of the cone instead, is rather strong, since the flow should rotate around the periphery at the inlet in Figs. 5(d) and 5(e).

![Fig.5 Sequential density contours during shock wave interaction with a conical baffle](image)

4. Attenuation of shock waves

In the present computation three kinds of obstacles are discussed to decrease the strength of incident shock waves. The most effective geometry to attenuate propagating shock waves by an obstacle is to use a conical nozzle in a tube. The flow condition in front of the inlet of the obstacles influences the shock attenuation downstream in tubes. Especially the role of the jet generated close to the inlet of the obstacles is significant. In the case of both an orifice and a
diverging nozzle, the pressure behind the reflected shock wave becomes relatively high due to the normal reflection of the incidence of shock wave in front of the inlet of the obstacles. Such the high-pressure gas generates jet flow behind the transmitted shock wave. In the case of the cone, the jet flow is also generated behind the transmitted shock front. In this case, however, the pressure to push the jet into the inside of the cone is not so high to create the x-type shock in the obstacle, since the jet is pushed out by the high-pressure gas generated behind incident shock front. As a result, the shock wave that transmits downstream inside the cone cannot be effectively strengthened by the jet flow that compresses the gas behind the transmitted shock. It should be noticed that a part of the incident shock front propagates further downstream outside the cone and does not contribute to pressurize the gas around the inlet of the obstacles. While in the case of an orifice plate and a diverging nozzle, the pressure behind the reflected shock front from either a plate or a normal wall that fixes a nozzle is high enough to generate a jet flow.

Fig. 6 Shock wave interaction with various baffle obstacles in ax-symmetrical tubes

In order to verify the process to generate a jet flow around the inlet of obstacles, numerical computations were performed to the case of axi-symmetric flows. Figure 6 shows the density profiles of flows for each model at the instance of
600µs from the start, which is expected to be the time where the shock wave might be fully developed to nearly become a normal shock wave after the interaction with each obstacle. During the shock wave interaction with the obstacles, the flow field shows complex pattern. After the transmitting shock wave passes by the orifice or comes into either the nozzle or the cone, jet flow is generated behind the transmitted shock. The secondary shock wave is also generated in front of the jet. The strength as well as the shape of the secondary shock wave are influenced by the jet strength and vary depending on the obstacles. In the case of an orifice or a diverging nozzle, the x-type shock wave is generated. While in the case of a conical baffle, the strength of the secondary shock is very weak. The reason is that the pressure in front of the inlet of baffle plates cannot be increased by means of normal reflection of shock waves, since the shock front that is bifurcated by the edge of the cone may not contribute to increase the pressure in front of the inlet of the cone. When the gas in front of baffles flows downstream, the gas should turn around the aperture of the obstacles to cause strong vortices. The most effective geometry to attenuate incident shock waves seems to be the conical baffle.

Fig. 7 Calculated pressure profiles behind the transmitted shock wave monitored at 500mm downstream from the baffles
In order to estimate quantitatively the attenuation of the incident shock waves by means of these obstacles, the pressure change with time is compared at the distance of 500mm downstream from the baffle entrance in Fig. 7 corresponding to the flow phenomena in Fig. 6. Figure 7 shows both the pressure distributions over the tube wall and along the center line of the tube during a period of within about 1ms after the shock wave passage. The pressure behind transmitted shock waves, in general, decreases due to expansion of wave front, during flow expansion from the baffle aperture. The change in pressure is larger along the center line than over the wall of a tube.

In the case of the interaction of an orifice with shock wave, the sudden increase in pressure is due to the shock wave arrival and after that the pressure fluctuates around the averaged pressure of 1.2. The large decrease at the time of 2.4ms is considered to having been caused by vortices behind the passing shock wave, and the pressure reaches less than the base pressure in the tube, since the expansion rate of the flow is higher and the vortex intensity is greater compared to the other two cases. The reason why the no pressure decrease is observed just behind the shock is the driving force of the transmitted shock wave provided with the high pressure region, which is generated by the shock reflected from the orifice plate.

In the case of a diverging nozzle, the sudden increase in pressure is due to the shock arrival as in the case of the orifice and the pressure is slightly decreased with time. This is because that the reflected shock wave moves from the tube wall towards the center axis of the nozzle. After the transmitted shock wave is passed away further downstream, the pressure profile fluctuates significantly with time. The fluctuation may be caused by transverse motion of reflected shock waves between the wall and the center axis in a tube. The pressure profile along the center axis of the tube, however, is smaller than that of the case of the orifice, in total. So, one can say that the incident shock wave can be more effectively attenuated by using a diverging nozzle.

In the case of the conical baffle, the sudden increase in pressure caused by the incident shock wave is rather small and after that decrease in pressure can be observed as well. The shock strength is directly decreased by the expansion, namely the enlargement of the cross-section, of shock front. In addition, the effect of jet generated by high pressure behind reflected shock on the shock attenuation is small in comparison with the flow in an orifice and a nozzle. The pressure fluctuation with time is also very small. As a result, the attenuation of the shock waves is executed most effectively from comprehensive viewpoint.

5. Conclusion

The 2-D computations for the ideal gases were performed to evaluate the effect of obstacles on attenuation of incident shock waves in a tube. An orifice, a diverging nozzle, and a conical baffle are considered as the obstacles. These obstacles baffle the strength of transmitted shock wave. In the present investigation the influence of various geometries of the obstacles on the
Shock wave attenuation

attenuation of transmitted shock waves is discussed. As a result, one can conclude as follows. The result may be applicable to design synchrotron radiation beamlines.

The most effective configuration among three obstacles to attenuate incident shock strength is a conical baffle. In the case of a conical baffle, the high-pressure region in front of the inlet of the baffle is not created, since a part of shock front propagates further outside of the baffle. It means that the pressure increase behind reflected shock waves cannot be realized. The role of jet formation appeared around the inlet region of the obstacles is important. In both the case of an orifice and a diverging nozzle, the jet is clearly generated, when the high-pressure gas behind reflected shock waves flows out from the inlet region to the downstream.

In the case of an orifice and a diverging nozzle, the high-pressure region behind reflected shock waves is realized between the reflected shock front and the baffle plate of obstacles. The supersonic jet is created when the high-pressure gas flows downstream. In the case of the orifice, the strength of transmitted shock waves is not so diminished, since a supersonic jet compresses the flow behind transmitted shock waves. Although the expansion rate of shock front is very large by the sudden expansion of cross-sectional area, the transmitted shock front is accelerated by supersonic jet.

In the case of a diverging nozzle, a supersonic jet is also generated and flows downstream into the nozzle. However the effect of the jet on accelerating the transmitted shock is not strong as in the case of orifices based on the pressure increase behind reflected shock waves.

References


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