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Effect of Wall Confinement on the Reflection of Diffracted Shock Wave

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Keywords： wall confinement, expansion ratio, diffracted shock.

ABSTRACT

The effect of wall confinement on propagation of a diffracted shock wave in an expansion tube is investigated. The pressure distribution shows a plateau of high pressure, following by a pressure drop. An increase in the expansion ratio results in a decrease in the amplitude of peak wall pressure. The concept of piston work is also adopted in this study. The maxima of peak wall pressure in an expansion tube can be correlated with the equivalent piston work of an incident wave and the expansion ratio.

INTRODUCTION

Pulse detonation engines have attracted much research attention in recent years due to their high thermal efficiency and scalability compared to the engines using a conventional combustion process. For these engines, a detonation wave is usually initiated via a deflagration-to-detonation (DDT) process. For a less sensitive fuel mixture, however, the DDT distance is too long for practical applications. Hence, the concept of a pre-detonator filled with a highly sensitive mixture is proposed. Considering the required thrust, the scalability means a detonation wave that expands from a relatively small tube (a donor with a highly sensitive mixture) to a larger tube (an acceptor with a less sensitive mixture). For the successful transmission of a detonation wave (Edwards *et al.*, 1979; Moen *et al.*, 1982; Desbordes, 1988; Ciccarelli, 2002; Sorin *et al.*, 2009), the critical diameters for most hydrocarbon mixtures are approximately 13 times the cell width of a mixture. However, since the size of an acceptor is finite, the influence of wall confinement on the propagation of a diffracted detonation wave should be addressed. A study by Vasil'ev (1988) found that the effect of wall confinement is minimized when the expansion ratio is larger than 3. A numerical simulation by Papalexandris *et al.* (2007) showed the effect of the activation energy and the expansion ratio. In a narrow channel, Wu and Kuo (2012) also showed that the step height of an expansion tube can be used as a characteristic length for a correlation between re-initiation distance and detonation cell size.

To simplify the complex shock-flame problem, shock wave propagation in an expansion tube is useful for future study on propagation of diffracted detonation waves and on detonation re-initiation. Jiang *et al.* (1997) investigated the effect of expansion ratios (= 2 and 3) on the transient phenomenon of a diffracted shock wave. In this study, a numerical simulation is conducted to study the wall confinement on reflection of a diffracted shock wave. Further, the concept of piston work W_p is adopted. Matsui and Lee (1979) shows that the critical energy for direct initiation of a detonation wave is associated with the cubic diameter of a tube. A revised model by Sochet *et al.* (1999) is available for both detonation and shock waves, as shown in Table 1 and Equation 1.

Table 1. Rankine-Hugoniot relations through detonation wave and shock wave (Sochet *et al.*, 1999)

	CJ detonation	Shock wave
p	$\frac{\rho_0 D_{CJ}^2}{\gamma_{CJ}+1}$	$\frac{2\gamma_0 M_s^2-(\gamma_0-1)}{\gamma_0+1}p_0$
u	$\frac{D_{CJ}}{\gamma_{CJ}+1}$	$\frac{2S(M_s^2-1)}{(\gamma_0+1)M_s^2}$
a	$\frac{\gamma_{CJ}D_{CJ}}{\gamma_{CJ}+1}$	$S\left[\frac{2+(\gamma_0-1)M_s^2}{(\gamma_0+1)M_s^2}\right]\left[\frac{2\gamma_0 M_s^2-(\gamma_0-1)}{(\gamma_0-1)M_s^2+2}\right]^{1/2}$

p_o: initial pressure; γ_o: specific heat ratio; S: shock speed; M_s: shock Mach number; d: tube diameter; ρ: density

$$W_p = \frac{\pi}{3.47} p \frac{u}{a} d^3 \qquad (1)$$

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where a is the speed of sound and u is absolute particle velocity.

NUMEWRICAL SIMULATION

The numerical simulation is performed with the "Fluent" software. The Euler equation under adiabatic wall boundary layer condition and the axisymmetric, inviscid, implicit and second-order Roe flux difference splitting scheme are used. The time step for the transient simulation is 0.1 μs and the convergence criterion is 10^{-6}. The initial conditions are shown in Table 2. A 1.5–m long shock tube (donor) with a diameter d of 50.8 mm is connected to a 1–m expansion tube (acceptor) with a diameter D = 101.6 mm, 152.4 mm and 203.2 mm. The expansion ratios D/d are 2, 3 and 4. A sketch of the expansion tube is shown in Fig. 1. An example of the grid independence test is shown in Fig. 2. For D/d = 2 and W_p = 663 J, the pressure profile at 76.2 mm from the diffraction plane (or x^* = 0.75) with 395307 meshes is almost identical with that for the case of 610105 meshes. Therefore, the mesh number is set to 395,307 in this case. For D/d = 3 and 4 with the same grid density, the mesh number is set to 545107 and 695505, respectively. Table 2 shows the test conditions, in which the shock Mach number M_s ranges from 2.9 to 5.7.

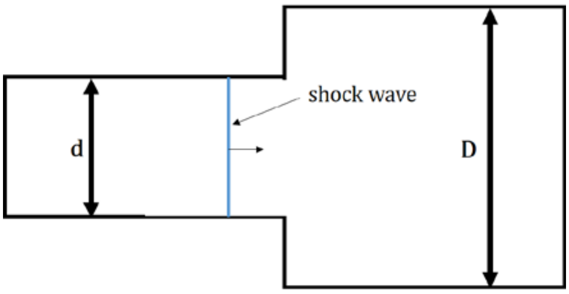

Fig. 1. Sketch of an expansion tube.

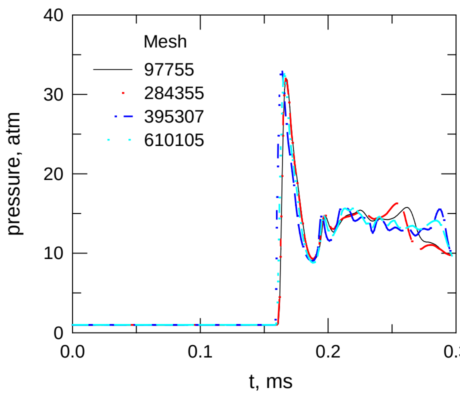

Fig. 2. Grid independence test (D/d = 2, x^* = 0.75, W_p = 663 J)

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Table 2. Test conditions (p_4: driver pressure; T_4: driver temperature)

p_4, bar	T_4, K	M_s	W_p, J
500	300	2.9	157
500	900	4.1	366
500	1500	4.7	527
500	2100	5.3	663
500	2700	5.7	781

RESULTS AND DISCUSSION

Diffracted Shock in an Acceptor

The propagation of a diffracted shock wave for D/d = 3 is presented in Fig. 3. A planar shock wave is diffracted at the plane of area change and is transmitted to a hemispherical shock wave. Reflection of the hemispherical shock wave results in higher wall pressure than that in the centerline. A regular reflection is formed initially, following a Mach reflection downstream. The Mach stem gradually catches the precursor shock wave at the centerline. A high centerline pressure occurs here because of shock reflection. Dewey (2001) found that the pressure jump of a spherical shock wave can be estimated by the scaling law of a blast wave with certain energy release from the center. The peak wall pressure p_{peak} along the streamwise direction for D/d = 2 and 3 is plotted against W_p, as shown in Fig. 4. At a given location, the amplitude of p_{peak} increases linearly with W_p. The effect of D/d is also evident.

Effect of Expansion Ratio

The distributions of p_{peak} for Wp = 663 J are presented in Fig. 5 and the pressure distribution in the centerline is also shown for comparison. The amplitude of p_{peak} immediately downstream from the diffraction plane is lower than that on the centerline, which is due to flow expansion near the sharp corner. At further downstream locations, reflection of a diffracted shock wave results in an increase in p_{peak}, following a drop. The amplitude of p_{peak} in the plateau region for D/d = 2 is higher than that in the centerline, but not for D/d = 3 and 4. Notably, the value of D/d represents the wall confinement on shock reflection. A decrease in p_{peak} demonstrates that the wall confinement is less significant for $D/d \geq 3$, which agrees the study by Vasil'ev (1988). Further, the distributions of p_{peak} are plotted against the normalized distance from the diffraction plane x^* and are shown in Fig. 6. A high p_{peak} is maintained for a long distance at a low D/d. Attenuation of the diffracted shock wave is observed at $x^* < 1$, indicating the D/d effect on propagation of a diffracted shock wave in an expansion tube.

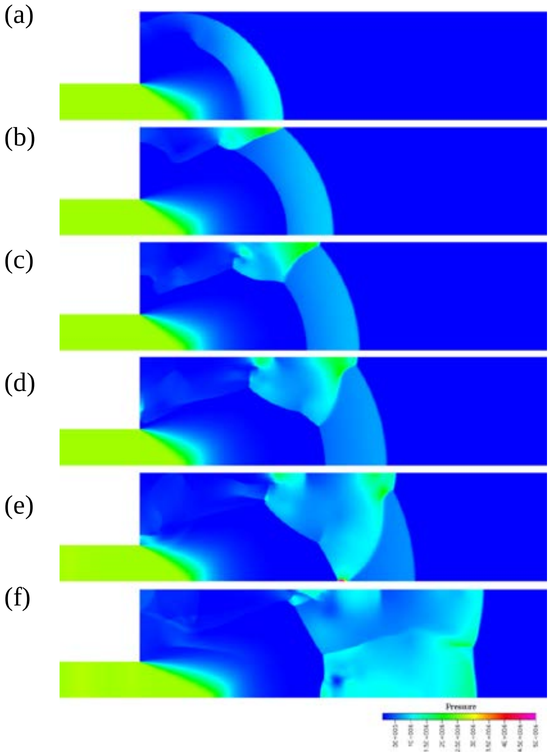

Fig. 3. Pressure profile for D/d = 3 (bottom: centerline): (a) t = 666 µs, (b) t = 700 µs, (c) t = 719 µs, (d) t = 740 µs , (e) t = 763 µs , (f) t = 816 µs.

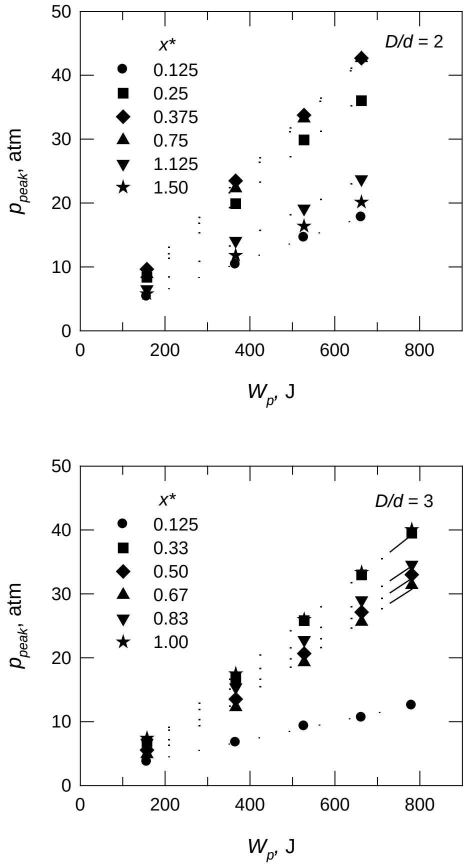

Fig. 4. The peak pressure versus piston work (a) D/d = 2; (b) D/d = 3.

The maximum p_{peak} at $x^* \approx 0.5$ can be used as an indication of wall confinement on propagation of a diffracted shock wave. In Fig. 7, the maxima of p_{peak} are plotted versus D/d at a given W_p, indicating that p_{max} decreases linearly with D/d. Then taking both D/d and W_p into account, a linear regression can be obtained, in which $p_{max} = 0.053W_p - 7.554(D/d) + 21.07$. The deviation is less than 2%.

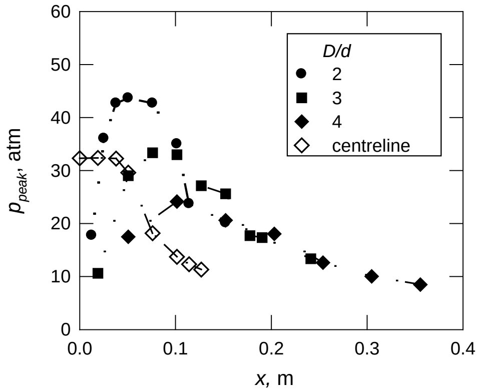

Fig. 5. Peak wall pressure and centerline pressure in the acceptor, W_p = 663 J.

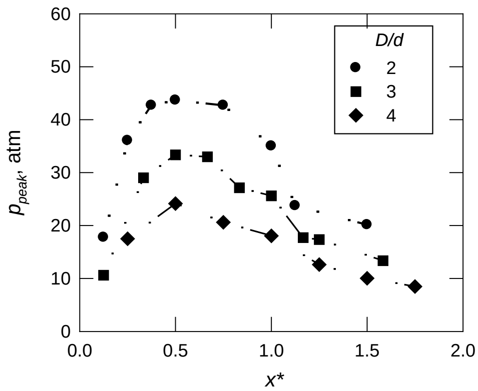

Fig. 6. Peak wall pressure.

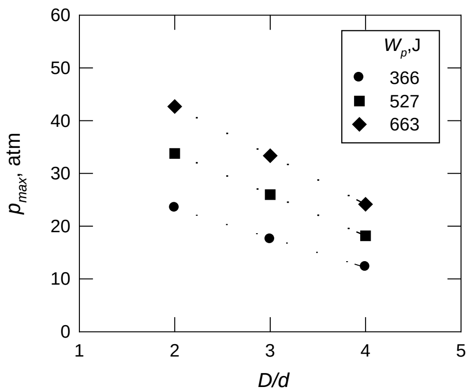

Fig. 7. The maxima of peak wall pressure versus the expansion ratio.

CONCLUSIONS

The propagation of a diffracted shock wave in an expansion tube is investigated numerically. The effect on the peak wall pressure due to the equivalent piston work of an incident shock wave and the expansion ratio is evident. At a given location, a linear relationship is observed between the peak wall pressure and the piston work. The maxima of peak wall pressure are observed at approximately one diameter downstream of the diffraction plane and their amplitude decreases with an increase in the expansion ratio. The maxima can be presented in terms of the piston work and the expansion ratio. This result is useful for future research on propagation of diffracted detonation waves and on detonation re-initiation in an expansion tube.

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擴張圓管直徑對繞射震波影響之研究

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摘 要

本研究以定性與定量的方式來探討在擴張圓管直徑大小對於繞射震波於壁面上反射與傳遞之影響。由數值模擬的結果發現，入射震波活塞功與壁面反射震波所產生的壓力峰值呈現線性關係。此外在擴張圓管下游約 0.5 倍直徑處，顯示一高壓區，在 1 倍直徑處，壓力峰值則快速下降。此高壓區亦會隨著直徑的增加而逐漸消失。最高壓力峰值與管徑呈線性反比的關係，利用線性回歸來找出可以同時滿足活塞功以及擴張比的關係。