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CHARACTERISTICS OF COMPRESSION WAVE CAUSED BY REFLECTION OF EXPANSION WAVE AT OPEN END OF TUBE

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ABSTRACT

When an expansion wave propagating along a constant area straight tube reaches at the open end, the emission and reflection of an expansion wave occurs. The negative impulsive wave is emitted toward the surrounding area and causes an impulsive noise like the sonic boom. The compression wave formed by reflection of an expansion wave propagates in the tube toward the upstream. In this study, the formation of a compression wave at the open end of a tube, the characteristics of a propagating expansion and compression wave are investigated by the experiment and the numerical calculation. A simple open ended shock tube with the flange at the tube exit is used and the numerical calculation using the TVD scheme is performed. In this paper, the relation between the strength and the maximum pressure gradient of an expansion and a compression wave, the distortion of a compression wave are discussed.

Keywords: compressible flow, unsteady flow, expansion wave, compression wave, impulsive wave.

INTRODUCTION

When the propagating pressure wave like the shock wave reaches at the open end of a tube, the impulsive wave and the reflected wave are generated as a result of the discharge and reflection of a pressure wave. This phenomena is related with some problems of the industrial engineering. The many studies of the discharge of a weak shock wave have been reported in relation to the gun muzzle[1-4], the super charger using the pressure wave[5], the pulse combustion device[6] and pulse jet filter[7]. The discharge of a weak compression wave have been investigated owing to reduce the impulsive noise in relation to the high speed railway tunnel in Japan[8]. But, the discharge of an expansion wave have not detailed in the past papers and with the advent of high speed train, it seems that the discharge of an expansion wave formed by the entering the rear of a train becomes important problems. In this study, the formation of a compression wave generated by the reflection of an expansion wave and the characteristics of a compression wave are investigated by the experiment and the numerical calculation using the shock tube and the TVD method.

NUMERICAL CALCULATION AND EXPERIMENT

Figure 1 represents the wave diagram showing the discharge and reflection of an expansion wave at the open end of a tube and the symbols used in this study. As shown in Fig.1(a), the negative impulsive wave and compression wave are formed as a result of the discharge and reflection of an expansion wave. The negative impulsive wave spreads out toward the surrounding area and the compression wave propagates in the tube toward the entrance. Fig.1(b) shows the pressure change with time in the tube. The initial pressure in the tube is indicated by the symbol p_a and the pressure reduce caused by the expansion wave is represented by the symbol Δp_{ie}. As a result of the passage of compression wave, the pressure rises to Δp_{rc}. In this study, the maximum pressure gradient $(\mathrm{d}\Delta p/\mathrm{d}t)_{ie,max}$, $(\mathrm{d}\Delta p/\mathrm{d}t)_{re,max}$, the length of an expansion wave L are defined as shown in Fig.(c).

A numerical calculation was carried out for the discharge and reflection of an expansion wave at the open end of a tube. The x - y cylindrical coordinate system originated at the center of an open end of a tube were considered as shown in Fig.1. The basic equations used in this study is a compressible unsteady axisymmetric equation and it can be written in the Eq.(1) by the conservation forms.

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \mathbf{W} = 0 \tag{1}$$

$$\mathbf{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ (e+p) u \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ (e+p) v \end{bmatrix},$$

$$\mathbf{W} = \frac{1}{y} \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 \\ (e+p) v \end{bmatrix} \tag{2}$$

where x is the longitudinal distance, y is the radial distance, t is the time, ρ is the density, e is the total energy per unit volume of the gas, u and v are the velocity components for x and y directions, respectively. These quantities are nondimensionalized by the atmospheric condition.

Eq.(1) was solved by the second-order TVD scheme of Harten-Yee[9] with the operator splitting technique[10]. For the initial condition, the pressure distribution of an expansion

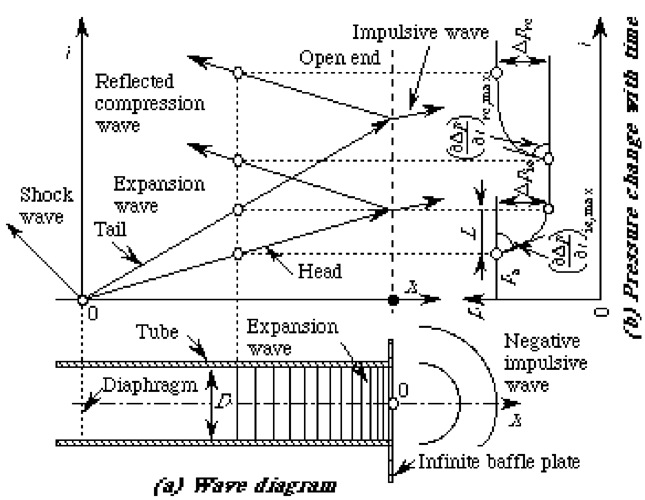


Fig.1 Schematic explanation of propagating expansion wave in tube

wave was given inside the tube. The numerical conditions are as follows : p_a=101.3kPa, L/D=1~4 and Δp_{ie}=4~12kPa.

The shock tube that the high pressure chamber (driver section) was opened in the atmosphere was used to this experiment. The details of a shock tube are shown in Fig.2. The length of the driver section and driven section are 1.4 or 1.92m and 2.52m respectively, and inside diameter D is 66mm with in all of both section. The pressure transducer is settled at the distance 636mm from the open end of a tube to measure the pressure change caused by propagating pressure waves in the tube. As shown in this figure, the distance from the diaphragm to the measuring position is represented the symbol H and H is 764mm for the length of a driven section 1.4m, H is 1284mm for the length of a driven section 1.92m, respectively. The driver gas of the driver section is air and the cellophane is used to the diaphragm. The initial pressure ratio p_a/p_1 is varied from 1.31 to 1.727. The output signals from a pressure transducer were amplified by an amplifier and analyzed by a computer after passing through an A-D converter.

RESULTS AND DISCUSSIONS

The typical pressure contours obtained by numerical calculation at several times are shown in Fig.3. In Fig.(a), the pressure contour near the corner is transformed from a plane contour because of the interaction with the weak pressure wave formed at the corner and the negative impulsive wave is formed outside of tube. This wave spread out to surrounding area as the spherical wave. In Fig.(b), the reflected compression wave is observed in the tube. The space of a pressure contour near the open end of a tube is clogged so that the pressure rapidly changes in this region. The compression wave advances toward the upstream and the pressure change outside of an open end reduces due to pass through the impulsive wave in Fig.(c). In Fig.(d), the wave front of a compression wave becomes to the plane wave. It is remarkable that the three dimensional flow structure is formed around the open end of a tube because of the interaction between the expansion wave and the weak pressure wave formed at the corner of an open end.

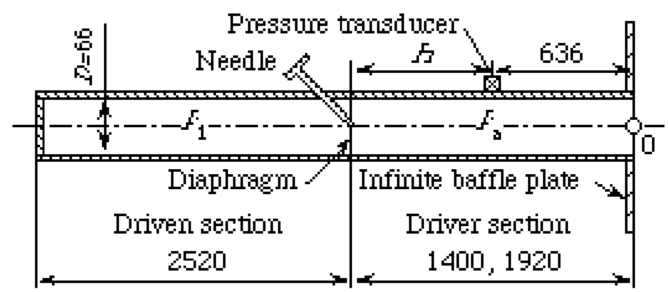


Fig.2 Experimental apparatus

Figure 4 shows the typical pressure histories at the measuring position for various initial pressure ratio p_a/p_1. Figure (a) is the case of H=764mm and Fig.(b) is the case of H=1284mm. The ordinate and the abscissa of this figure represent the gauge pressure Δp from the atmospheric pressure and the time t. It is clear that the maximum pressure gradients of an expansion and a compression waves $(\mathrm{d}\Delta p/\mathrm{d}t)_{ie,max}$, $(\mathrm{d}\Delta p/\mathrm{d}t)_{re,max}$ are constant for increasing of p_a/p_1 at same length H. After the expansion wave passes through the measuring position, the pressure slightly increases from Δp_{ie} due to the friction on the wall surface and the pressure rises to Δp_{rc} caused by the compression wave. The pressure behind the compression wave do not recover to atmospheric pressure because of the discharge from the open end of a tube and the induced flow formed by the expansion wave.

The relation between the strength of an expansion and compression waves Δp_{ie}, Δp_{rc} and the initial pressure ratio p_a/p_1 is shown in Fig.5. It is clear that the value of Δp_{ie}, Δp_{rc} is proportional to the initial pressure ratio p_a/p_1 and little depends on the length of a driver section. The value of Δp_{rc} decreases for Δp_{ie} same as Fig.4.

The relation between the length of an expansion wave L and the strength of an expansion wave Δp_{ie} is indicated in Fig.6. The solid and broken lines show the results of the normal shock wave theory[11] for a shock tube and are obtaiend by the following equation.

$$L = H\left(\frac{a_4}{a_3 - u_3} - 1\right) \quad (3)$$

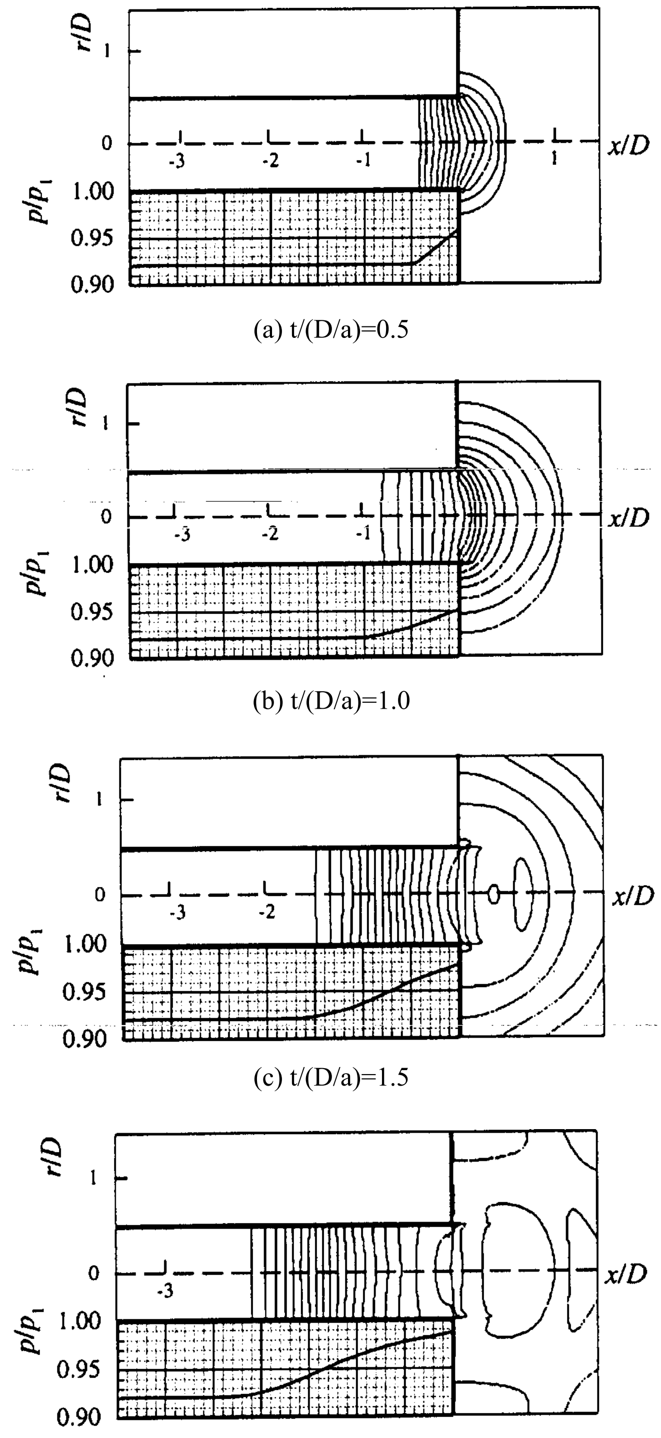
where, a_3 and u_3 are the sonic and gas speed behind the expansion wave, a_4 is the sonic speed for the rest air in the driver section.

The broken line shows the cases of H=764 and 1284mm, which is the value of an experimental apparatus, and the solid line indicates the cases of H=1350mm and 1950mm, which fits to the experimental results. Because the finite time is needed to brake the diaphragm so that the propagating distance H has to be increase for the analytical treatment. It is noticed that the length L is proportional to Δp_{ie} and H and these characteristics correspond to the result of Eq.(3).

Figure 7 shows the relation between the maximum pressure gradients of an expansion and a compression waves $(\mathrm{d}\Delta p/\mathrm{d}t)_{ie,max}$, $(\mathrm{d}\Delta p/\mathrm{d}t)_{re,max}$ and the strength of an expansion wave Δp_{ie}. The solid line indicates the result of the normal shock wave theory[11] for $(\mathrm{d}\Delta p/\mathrm{d}t)_{ie,max}$ and is obtained by the following equation.

$$\left(\frac{\partial \Delta p}{\partial t}\right)_{ie,max} = \frac{2\kappa}{\kappa - 1}\frac{a_4\, p_a}{L}\left\{\left(1 - \Delta p_{ie}/p_a\right)^{\frac{\kappa-1}{2\kappa}} - 1\right\} \quad (4)$$

where, κ is the ratio of specific heats.



(a) t/(D/a)=0.5

(b) t/(D/a)=1.0

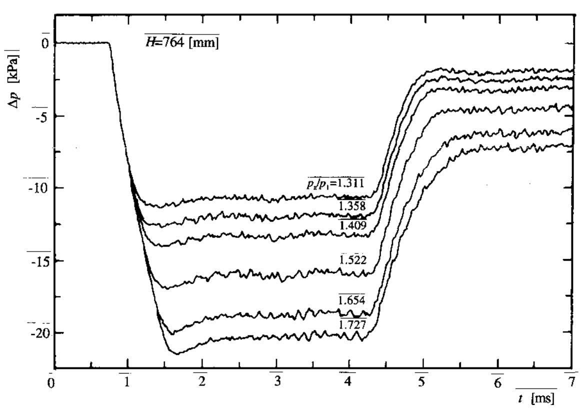
(c) t/(D/a)=1.5

(d) t/(D/a)=2.0

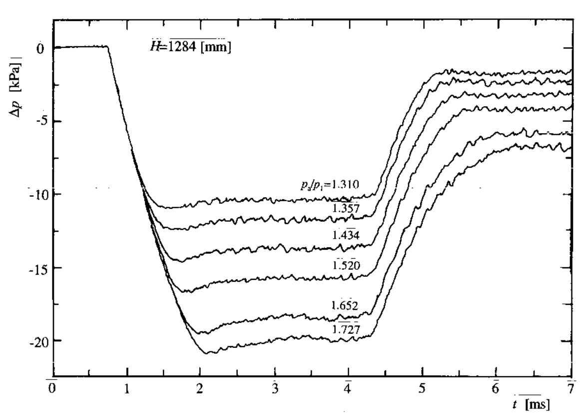
Fig.3 Computed pressure distributions showing generation of compression wave near tube exit

It is remarkable that the experimental value of $(\mathrm{d}\Delta p/\mathrm{d}t)_{\mathrm{ie,max}}$, $(\mathrm{d}\Delta \mathrm{d}p/\mathrm{d}t)_{\mathrm{re,max}}$ little varies for Δp_{ie} and decreases with increasing of length H in this experimental condition. The letter characteristic is well agreement with the result obtained by Eq.(2), but $(\mathrm{d}\Delta p/\mathrm{d}t)_{\mathrm{ie,max}}$ obtained by Eq.(2) decreases with increasing of Δp_{ie}. When the compression wave propagates in the tube, the wall friction and the nonlinear effect occurs to the compression wave. The maximum pressure gradient of a compression wave increases by the nonlinear effect and decreases by the wall friction. In this experiment, it seems that the maximum pressure gradient decreases because the influence of a wall friction is more than the nonlinear effect. Furthermore, the experimental value of $(\mathrm{d}\Delta p/\mathrm{d}t)_{\mathrm{re,max}}$ drops against the $(\mathrm{d}\Delta p/\mathrm{d}t)_{\mathrm{ie,max}}$ due to reflect and discharge at the open end of a tube.

The relation between the nondimensional parameter K and the strength of an expansion wave Δp_{ie} is shown in Fig.8. The nondimensional parameter K is based on the maximum pressure gradient and defined by the following equation.



(a) H=764mm



(b) H=1284mm

Fig.4 Typical pressure histories in tube obtained by experiment

$$K \equiv \frac{\left(\dfrac{\partial \Delta p}{\partial t}\right)_{\mathrm{rc,max}} / \Delta p_{\mathrm{rc}}}{\left(\dfrac{\partial \Delta p}{\partial t}\right)_{\mathrm{ie,max}} / \Delta p_{\mathrm{ie}}} \tag{5}$$

It is clear that the value of K is less than unity and increases with increasing of the length L. Therefore, the maximum pressure gradient of a compression wave decreases for that of an expansion wave because of the reflection and the discharging at the open end of a tube. Furthermore, the value of K increases with increasing of Δp_{ie} and it means that the nonlinear effect is large for increasing of Δp_{ie}.

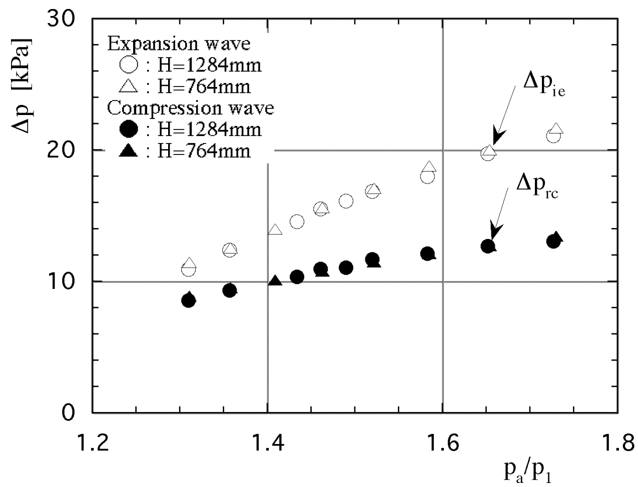


Fig.5 Relation between strength of expansion and compression waves Δp_{ie}, Δp_{rc} and initial pressure ratio p_a/p_1

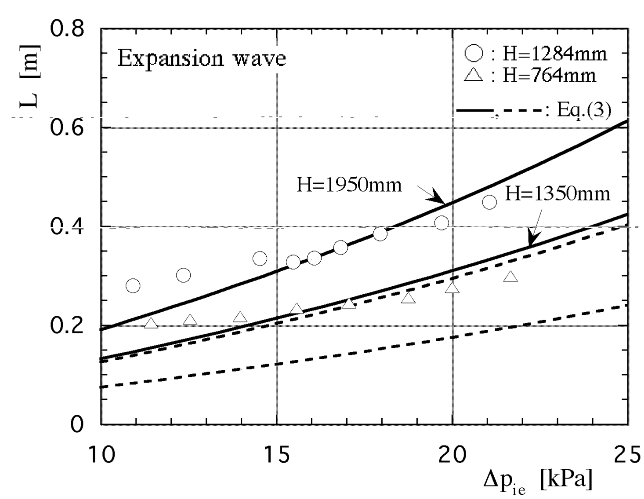


Fig.6 Relation between length of expansion wave L and strength of expansion wave Δp_{ie}

The relation between the nondimensional parameter ξ and the nondimensional length of an expansion wave x/L is shown in Fig.9. The symbol x denotes the distance from an open end of a tube and defines x=0 at open end of a tube. The nondimensional parameter ξ is based on the nondimensional parameter K and the length and defined by the following equation.

$$\xi = \frac{K - 1}{L/D} \tag{6}$$

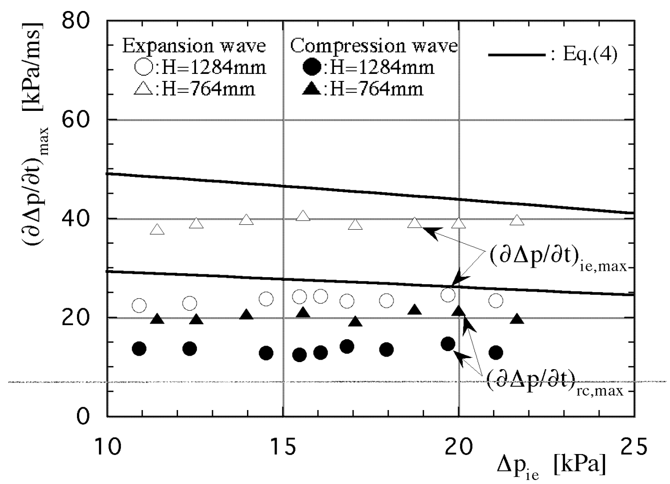


Fig.7 Relation between maximum pressure gradients of expansion and compression waves $(\Delta dp/dt)_{ie,max}$, $(\Delta dp/dt)_{re,max}$ and strength of expansion wave Δp_{ie}

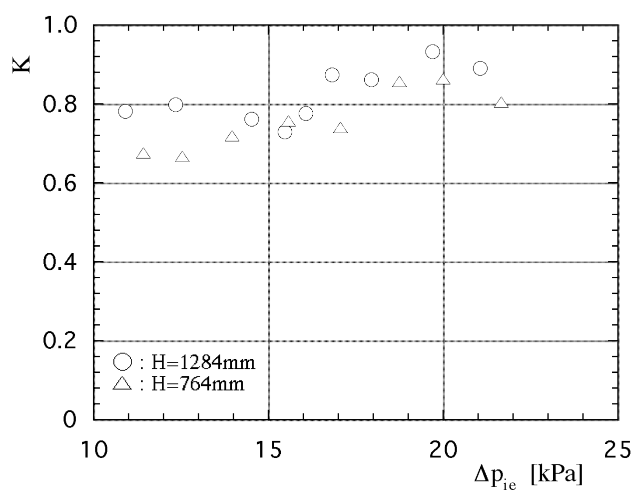


Fig.8 Relation between nondimensional parameter K and strength of expansion wave Δp_{ie}

In this figure, the result of a numerical calculation is indicated by the black color points. It is noticed that the value of ξ in the range of smaller x/L is ξ<0 and increases with increasing of x/L. The maximum pressure gradient of a compression wave is less than that of an expansion wave for the case of ξ<0 so that the maximum pressure gradient of a compression wave decreases near the open end because of the influence of a wall friction. With increasing of x/L, the value of x is ξ>0 and it is concluded that the influence of a wall friction is more than the nonlinear effect in the range of smaller x/L and the nonlinear effect exceed in the range of lager x/L.

CONCLUSIONS

The formation of compression and impulsive wave and the characteristics of a compression wave formed by the reflection of an expansion wave are investigated by the experiment and the numerical calculation using the simple open ended shock tube and the TVD method in this paper. The conclusions are summarized as follows:

(1) In the numerical calculation, the three dimensional flow is structured at the open end of a tube because of the interaction an expansion wave with a weak pressure wave formed at the corner.

(2) In this experiment, the strength of an expansion and a compression wave Δp_{ie}, Δp_{rc} is proportional to the initial pressure ratio p_a/p_1 and little depends on the length of a driver section. The value of Δp_{rc} decreases for the strength Δp_{ie}. The length of an expansion wave L is proportional to the strength Δp_{ie} and the length H. The maximum pressure gradients of an expansion and a compression waves $(d\Delta p/dt)_{ie,max}$, $(d\Delta p/dt)_{re,max}$ depend on the length H.

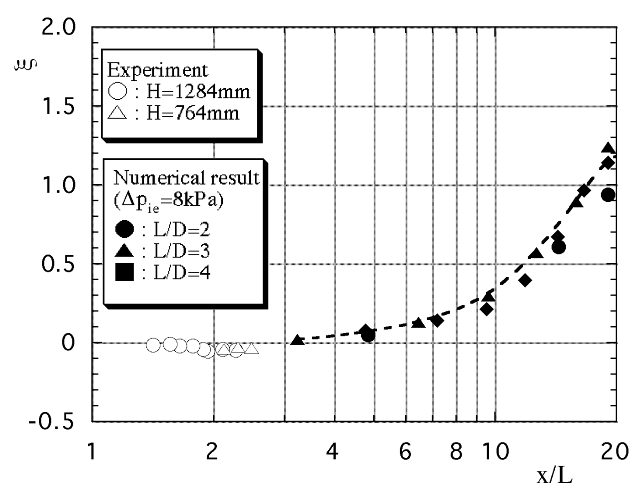


Fig.9 Relation between nondimensional parameter ξ and nondimensional length of expansion wave x/L

(3) The nondimensional parameter K obtained by the experiment is less than unity because the maximum pressure gradient of a compression wave decreases for that of an expansion wave. The value of K increases with increasing of the length L.
(4) The nondimensional parameter ξ in the range of smaller x/L is ξ<0 and increases with increasing of x/L. It means that the maximum pressure gradient of a compression wave decreases near the open end because of the influence of a wall friction. And it is concluded that the influence of a wall friction is more than the nonlinear effect in the range of smaller x/L and the nonlinear effect exceed in the range of lager x/L.

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