Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 22 (2008) 755~760

www.springerlink.com/content/1738-494x

Effect of rupture disc curvature on the compression waves in S/R valve

Dong-Won Lee, Jung-Myung Park, Young-Doo Kwon and Soon-Bum Kwon*

School of Mechanical Engineering, Kyungpook National University 1370, Sankyuk-dong, Puk-gu, Daegu 702-701, Korea

(Manuscript Received August 31, 2006; Revised October 5, 2007; Accepted January 1, 2008)

Abstract

When the pressure at a weak spot established at a certain part of a high pressure vessel or piping system exceeds a design pressure, this weak spot bursts, and the pressurized gas emitted through the weak spot generates a compression wave system at the downstream of the disc. In this connection, an experimental study was performed by using a shock tube facility with dimensional analysis to relate the valve opening time and shock wave formation distance with the diaphragm radius of curvature, the pressure ratio and depth of cross type groove. Four kinds of curvature radii were used with and without 90° groove. It was found that the smaller the radius of curvature of the rupture disc is, the thinner the thickness of the rupture disc is; and the smaller the ultimate strength of the rupture disc is, the shorter the valve opening time becomes. The radius of curvature and the ultimate strength of the rupture disc for the same conditions are smaller; the maximum pressure rise caused by the coalescences of the compression wave at the downstream of the valve is smaller. Finally, we found that the formation distance of the shock wave for the case of smaller curvature is longer than that for the case of a larger one because of the retardation of accumulation of the compression wave.

Keywords: Rupture disc; Radius of curvature; Safety and relief valve; Shock formation distance; Shock wave

1. Introduction

When the pressure at a weak spot established at a certain part of a high pressure vessel or piping system exceeds a design pressure, this weak spot bursts and the pressurized gas of the high pressure tank is discharged through this weak spot. And the bursting of the disc established at the weak spot, which is named as rupture disc or burst disc (called as RD unit) [1], will cause a compression wave system at the downstream of the weak spot.

It is known that the RD unit is very effective in handling combustible and toxic gases and the problem of leakage of dangerous radioactive substances [2]. If the RD unit is ruptured due to the pressure being higher than the design one, then, a series of compression waves during the valve opening are generated at the downstream of the disc. Also, in a certain case, the successive coalescences of these compression waves in the pipe which is used to reduce the danger from the scattering of RD unit's fragment due to the rupturing of disc may develop a shock wave [3]. In these respects, the shock formation distance is a very important factor in the problem of RD unit design. In general, the formation distance of a shock wave is greatly affected by the opening time of disc in RD unit (that is, relief valve) [4].

Hitherto, as a research about disc's opening time, Matsuo did a dimensional analysis for the opening time of a flat disc, and showed the relation between the shock wave formation distance and pressure ratio in a conventional shock tube system [5]. Andrews et al. studied the relation between the disc opening time and ultimate strength of the material used in the disc by using thin metal foils, and presented the mode and speed of disc opening for a copper foil [6].

Recently, Shugaev et al. studied the depend-ency of the material on the disc opening time for the case of flat type disc, and showed that the disc opening time

*Corresponding author. Tel.: +82 53 950 5578, Fax.: +82 53 950 6550
E-mail address: sbkwon@knu.ac.kr
DOI 10.1007/s12206-008-0101-x

depends linearly upon the $(\rho_D t_d D/\Delta P)^{1/2}$ [7]. On the other hand, the PSI team measured the disc's opening time in a shock tube consisting of a water-filled column, which was possible to obtain by measuring the transient pressure in the water-filled column [8].

But, we could not find a study on the effects of the disc shape, depth of groove and radius of curvature on the opening time up to now. So, in the present study, the effects of disc thickness, depth of groove and radius of curvature on the disc opening time and shock formation distance are investigated. In particular, from dimensional analysis, we found a relation between the valve opening time and radius of curvature of a disc. Discs made of an aluminum 1050 series with a cross type groove are used.

2. Experimental work

2.1. Experimental setup

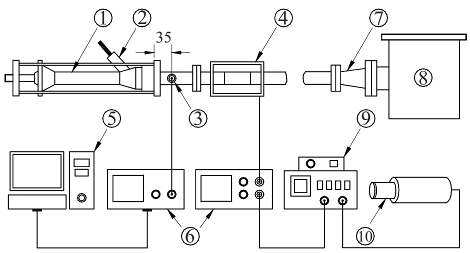
Fig. 1 shows the facility used in this experi- mental work. The device consisted of high and low pressure chambers, disc part, pressure mea-surement system and so on.

2.1.1 Drive section

The inside diameter of the high pressure chamber corresponding to the high pressure vessel or piping system is 150mm, the chamber length is 1,200mm, and to burst the disc we adopt a cone type needle rupturing system. And, it is designed so that the apex of the needle pierces the center of the disc for all cases of RD unit.

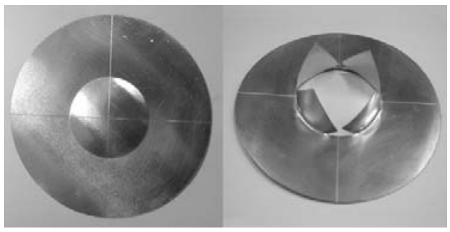
2.1.2 Disc

Fig. 2 shows a typical disc used in the present experiment; here, the thickness td is 0.5mm, the disc diameter with the cross type groove depth of t_g=0.1mm is 54mm, the radius of curvature is 80mm, case (a) denotes before rupture is done, case denotes (b) after rupture is done, respect-tively.



① High-pressure chamber ② Needle chamber
③ Pressure transducer ④ Test section
⑤ Personal computer ⑥ Oscilloscope
⑦ Diffuser ⑧ Dump tank
⑨ Time delay unit ⑩ Light source

Fig. 1. Schematic of experimental apparatus.



(a) Before (b) After

Fig. 2. Photographs for ruptured and un-ruptured discs.

Fig. 3 shows the specifications of disc system used in the study, that is, the disc's radii of curvature, the depths from the apex of disc to the installation position of disc, the installation posi- tion of static pressure sensor and the diameter of downstream tube of RD unit. Here, h denotes the maximum disc depths for four cases.

The radii of curvature of disc R are 60, 80, 120mm and ∞, respectively. In which the case of radius of curvature R=∞ corresponds to the case of a flat one. Thicknesses of disc t_d are 0.3 and 0.4mm of non-grooved case, and 0.5mm of grooved case, respectively. Groove depth t_g is 0.1mm. The depth of cross type groove with the wedge angle of 90° is machined by an NC milling having an error of ±1/1,000mm.

2.1.3 Downstream pipe of RD unit

In the present study, an aluminum pipe of 54mm in inner diameter is used as the disc downstream discharging part of the RD unit. To measure the pressure rise due to the rupturing of the disc, a pressure transducer having 500kHz in natural frequency is installed

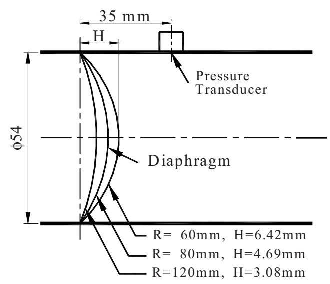


Fig. 3 Specifications of disc.

at 35mm downstream of the rupture disc. Furthermore, from these measured pressure histories, we can deduce the compression wave pattern and measure the shock wave formation distance.

2.2 Experimental method

In the present study, the RD valve opening time is defined as the period from where the pressure begins to change from the null position to the position of maximum value in an oscilloscopic system [3]. To measure the shock formation distance by the Schlieren visualization results using the nano-light of xenon with the variations of radius of curvature, groove depth of disc and so on, we used a rectangular acrylic duct of 54mm which corresponds to the case of 54mm in hydraulic inner diameter.

3. Dimensional analysis

3.1 Relation between the radius of curvature and opening time of disc

The disc's opening time can be deduced as a function of following parameters.

1. Pressure difference ($\Delta P = P_4 - P_1$)
2. Hydraulic diameter D
3. Thickness h (Disc thickness minus groove depth)
4. Limit strength of disc σ_B
5. Density of disc ρ_D
6. Radius of curvature R

The other parameters affecting the valve opening time can be thought to be the initial driven section pressure (P_1), the initial pressure ratio (P_4/P_1) and the modulus of elasticity of disc material, etc. But comparing the influence of these parameters with the influence of above mentioned parameters on the valve opening time, the influence by P_1, the initial pressure ratio and the modulus of elasticity of disc is so small, so we neglect the influence of these parameters [2].

$$f\left(\tau_{op}, \Delta P, D, h, \sigma_B, \rho_D, R\right) = 0 \tag{1}$$

As a result, the above variables related with the valve opening time can be arranged as follows:

Using Buckingham's π theorem to Eq. (1), Eq. (1) can be rewritten as Eq. (2).

$$f\left(\frac{\tau_{op}\,\Delta P^{\frac{1}{2}}}{D\rho_D^{\frac{1}{2}}}, \frac{h}{D}, \frac{R}{D}, \frac{\sigma_B}{\Delta P}\right) = 0 \tag{2}$$

If the hydraulic diameter, the pressure difference between the lower and higher cham- bers and the material and depth of disc are fixed in Eq. (2) and because h/D correlates directly to R/D, Eq. (2) can be written finally as Eq. (3).

$$\tau_{op} \approx D \cdot \frac{\sigma_B}{\Delta P} \cdot \left(\frac{\rho_D}{\Delta P}\right)^{\frac{1}{2}} f_1\left(\frac{R}{D}\right) \tag{3}$$

It is the one primary objective in the present study to find f_1.

4. Experimental results and discussion

4.1 Non-grooved case

Fig. 4 shows the results for disc opening time with the variations of radius of curvature in the case of disc thickness t_d=0.3mm, pressure difference ΔP=900kPa and no groove.

Here, by using curve fitting, the pressure histories shown as a line can be obtained from the live data of the oscilloscope. Because the increase of disc radius of curvature results in the increase of the traveling distance from the piercing point of the disc to the pipe wall (for example, in the cases of R=∞ and 60mm, both distances are 42.4 and 39.5mm, respectively), the larger the radius of curvature of disc is, the longer the disc opening time is.

Because the traveling distance differences among the particles from just behind the disc to the installation section of pressure sensor for the case of smaller R is large, the smaller R is, the smaller the maximum pressure at 35mm downstream of the disc is. Fig. 5 shows the pressure histories with the variations of radius of curvature for the case of t_d=0.4mm, ΔP=900kPa and no groove. The trend with the variations of R is the same as that case of Fig. 4. But, compared with the case of t_d=0.3mm, the valve opening time and pressure increase due to the compression effect from the upstream of disc for the case of thinner disc are shorter and larger, respectively.

Also, Fig. 6 shows the pressure histories with the variations of R for the case of t_d=0.4mm, ΔP=1,100kPa and no groove. Comparing the results

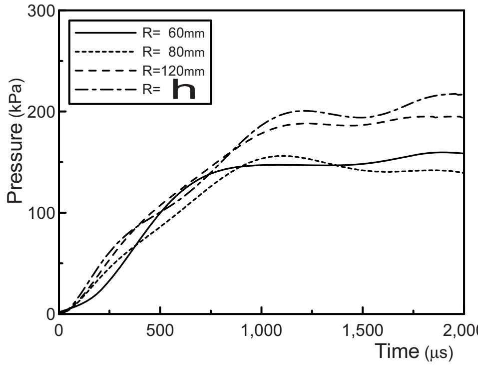


Fig. 4. Pressure histories with the variations of radius of curvature for t_d=0.3mm, ΔP=900kPa and no groove.

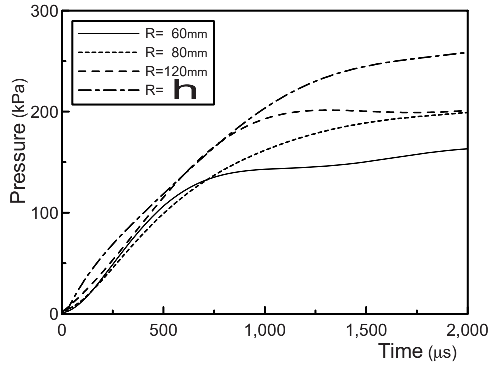


Fig. 6. Pressure histories with the variations of curvature of radius for t_d=0.4mm, ΔP=1,100kPa and no groove

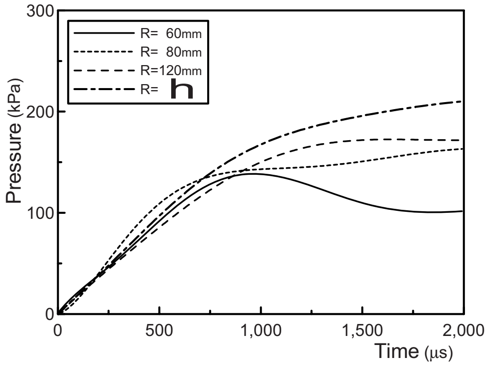


Fig. 5. Pressure histories with the variations of radius of curvature for t_d=0.4mm, ΔP=900kPa and no groove

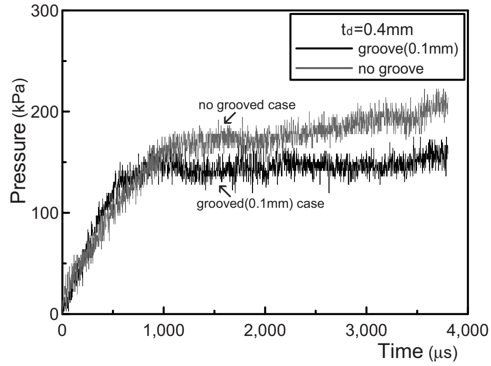


Fig. 7. Pressure histories by the same resulting thickness of disk for t_d=0.4mm, ΔP=900kPa and R=120mm

between the cases of Figs. 5 and 6, the valve opening time and the maximum pressure at the 35mm downstream of the disc for the large pressure difference are shorter and larger than those for the smaller one.

4.2 Grooved case

To investigate the effect of grooves on the valve opening time and pressure histories, two cases of experiments are conducted: one is no groove and the other is groove with t_g=0.1mm so that the resulting depth of the disc is the same as that of no groove for the same other conditions. , The live pressure histories from the oscillogram taken at 35mm downstream of the disc are shown in Fig. 7. As shown in figure, due to the degree of concentration in stress at the groove, the valve opening time with a groove for the same thickness of disc is faster than that case of no groove. Furthermore, the gradient of pressure increment for the case of groove is steeper.

4.3 Formation distance of shock wave without groove

Fig. 8 shows an example of live pressure his-tories to decide the shock formation distance with the variations of x (in actual, we took the signals with the interval of 10mm in x) for the case of P_4/P_1=10.0, t_d=0.3mm, ΔP=900kPa and no groove of R=∞.

To decide the shock formation distance from the measured pressure histories, we used the criterion suggested by Rothkopf[9]. According to this criterion, that is, the formation distance of a normal shock coincides with the distance from the disc to the position having a maximum in pressure, the shock formation distance for the case of Fig. 8 can be decided as 440mm.

The shock formation distance with the variations of radius of curvature of the disc is shown in Fig. 9. As is discussed in Fig. 4, it turns out that because the position differences in axial direction among the particles of the high pressure chamber for the case of the smaller R are larger than those for the larger R, the smaller R is, the longer the shock formation distance becomes. To know the effect of grooves on the flow at the neighbor of the disc by flow visuali- zation, we used a Schlieren system with Xe nano-light whose spark duration time is 20ns.

Two Schlieren photos of (a) and (b) taken at a lapse time of 100ms from the bursting of the disc are shown in Fig. 10; cases (a) and (b) denote the results for no groove and groove with 0.1mm, that is, the resulting thickness of the disc for both cases is the same, respectively. As is discussed above, for the same resulting disc thickness, while a normal type shock wave for the case of grooves is generated at the downstream of the disc (that is case (b)), we can't find a shock wave in the case of no groove (case (a)) for the same lapse time of 100μs from the bursting of the disc. Because of the degree of concentration in stress working at the groove, the disc opening time with a groove for the same thickness of disc is faster than that case of no groove.

As a result, the gradient of pressure increment for the case of groove is steeper, and also the shock formation distance is more shortened.

In particular, to confirm the validation of the present study, we compared the obtained result of Fig. 8 with the result by Reference [10]; the two results show a good agreement as x/D=8.1 in shock formation distance, here x and D denote the shock formation distance and hydraulic diameter of flow passage, respectively.

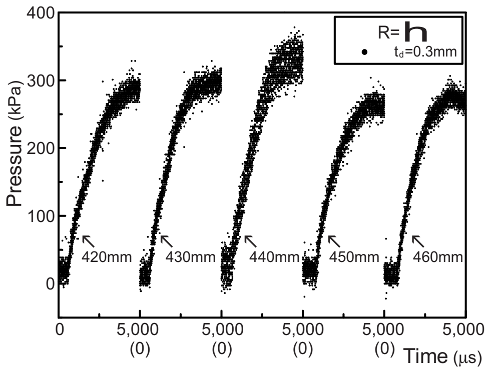


Fig. 8. Pressure histories with the variations of x for ΔP=900 kPa, t_d=0.3mm, R=∞ and no groove.

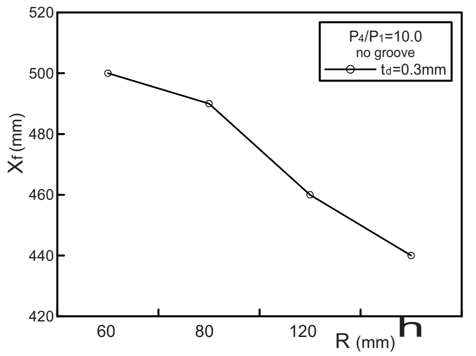
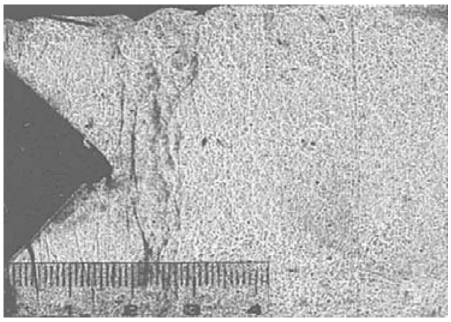


Fig. 9. Shock formation distance with the variations of R for ΔP=900kPa, t_d=0.3mm and no groove

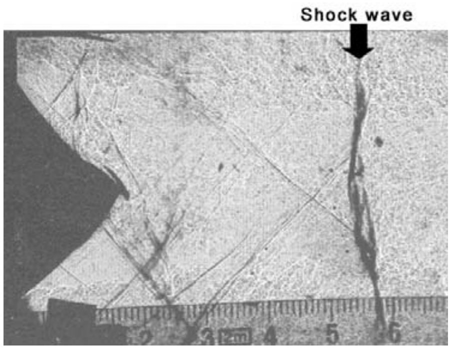
5. Relation between valve opening time and radius of curvature of disc

Eq. (3) can be written as Eq. (4) in the case of the same depth of groove and hydraulic diameter, the pressure difference and material of disc.

$$\tau_{op} = \kappa \cdot f_1 \frac{R}{D} \tag{4}$$



(a) T_d=100μs (no groove)



(b) T_d=100μs (groove)

Fig. 10. Schlieren photos without and with grooves for ΔP= 900kPa, R=∞ and t_d=0.4mm

Here, in the case of a disc of aluminum 1050 series, no groove, t_d=0.3mm, pressure ratio P_4/P_1=10.0 namely ΔP=900kPa, σ_B=270MPa and ρ=2,700kg/m^3, the non-dimensional con-stant κ of Eq. (4) becomes 0.00286.

Also the relation between the valve opening time and non-dimensional radius of curvature in experimental result shows to be linear as shown in Fig. 11; as a result, we obtained the final result for the relation between shock formation distance and R/D under the present experimental con-dition, and whose final result is given as Eq. (5).

$$\tau_{op} = \kappa \cdot 0.22 \frac{R}{D} \tag{5}$$

6. Conclusions

The effects of the radius of curvature, with or without groove and thickness of disc on the valve opening time and shock formation distance are investigated, and the obtained results are summarized as follows.

1. The smaller the radius of curvature is, the shorter the disc opening time is, and the maximum pressure at the just downstream of the valve is lower.

2. Valve opening time with a groove at disc is shorter than that case without groove for the same pressure ratio and difference and disc thickness.

3. Under the present experimental conditions, the relation between the valve opening time and radius of curvature of disc shows to be linear.

4. The smaller the radius of curvature of disc is, the longer the formation distance of shock wave is.

Nomenclature

D	: Hydraulic diameter of disc (mm)
H	: Distance from the apex to the installation position of disc(mm)
h	: Actual thickness of disc (mm)
M_s	: Propagating shock Mach number
P_1	: Driven chamber pressure (kPa)
P_4	: Drive chamber pressure (kPa)
P_i/P_4	: Operating pressure ratio
ΔP	: Pressure difference (kPa)
$dP/d\tau_{op}$	: Ratio of increment of pressure to disc opening time
R	: Radius of curvature of disc (mm)
T_d	: Lapse time (sec)
t_d	: Thickness of disc (mm)
t_g	: Groove depth of disc (mm)
X_f	: Shock formation distance (mm)
σ_B	: Limit strength of disc (N/m^2)
ρ_D	: Density of disc (kg/m^3)
τ_{op}	: Disc opening time (sec)

References

[1] Pipeline Simulation and Integrity LTD, Testing and Analysis of Relief Device Opening Times, Health & Safety Executive, Offshore Technology Report, 23 (2002) 20-23.

[2] P. Leckner, Rupture Disks for Process Engineers Part 1, Cheresources (2004).

[3] V. D. Sharma, R. Shyam and L. P. Singh, Shock formation distance in a two-dimensional steady supersonic flow over a concave corner in radiative magnetogasdynamics, *Zeitschrift Fuer Angewandte Mathematic und Mechanik*, 67 (2) (1987) 87-92.

[4] E. M. Rothkopf and W. Low, Diaphragm opening process in shock tubes, *Phys. Fluids*, 17 (6) (1974) 1169-1173.

[5] T. Ikui and K. Matuo, 1st report the effect of Hydraulic diameter of diaphragm on efficiency in a shock tube, *J. of JSME*, 34 (267) (1968) 1961-1968.

[6] D. R. Andrews, The bursting diaphragm as a fast-acting valve, *J. of Phys. Eng.*, 16 (1983) 192-193.

[7] F. V. Shugaev and L. S. Shtemenko, Propagation and reflection of shock waves, *World Scientific Publishing*, Singapore, 49 (1997) 20-23.

[8] B. C. R. Ewan, D. Nelson and P. Dawson, Examination of the effect of relief device opening times on the transient pressures developed within liquid filled shells, *Health & Safety Executive*, Offshore Technology Report, (2000) 130-134.

[9] E. M. Rothkopf and W. Low, Shock formation distance in a pressure driven shock tube, *Phys. of Fluids*, 19 (12) (1976) 1885-1888.

[10] T. Ikui and K. Matsuo, Mechanics of Shock Waves, Corona Book Co., Japan, (1983).