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Numerical Study of the Effects of the Rupture Process of a Secondary Diaphragm in Expansion Tubes

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Abstract : The results of a numerical study are described in which the interactions of a primary shock wave with a secondary diaphragm in expansion tubes are taken into account. The developing wave pattern in the interacting process of the shock with a secondary diaphragm are visualized by many kinds of figures (e.g., the time-distance diagrams of the wave phenomena on the axis, the acoustic impedance contours, and the time histories of the pitot pressure on the axis), and the influences of the shape and rupture process of the diaphragm on the quality of the test gas are explored.

Keywords : Expansion tubes, Secondary diaphragm, Shock propagation, Numerical visualize-ation, Contact surface.

1. Introduction

The expansion tube is an impulse-type wind tunnel facility, capable of producing high-enthalpy test gas flows for aerothermodynamic investigations (e.g., Neely and Morgan, 1994). In the expansion tube, the test gas is heated and accelerated by a primary shock and is then further accelerated by unsteady expansion waves at the secondary diaphragm. However, the secondary diaphragm influences the quality and the duration of the test flow that is produced, mainly due to its finite rupture time (e.g., Shinn and Miller, 1978).

In earlier studies (e.g., Roberts et al., 1995), it was shown experimentally that wave reflections resulting from the interaction of the primary shock and the secondary diaphragm can cause early distortions of the test gas flow. In subsequent experiments (e.g., Roberts et al., 1998), the trajectories of the reflected and transmitted shocks were investigated. However, the origin of the disturbances influencing the flow remains unclear. The results of the numerical study by Kage et al. described the influences of the rupture time of the diaphragm on the quality of the test gas, and the numerical results of the two-dimensional flow agreed qualitatively with the experimental results of the Roberts et al. (1998).

In this paper, the details of the interaction of a primary shock and a secondary diaphragm and the consequent disturbances to the test flow in two cases, i.e., the shapes and rupture processes of the diaphragms were different, were explored in a numerical study. The influences of the shape and the rupture process of the diaphragm on the developing wave pattern and the quality of the test gas are illustrated and visualized by various figures.

2. Numerical Method

The computations were carried out by solving the governing conservation equations for the viscous, unsteady and compressible flow in two dimensions using a total variation diminishing (TVD) scheme (Yee and Harten, 1987).

The initial condition is shown in Fig.1. The primary shock wave and the primary contact surface produced by the burst of the primary diaphragm are indicated by PS and PC, respectively. The secondary diaphragm is indicated by D. PS and PC move toward the secondary diaphragm D. This condition is before the time when PS interacts with D. In the figure, x is the dimensionless distance normalized by the duct height H and D, PS and PC are located at x=3.5, x=2.7 and x=0.2, respectively. In (a), in which the form of the diaphragm is normal plane, and in (b-1) and (b-2), in which the form of the diaphragm is convex, the diaphragm was allowed to burst (i.e. vanish) at the delayed dimens- ionless time (t_b=0.193) after the impact by the primary shock. The values of δ/H in (b-1) and (b-2) are 0.12 and 0.04, respectively. The dimensionless time t is normalized by u_2/H, where u_2 is the velocity of the flow induced by the primary shock. In the cases of (c-1) and (c-2), the central part of the normal plane diaphragm burst earlier than t_b by Δt_b=0.116 and Δt_b=0.039, respectively. The numbers of cells in the computational domain are 51×402. The numerical simulations were carried out with argon as the driver, and the test Mach number of the primary shock (Ms) and the sound speed ratio(c_2/c_3) across the primary contact were 4.0 and 2.0, respectively.

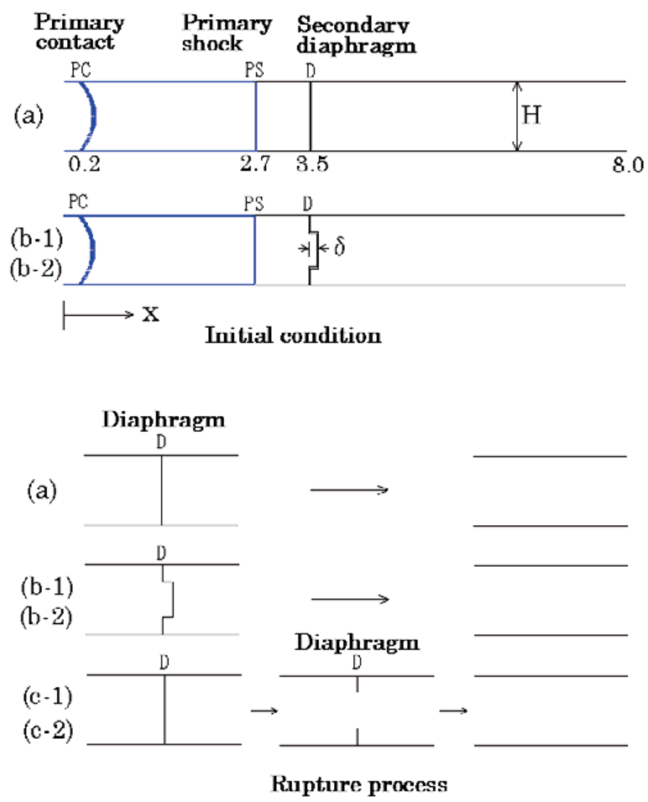

Fig. 1. Initial condition and rupture process.

3. Results

Figure 2 shows the time-distance plots of the wave phenomena occurring on the axis for cases (a), (b-1) and (c-1). The primary shock (PS) interacts with the secondary diaphragm (D) which, since it does not burst instantaneously, causes a reflected shock (RS) to form and propagate back upstream. Once the diaphragm has burst, a centered expansion wave (E) forms and an incident shock (IS) is propagated in the downstream test gas. The expansion interacts with and weakens the reflected shock, causing the shock to slow and its trajectory to curve. At some time later, the reflected shock interacts with the primary contact surface (PC). As the sound speed ratio c_2/c_3 across PC is greater than unity (over-tailored condition), a shock wave (termed the disturbance shock, and labeled DS) is propagated downstream as a result of the interaction of RS with PC. DS passes through the expansion and travels in the test gas at a higher velocity than IS. In a similar fashion, the expansion as a result of the interaction of E with PC follows closely behind DS. The reflected shock RS which was transmitted through PC is propagated downstream by the flow of the relatively cool driver gas behind PC. The primary contact surface PC after the interaction with RS is slightly slowed by the interaction with E and then moves downstream at nearly equal velocity to that before the interaction. These features are similar in the cases of (a), (b-1) and (c-1). However, comparing the results obtained for each case, the following features are observed. The trajectory of IS is straight (corresponding to constant velocity) and there is no-disturbance closely behind IS in (a). On the other hand, the trajectory of IS is fairly curved at several points (indicating that the velocity of IS is not constant) and there are strong disturbances behind IS in (b-1). In the case of (c-1), the trajectory of IS is slightly curved at several points, and there are weak disturbances behind IS. The trajectory of the disturbance shock DS is very clear in case (a). However, in cases (b-1) and (c-1), the trajectory of DS is not clear.

Wave phenomena on the axis in the cases of (b-2) and (c-2) are qualitatively similar to tose of cases (b-1) and (b-2). As the value of δ/H in (b-2) is less than that in (b-1), the curvature of the trajectory of IS at several points is smaller than in case (b-1). As the value of Δt_b (i.e. the time difference between the rupture time of the central part and t_b) in (c-2) is less than that in (c-1), the curvature of the trajectory of IS at several points is smaller than in case (c-1).

Figure 3 shows the shapes and locations of RS, IS, E, PC and DS at various times (t=0.792, 1.159, 2.318, 3.091, and 3.478) after the rupture of the secondary diaphragm in the cases of (a), (b-1) and (c-1). At t=0.792 (just after the rupture of the diaphragm), the primary contact surface PC whose shape is parabolic, is observed in each case. The incident shock IS and the reflected shock RS are straight in (a). In the case of (b-1), the shape of IS is similar to that of the diaphragm, and the reflected shock RS is extremely curved. In the case of (c-1), the shape of IS is extremely curved in its central part, and RS generated by the rupture of the diaphragm is straight. At t=1.159 (a little after the rupture and before the interaction of RS and PC), the expansion E follows RS in each case. In both cases (b-1) and (c-1), Mach reflection of the incident shock IS on the side walls and slightly curved RS are observed. At t=2.318 (the moment of the interaction of RS and PC), slightly curved IS followed by several reflected shocks and some disturbances behind IS are observed in (b-1) and (c-1). At t=3.091 (just after the interaction of RS and PC), the slightly curved disturbance shock DS by the interaction of RS and PC is very clearly observed in (a). However, the disturbance shock DS is not clear in (b-1) and (c-1) because DS is in the flow field of the disturbances produced by several reflected shocks on the walls. The shape of IS is distorted in (b-1) and (c-1). In every case of (a), (b-1), and (c-1), the reflected shock RS on passing through the primary contact surface PC into the relatively cool driver gas is intensely bifurcated by the strong interaction with the boundary layer of the flow behind PC. At t=3.478 (somewhat after the interaction of RS and PC), the disturbance shock DS by the interaction of RS and PC is observed in (a), (b-1) and (c-1) but is not clear in (b-1) and (c-1). In each case, the bifurcation of RS increases.

Thus, complex flow fields are produced by the presence of the secondary diaphragm (delayed burst, convex shape of the diaphragm, non-uniform rupture). The overall effect on test gas flow

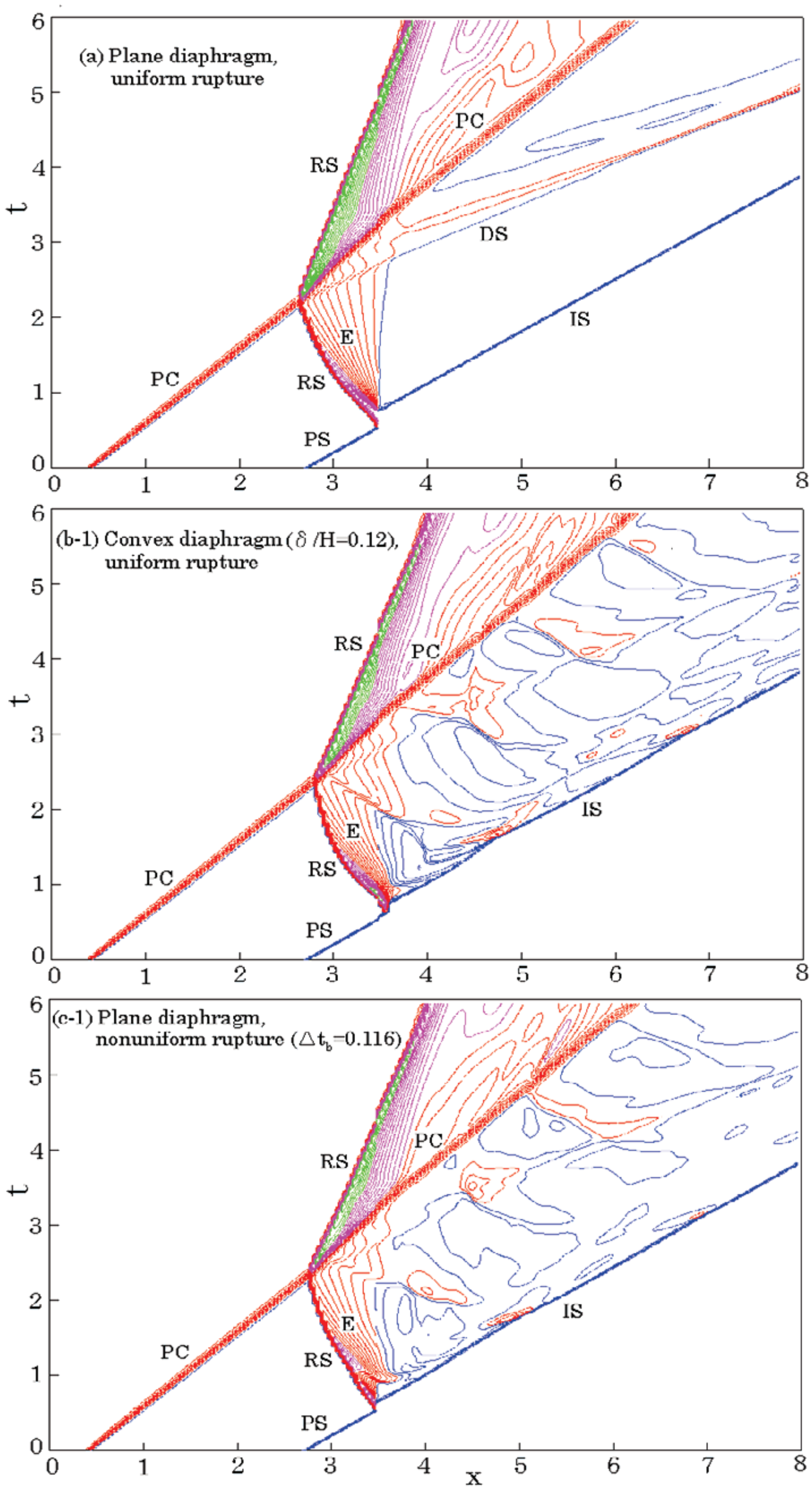

Fig. 2. Time-distance diagrams of wave phenomena on axis.

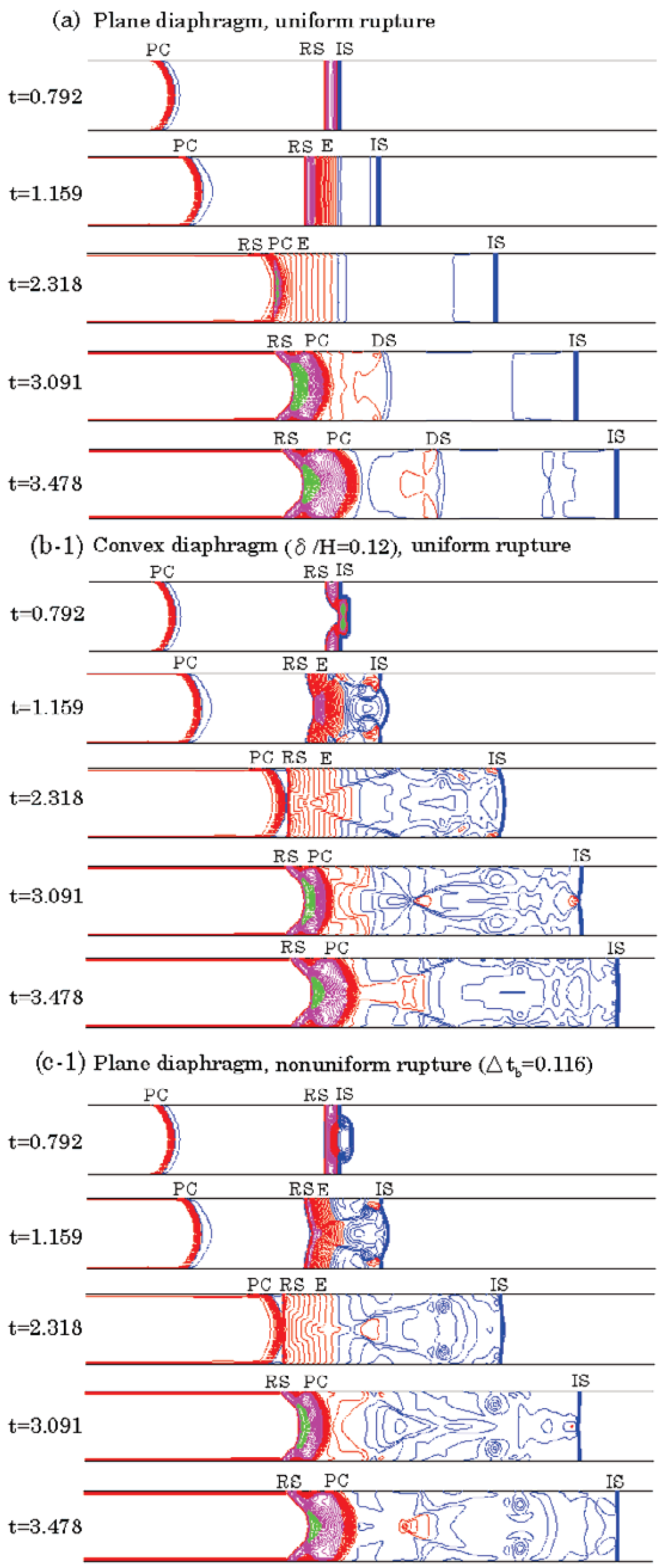

Fig. 3. Acoustic impedance contour.

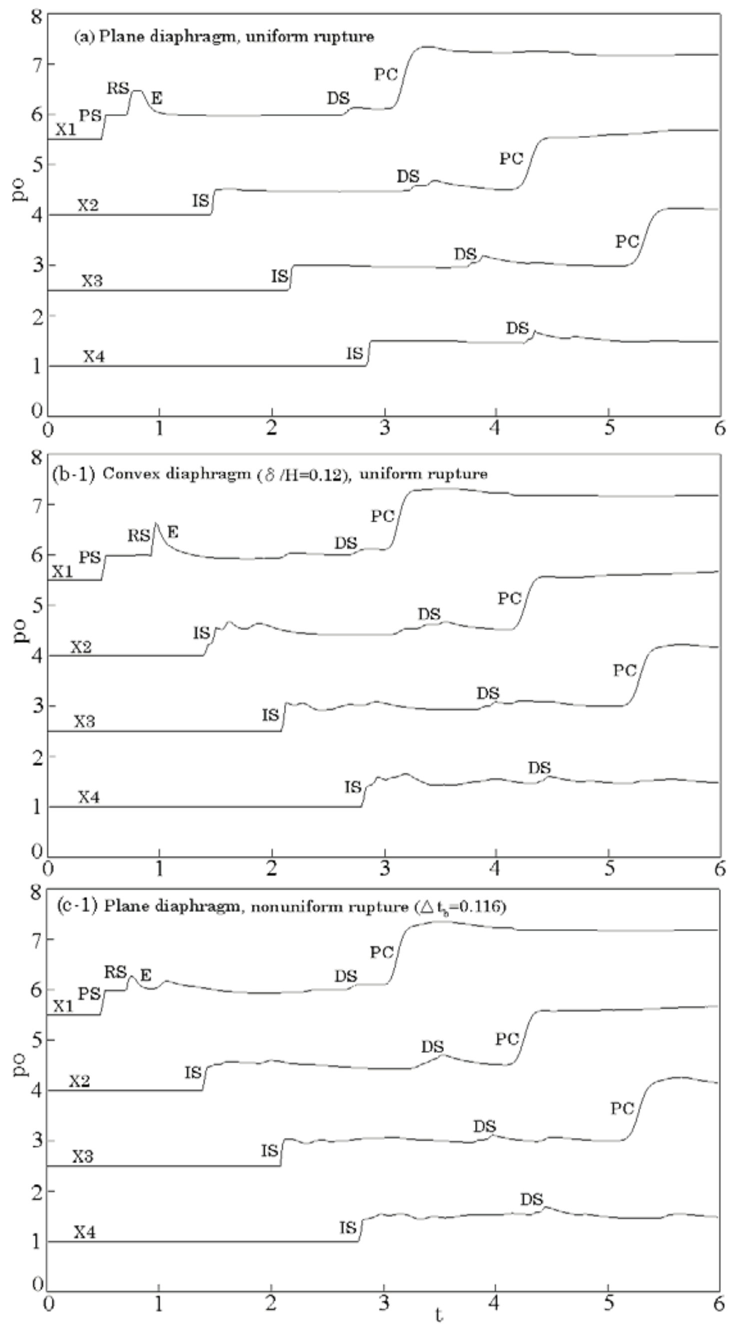

Fig. 4-1. Time histories of pitot pressure on axis(po).

quality can be clarified by observing the jump or fluctuation of the pitot pressure produced by the disturbance shocks. Figures 4-1 and 4-2 show the time variations of pitot pressure on the axis at various locations along the axis of the duct. The locations are upstream (X1=-0.1) and downstream (X2=1, X2=2, X3=3) of the secondary diaphragm (negative and positive values of X mean upstream and downstream distances from the secondary diaphragm, respectively). Just upstream of the diaphragm (X1=-0.1), the arrival of the primary and reflected shocks (PS and RS), followed by the expansion E are clearly observed in the pitot pressure variations. Some time later, the disturbance shock arrives just ahead of the primary contact surface. The disturbance shock DS by the interaction of RS and PC is very clearly observed in (a), but is not easy to identify in (b-1) and (c-1) because the strength of the disturbances due to the reflected shocks on the side walls, is comparable order with that of DS. It is not so difficult to identify DS in (b-2) and (c-2). At downstream locations of the diaphragm (X2=1, X2=2, X3=3), the disturbance shock DS by the interaction of RS and PC arrives after the incident shock IS, and its arrival is earlier than the primary contact surface PC. As the test flow continues until the disturbance shock arrives in the expansion tube flow, it is clear that the run duration of the test flow is being reduced because the disturbance shock arrives before the primary contact surface. As the time interval between the arrival of the incident shock IS and the disturbance shock DS decreases with increasing distance downstream of the diaphragm, it is expected that the run duration of the test gas flow reduces. In (b-1), (c-1), (b-2) and (c-2), the disturbances by the reflected shock at the side walls behind the incident shock are added to the disturbance shock DS by the interaction of RS with PC, and these disturbances lower the quality of the test flow. The disturbances in (b-1) and (c-1) are comparable in strength to the disturbance shock DS. In (b-2) and (c-2), the disturbances are weak compared to the disturbance shock DS.

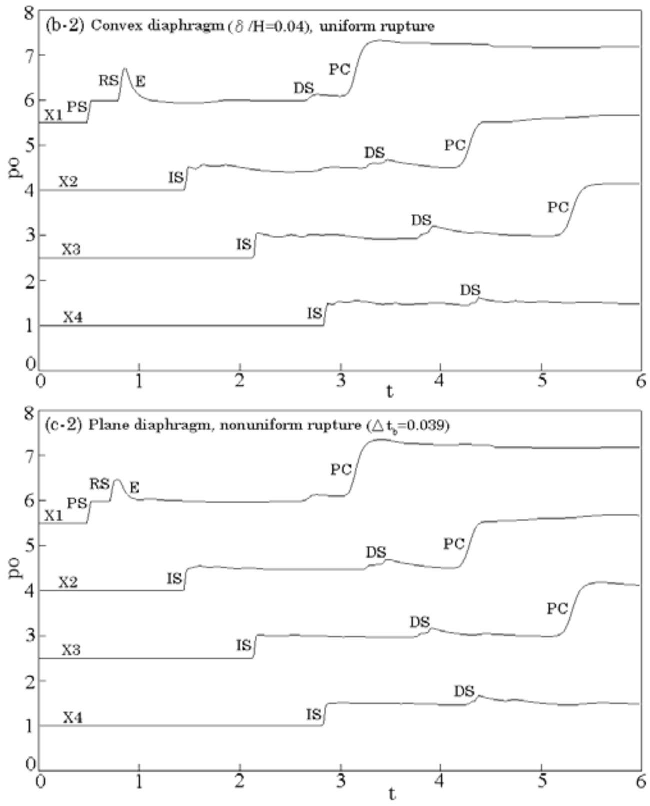

Fig. 4-2. Time histories of pitot pressure on axis(po).

4. Conclusion

The results of the numerical simulation and the flow visualization have highlighted one possible cause of the disturbances to the test gas flow. It is evident that delaying the burst of the secondary diaphragm can cause a strong interaction between the reflected shock and the primary contact surface, which then results in a disturbance shock being propagated into the test gas flow and shortening of the run duration. In the case in which the shape of the secondary diaphragm is convex, or in the case in which the rupture process is not uniform, the disturbances by the reflected shock at side walls behind the incident shock are added to the disturbance shock by the interaction of the reflected contact with the primary contact, lowering the quality of the test flow. In the case in which the curvature of the diaphragm is small, or the time difference between the rupture time of the whole and the central part of the diaphragm is short, the disturbances by the reflected shock at side walls are weak.

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