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Effect of Porosity Distribution and Orifice Geometry on Blast-Wave Attenuation In Porous Plate Arrays

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ABSTRACT

Blast-wave attenuation using rigid porous barriers has received considerable attention as a passive mitigation strategy for protecting structures from impulsive loading. Previous investigations have primarily focused on porosity, plate spacing, and hole arrangement, while the influence of internal orifice geometry has received comparatively little attention. In the present study, shock-tube experiments and three-dimensional computational fluid dynamics simulations benchmarked against measured pressure histories were used to investigate blast-wave propagation through rigid porous plate arrays. Uniform porosity arrays, graded porosity arrangements, and several non-cylindrical orifice geometries were evaluated using upstream, downstream, and end-wall pressure histories together with numerical density-gradient (schlieren) fields. For the tested configurations, decreasing uniform porosity increased attenuation, whereas reversing the direction of porosity grading produced a much larger change in peak-end-wall pressure than in cumulative impulse. Among the shaped passages, the continuously diverging profile produced the lowest reported peak end-wall pressure and cumulative impulse, corresponding to reductions of 47.6% and 21.2%, respectively, relative to the blank configuration. The numerical fields show systematic differences in shock diffraction, reflection, secondary wave interaction, and jet development among the geometries and provide consistent interpretation of the measured performance. These results identify internal orifice geometry as an additional design parameter for porous blast barriers, while the detailed contribution of individual wave-interaction mechanisms remains a subject for further qualitative study.

KEYWORDS

Blast-wave attenuation; Porous plate arrays; Shock-wave diffraction; Orifice geometry; Computational fluid dynamics; Numerical schlieren.

NOMENCLATURE

Symbol/Abbreviation	Definition
AUSM+	Advection Upstream Splitting Method Plus
CFD	Computational fluid dynamics
CFL	Courant–Friedrichs–Lewy
E	Total energy per unit mass
e	Specific internal energy
FVS	Flux-vector splitting

Symbol/Abbreviation	Definition
I	Identity tensor
M	Mach number
MUSCL	Monotonic upstream-centered scheme for conservation laws
p	Pressure
P_{applied}	Applied pressure upstream of the porous plate array
P_{end}	End-wall pressure
P_{trans}	Transmitted pressure downstream of the porous plate array
RK4SSP	Strong stability-preserving fourth-order Runge–Kutta
RS	Reflected shock
SRS	Secondary reflected shock
STS	Secondary transmitted shock
t	Time
TS	Transmitted shock
u	Velocity vector
γ	Ratio of specific heats
ρ	Density
ϕ	Porosity

34

35 1 INTRODUCTION

36 Blast waves generated by explosions, industrial accidents, and military threats produce intense
37 transient pressure loads capable of causing severe structural damage and significant risk to
38 human life [1–4]. In confined and semi-confined environments, repeated wave reflections can
39 substantially amplify both peak pressure and impulse, increasing the loading imparted to sur-
40 rounding structures [3–5]. Consequently, considerable research has focused on passive blast
41 mitigation strategies capable of reducing transmitted blast loading while maintaining structural
42 simplicity and reliability [6–10]. Among these approaches, rigid porous barriers have demon-
43 strated significant potential by attenuating incident shock and blast waves through repeated
44 reflection, diffraction, transmission, viscous dissipation, and vortex generation [6–15].
45 Various rigid porous media, including metallic foams, granular materials, cellular structures,
46 woven meshes, and perforated plate arrays, have been investigated for shock and blast mitiga-
47 tion [11–21]. Among these, perforated plate arrays are particularly attractive due to their simple
48 manufacture, repeatable geometry, structural durability, and ability to provide significant at-
49 tenuation without permanent deformation [6,7,11–17]. Previous investigations have demon-
50 strated that reducing porosity generally increases blast attenuation through stronger reflected
51 shocks, increased shock trapping, and repeated wave interactions between adjacent plates [11–
52 17]. Similarly, Nguyen and Proud demonstrated that decreasing the open area of perforated
53 sheets in perforated-sheet/reticulated-foam sandwich structures increased peak-pressure atten-
54 uation and significantly influenced impulse transmission [18]. Additional studies have shown

that attenuation is influenced by parameters including plate spacing, stand-off distance, plate count, hole arrangement, perforation shape, and incident shock strength [7–19]. More recently, simplified analytical and semi-empirical models have also been developed to predict pressure buildup behind perforated plate arrays subjected to blast loading [11,15].

Although the effects of porosity, plate spacing, hole alignment, and perforation shape have been investigated extensively, comparatively little attention has been devoted to the influence of the internal geometry of the perforations themselves [7–19]. Most previous investigations have employed straight cylindrical perforations of uniform diameter despite studies of shock diffraction demonstrating that converging and diverging passages substantially modify reflected shock formation, transmitted shock evolution, expansion waves, and vortex generation [9,20]. To the authors' knowledge, no previous investigation has systematically examined the influence of continuously converging, continuously diverging, converging-diverging, diverging-converging, and stepped internal orifice geometries on blast-wave attenuation in porous plate arrays. Consequently, the influence of internal orifice geometry on blast attenuation remains poorly understood.

Experimental pressure measurements provide quantitative information regarding transmitted blast loading, while optical techniques such as schlieren and shadowgraph imaging have been widely employed to visualize shock-wave propagation and diffraction in compressible flows [22,23]. However, resolving the complete three-dimensional wave evolution within multi-plate porous arrays remains challenging because wave interactions occurring inside the array are partially obscured by the plates and cannot be directly observed throughout the flow field. Validated three-dimensional computational fluid dynamics simulations therefore provide an effective complementary tool for examining reflected shocks, transmitted shocks, secondary shock interactions, vortex development, and other compressible flow structures responsible for blast attenuation [9,14,16,19].

The present study combines experimental shock-tube testing with validated three-dimensional computational fluid dynamics simulations to investigate blast-wave attenuation through rigid porous plate arrays. The effects of uniform and graded porosity distributions are first examined to evaluate the influence of porosity sequencing on transmitted blast loading. Subsequently, the influence of internal orifice geometry is investigated through a series of converging, diverging, converging-diverging, diverging-converging, and stepped orifice profiles designed to modify the evolution of the transmitted shock within the porous array. Experimental pressure measurements are used to validate the numerical model, which is subsequently employed to investigate the underlying flow physics responsible for the observed attenuation characteristics.

2 EXPERIMENTAL SETUP

2.1 SHOCK TUBE FACILITY

Experiments were conducted using a compressed-gas-driven shock tube facility at the University of Rhode Island (URI) in the Dynamic Photomechanics Lab (DPML). The shock tube consisted of a high-pressure driver section and a low-pressure driven section separated by a frangible Mylar diaphragm with a thickness of 0.25 mm. The driver section had an inner di-

ameter of 152 mm and a length of 305 mm, while the driven section had the same inner diameter over a length of 4572 mm. The driven section then tapered to a diameter of 76 mm over a length of 914 mm, and subsequently to a 38 mm diameter muzzle over the final 914 mm. The total shock tube length was 7400 mm; the individual sections are shown in Figure 1.

Prior to each experiment, the driver section was pressurized using compressed nitrogen gas while the driven section remained at ambient atmospheric conditions. The shock wave was generated through a diaphragm rupture at an absolute driver pressure of 790 kPa. Rupture produced a nominal incident shock Mach number of 1.62 corresponding to an incident shock velocity of 555 m/s.

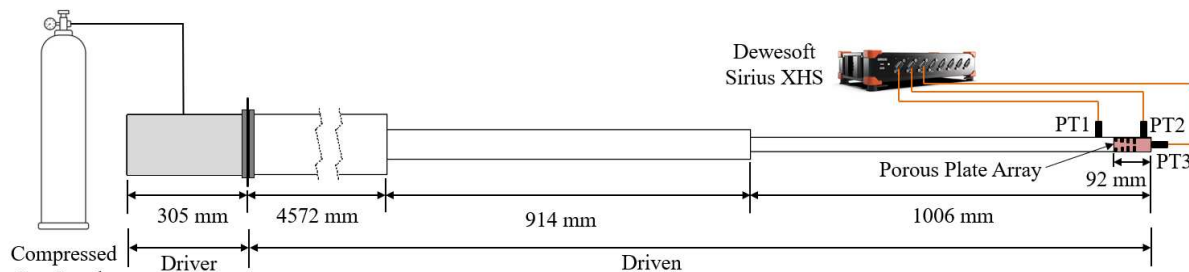


Figure 1. Shock tube schematic.

Dynamic pressure measurements were acquired using piezoelectric pressure transducers positioned flush-mounted along the shock tube wall at multiple axial locations. Three transducers were used to characterize the incident and transmitted shock wave behavior. Pressure signals were recorded using a high-speed data acquisition system, the Dewesoft Sirius XHS, at a sampling frequency of 500 kHz. Pressure sensors PT1 and PT3 had a sensitivity of 0.75 mV/kPa (PCB model 113B24) whereas PT2 has a sensitivity of 0.145 mV/kPa (PCB model 113B22). Incident shock velocity was determined from measured shock arrival times between pressure transducer locations separated by known distances.

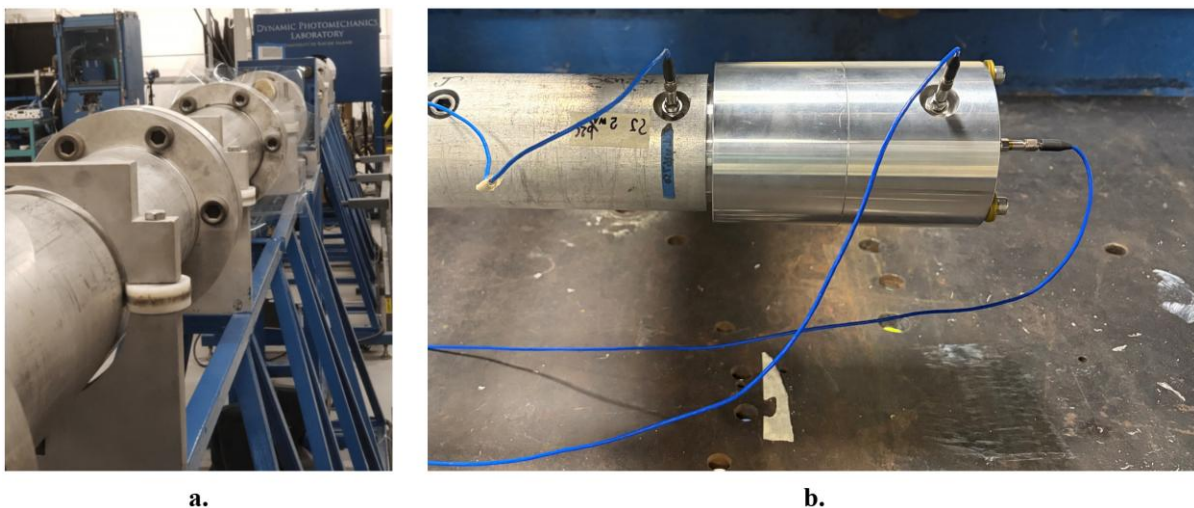


Figure 2. (a) Shock tube facility viewed down the length with the muzzle and end structure in background, (b) porous plate fixture threaded onto muzzle with pressure transducers in place.

The porous plate test section was mounted at the downstream end of the shock tube within a custom fixture designed to securely support interchangeable plate-array specimens. The fixture accommodated porous plate arrays with an outer diameter of 45 mm and an effective flow diameter of 38 mm. A rigid end-wall was positioned downstream of the specimen to measure reflected and transmitted pressure loading resulting from wave interaction with the porous structures. Sensors PT1 and PT2 were separated by 130 mm, and PT3 was located an additional 19 mm downstream of PT2, as shown in Figure 3. The downstream end of the porous plate array was positioned 38 mm upstream of PT3.

Experiments were conducted under nominally identical initial conditions for each test configuration to ensure repeatability and enable direct comparison between porous plate geometries. Measured pressure time histories were subsequently processed to determine peak overpressure, impulse, shock arrival time, and attenuation characteristics associated with the porous plate arrays.

2.2 POROUS PLATE ARRAY DESIGN

The porous plate arrays were designed to investigate the effects of porosity distribution and local orifice geometry on shock attenuation behavior. Each array had an overall length of 48 mm and consisted of four rigid plates separated by uniform inter-plate spacing. For all tests, individual plates were 6 mm thick and separated by 7.75 mm gaps, as shown in Figure 3. The arrays were fabricated from 3D-printed Polylactic Acid (PLA) material and mounted within a rigid aluminum fixture that was threaded onto the end of the muzzle.

Three different orifice profiles were investigated initially: straight, converging, and diverging. The straight-orifice plates consisted of constant-diameter cylindrical passages through the plate thickness. Four different hole diameters were used for the straight-orifice plates: 4.5 mm, 5.25 mm, 6 mm, and 6.5 mm, corresponding to plate porosities of 30%, 40%, 50%, and 60%, respectively. Initial experiments were conducted using uniform porosity arrays in which all plates within the array contained identical hole diameters. Subsequent configurations varied the porosity between successive plates to investigate the effects of porosity grading on transmitted shock behavior and downstream wave evolution.

The converging and diverging orifice geometries were designed to investigate the influence of local flow acceleration and expansion within the plate passages. Converging orifice plates tapered from an inlet diameter of 6.5 mm to an outlet diameter of 5 mm in the direction of shock propagation, while diverging orifice plates tapered from 5 mm to 6.5 mm through the plate thickness. A representative cross-section of the 60% porosity orifice geometry is shown in Figure 3.

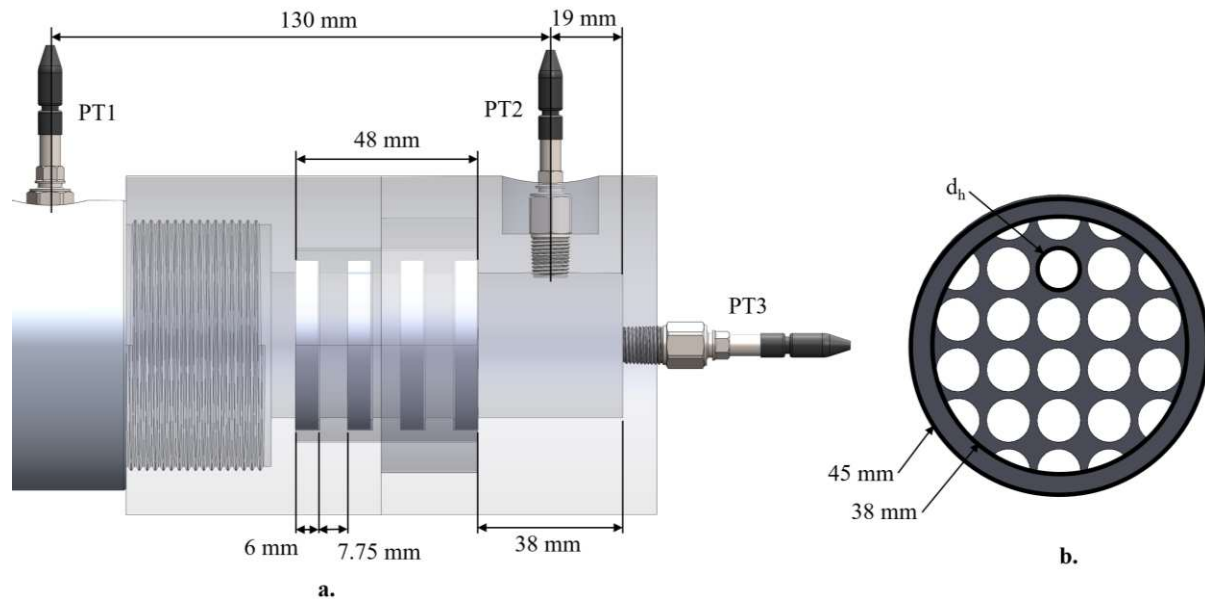


Figure 3. (a) Pressure transducer spacing and plate spacing, thickness, and overall array length, (b) plate array end view with outer diameter, effective flow diameter, and orifice diameter.

In addition to arrays composed entirely of converging or entirely of diverging plates, mixed-profile configurations containing both converging and diverging orifice plates were also investigated to evaluate the effect of staged flow contraction and expansion on shock attenuation and wave reformation. An additional orifice profile with a central expansion chamber, the Helmholtz-type profile, was also investigated. All profiles investigated are shown in Figure 4. Mixed converging-diverging and diverging-converging profiles had a maximum diameter of 6.5 mm and minimum of 4.25 mm. The Helmholtz-type profile had an inlet and outlet diameter of 4.25 mm, and a central expansion chamber with a diameter of 6.5 mm. The expansion chamber length was equal to half the plate thickness. These diameters were selected to match the dimensions used in the straight profile arrays. The overall array length and inter-plate spacing were held constant for all configurations to isolate the effects of porosity distribution and orifice geometry on attenuation performance.

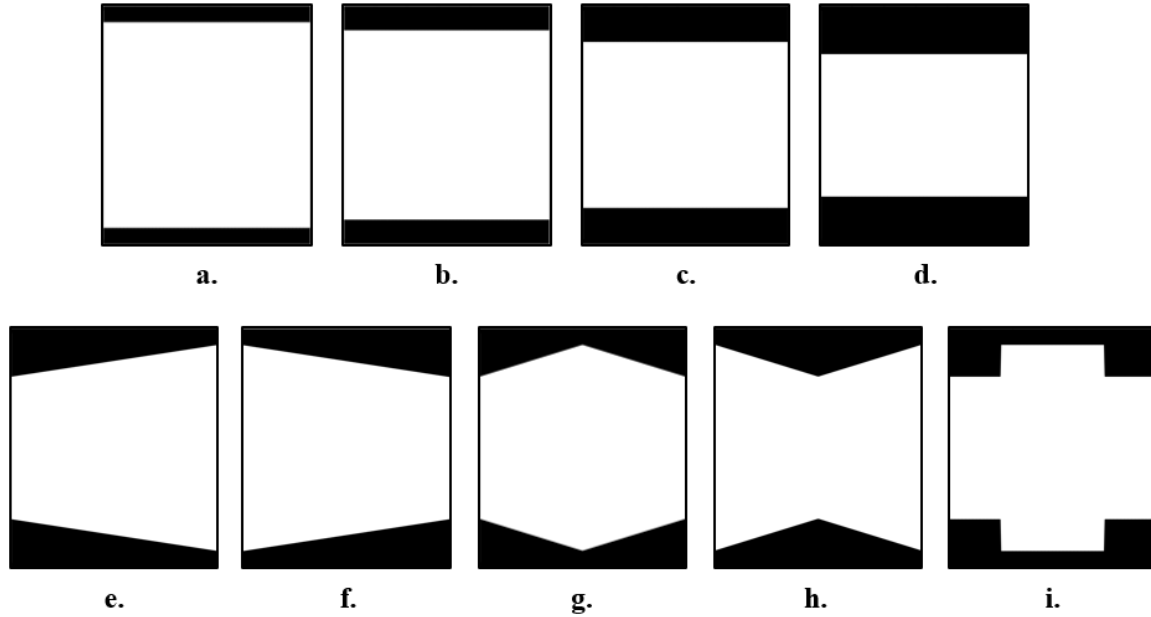


Figure 4. Orifice profiles investigated. (a-d) straight 6.5, 6.0, 5.25, and 4.5 mm, (e-f) continuously diverging and converging, (g, h) diverging-converging and converging-diverging, and (i) Helmholtz-type.

A summary of all porous plate configurations investigated experimentally and numerically is provided in Table 1 and Table 2.

Array ID	PORO-1	PORO-2	PORO-3	PORO-4	PORO-5	PORO-6
Plate 1 Porosity (%)	60	50	40	30	60	30
Plate 2 Porosity (%)	60	50	40	30	50	40
Plate 3 Porosity (%)	60	50	40	30	40	50
Plate 4 Porosity (%)	60	50	40	30	30	60

Table 1. Straight orifice profile, uniform and graded porosity plate array cases.

Array ID	CD-1	CD-2	CD-3	CD-4	HELM-1
Plate 1 Profile	Converging	Diverging	Converging-Diverging	Diverging-Converging	Stepped
Plate 2 Profile	Converging	Diverging	Converging-Diverging	Diverging-Converging	Stepped
Plate 3 Profile	Converging	Diverging	Converging-Diverging	Diverging-Converging	Stepped
Plate 4 Profile	Converging	Diverging	Converging-Diverging	Diverging-Converging	Stepped

Table 2. Converging, diverging, mixed converging-diverging, diverging-converging, and stepped (Helmholtz) plate array cases.

3 NUMERICAL SIMULATIONS

3.1 GOVERNING EQUATIONS

The transient propagation of shock waves through the porous plate arrays was modeled by solving the three-dimensional, compressible Euler equations in conservative form. The governing equations represent the conservation of mass, momentum, and total energy and are respectively given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u} + p \mathbf{I}) = 0 \quad (2)$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot [(\rho E + p) \mathbf{u}] = 0 \quad (3)$$

Where ρ is density, $\mathbf{u}$ is velocity, p is pressure, e is the specific internal energy, $\mathbf{I}$ is the identity tensor and E is total energy per unit mass given as:

$$E = e + \frac{1}{2} \mathbf{u} \cdot \mathbf{u} \quad (4)$$

$$e = \frac{p}{(\gamma - 1)\rho} \quad (5)$$

Air was modeled as a calorically perfect ideal gas using:

$$p = \rho R T \quad (6)$$

3.2 NUMERICAL SOLVER

Numerical simulations were performed using the open-source finite-volume solver `blastFoam`, which is based on the `OpenFOAM` framework and is designed for compressible high-speed flows involving shock waves and blast loading [24, 25]. The compressible Euler equations were solved using an explicit Runge–Kutta time integration scheme with second-order spatial accuracy.

Convective fluxes were evaluated using the Advection Upstream Splitting Method (AUSM+) flux-vector splitting (FVS) scheme to accurately capture strong shock discontinuities while minimizing numerical dissipation [26]. Primitive variables were reconstructed at cell faces using a quadratic monotonic upstream-centered scheme for conservation laws (quadratic MUSCL) with a van Leer limiter [27]. Spatial gradients were computed using the Gauss linear gradient scheme. The computational domain was assumed to be inviscid since viscous effects were negligible over the short-duration shock propagation through the tube and porous plate array. Consequently, turbulence modeling was not employed.

The solution was advanced using a strong stability-preserving fourth-order Runge–Kutta (RK4SSP) time integration scheme with adaptive time stepping [28]. A maximum Courant–Friedrichs–Lewy (CFL) number of 0.6 was enforced throughout the simulation to maintain numerical stability and accurately resolve the propagating shock wave. Solution stability was assessed by monitoring pressure histories at virtual sensor locations and verifying smooth shock propagation without spurious numerical oscillations.

3.3 COMPUTATIONAL DOMAIN AND BOUNDARY CONDITIONS

All shock-tube walls and porous plate surfaces were modeled as adiabatic walls. The shock tube included the driver-section end, the closed downstream end beyond the plate array, and the cylindrical inner wall; quarter-symmetry boundaries were applied on the vertical and horizontal symmetry planes, as shown in Figure 5.

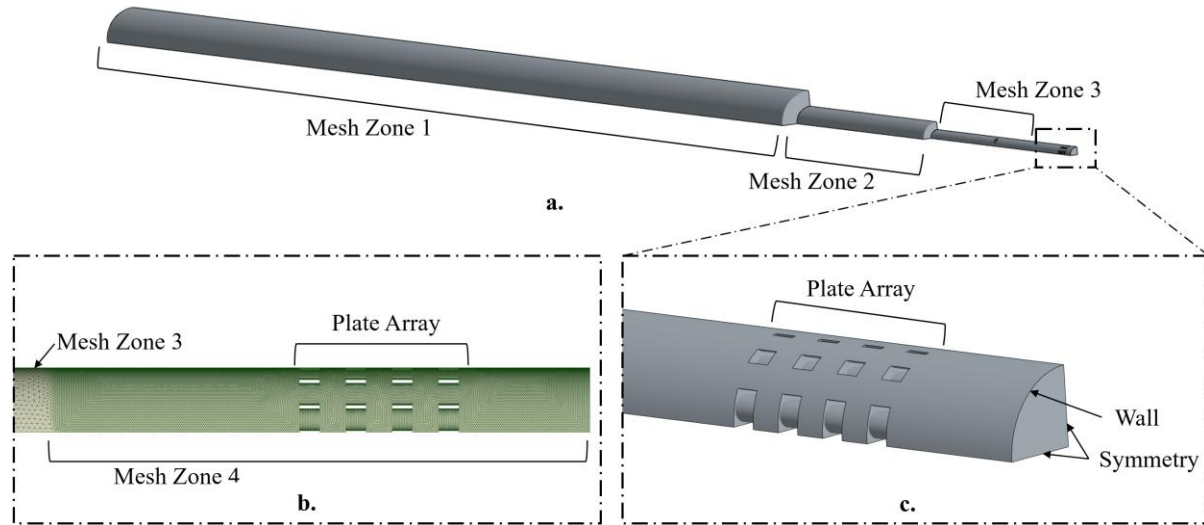


Figure 5. (a) Computational domain of shock tube, (b) mesh refinement at the shock tube end and near the plate array, (c) computational domain around plate array with symmetry boundaries and wall boundary around tube inner diameter and at the closed shock tube end.

An unstructured tetrahedral finite-volume mesh was generated using the open source software, SALOME and employed throughout the computational domain [29]. Local mesh refinement was applied in regions of expected strong shock gradients and complex shock–structure interactions near the porous plate arrays. The computational domain was divided into four primary mesh refinement zones corresponding to the major geometric sections of the shock tube. Mesh zone 1 included the driver section and initial driven section, Mesh zone 2 corresponded to the first shock tube diameter reduction, and Mesh zone 3 encompassed the remaining constant-diameter section of the shock tube upstream of the porous plate arrays. Mesh zone 4 consisted of a locally refined region extending 250 mm upstream of the porous plate arrays and through the array.

The diaphragm rupture process was approximated by imposing an initial pressure discontinuity between the driver and driven sections. The driver section was initialized to a pressure of 790 kPa, corresponding to the experimental diaphragm burst pressure investigated in this study, while the driven section was initialized to atmospheric pressure (101 kPa). The working fluid was air initialized at an ambient temperature of 300 K.

In addition to comparing numerical pressure histories with experimental measurements at the pressure transducer locations, numerical schlieren contours were generated to visualize the propagation and interaction of shock waves within the porous plate arrays. The schlieren images were computed from the density gradient magnitude, $|\nabla\rho|$, which highlights regions of

strong compressibility associated with shock waves, expansion regions, and other flow discontinuities. These contours were used to examine the evolution of transmitted, reflected, and secondary shock structures and to aid interpretation of the experimentally observed pressure attenuation mechanisms.

3.4 MESH INDEPENDENCE STUDY

A mesh independence study was conducted to assess the sensitivity of the numerical predictions to mesh resolution. Three progressively refined meshes were evaluated, as summarized in Table 3. Mesh refinement was applied only in mesh zones 3 and 4, where the strongest shock gradients and the most complex flow interactions occurred. The target element size in mesh zone 3 was reduced from 1.5 mm for mesh M1 to 1.0 mm for mesh M2 and M3, while the target element size in mesh zone 4 was reduced from 1.5 mm to 1.0 mm and finally 0.5 mm. The mesh sizes in zones 1 and 2 were maintained at 6.0 mm and 3.0 mm, respectively, for all three meshes. All simulations were performed using the same porous plate geometry and identical initial and boundary conditions.

The mesh-sensitivity study used CD-1, an array comprising four plates with continuously converging orifices. The end-wall pressure history at PT3 (Pend) was compared across the three meshes, as shown in Figure 7. M1 shows a visible deviation in the initial pressure rise and peak response, whereas the M2 and M3 pressure histories are visually very similar over the plotted interval. Based on this pressure-history comparison, the principal loading trends are not sensitive to refinement from M2 to M3. M3 was nevertheless retained for the subsequent simulations because the 0.5 mm refinement in mesh zone 4 provides greater spatial resolution for the schlieren-style density-gradient fields used to interpret local wave interactions. Because the present manuscript does not report numerical differences in peak pressure or impulse between M2 and M3, this study is best interpreted as a mesh-sensitivity assessment rather than a formal demonstration of grid convergence..

Mesh ID	Mesh Zone 1 (mm)	Mesh Zone 2 (mm)	Mesh Zone 3 (mm)	Mesh Zone 4 (mm)	Total Cells
M1	6.0	3.0	1.50	1.50	1.1 M
M2	6.0	3.0	1.00	1.00	1.7 M
M3	6.0	3.0	1.00	0.50	3.1 M

Table 3. Mesh convergence study element sizes per mesh zone.

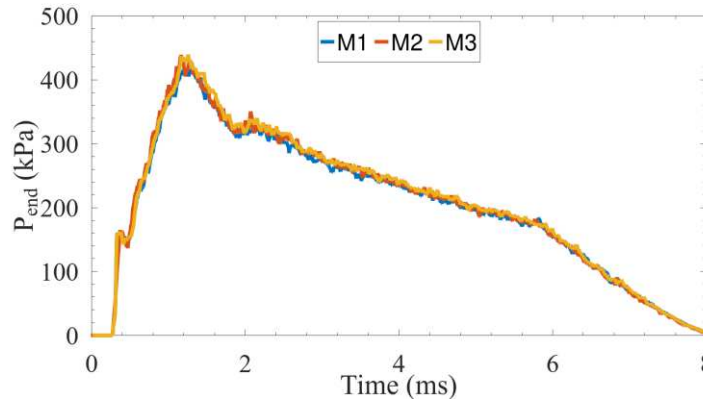


Figure 7. End-wall pressure time history for the mesh convergence study. Simulations were performed using the CD-1 plate array with continuously converging orifices.

3.5 EXPERIMENTAL REPEATABILITY

Experimental repeatability was evaluated to quantify the variability associated with shock generation, pressure measurement, and the overall test procedure. Three independent experiments were performed for each case shown in Table 1 and Table 2, in addition to the blank shock tube cases with no plate array present. Figure 8 compares the mean pressure time histories measured at pressure transducers PT1 and PT3 for each of the four uniform-porosity plate arrays (PORO-1 through PORO-4) and blank cases. These configurations span the full range of porosities investigated experimentally and provide representative bounds on the repeatability of the facility. Error bars represent one standard deviation calculated from the three repeated experiments. The PT1 (P_{applied}) measurements were used to assess the repeatability of the incident shock and the initial reflected shock generated by the first plate, while the PT3 (P_{end}) measurements quantify the repeatability of the transmitted loading at the end-wall. Mean applied and end-wall pressures are shown in Table 4. Standard deviations below 3% demonstrate excellent repeatability of the experimental facility and measurement procedure.

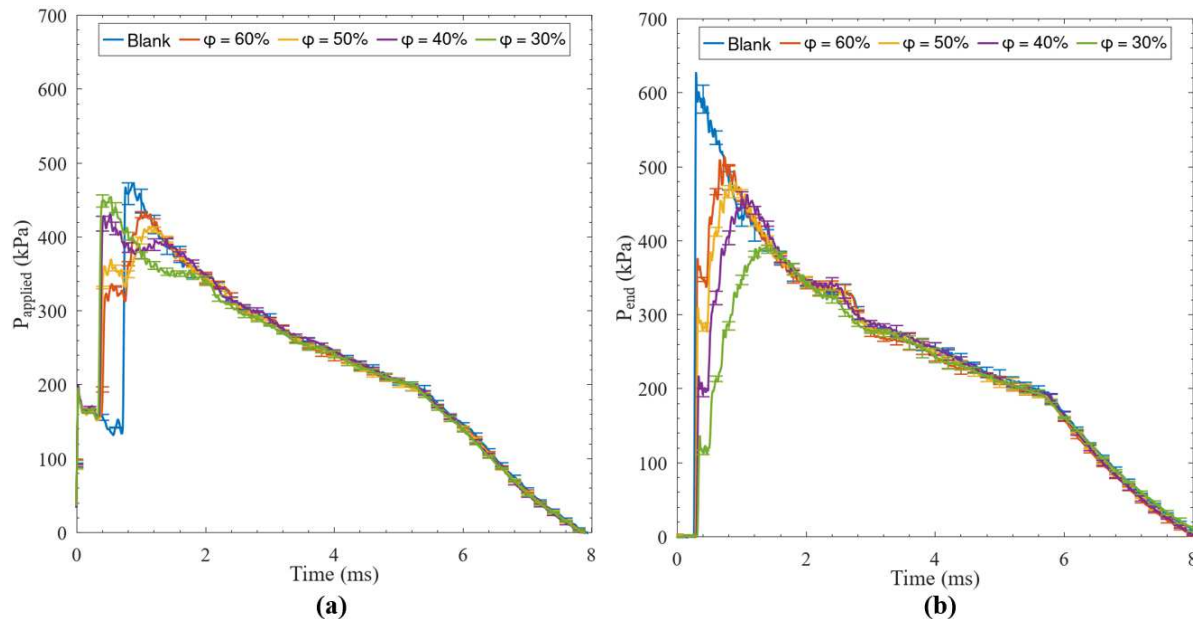


Figure 8. (a) Applied and (b) end-wall pressure time history with error bars for the blank, PORO-1 through PORO-4 configurations.

Array ID	Peak P_{applied}		Peak P_{end}	
	Mean (kPa)	Std. Dev. (%)	Mean (kPa)	Std. Dev. (%)
BLANK	196.8	2.0	629.6	3.0
PORO-1	198.4	0.5	514.9	1.0
PORO-2	195.5	0.6	481.1	0.8
PORO-3	200.0	1.1	463.4	2.3
PORO-4	196.1	1.3	392.9	1.7

Table 4. Mean and standard deviation for peak applied and end-wall pressure for blank and uniform porosity cases.

3.6 NUMERICAL VALIDATION

Predicted end-wall pressure histories (P_{end}) were compared with experimental measurements for three representative configurations: PORO-5, CD-1, and CD-4 (Figure 9). These cases sample the principal design variables considered in the study: graded porosity, a continuously converging orifice, and a diverging-converging orifice. For each case, the numerical history was compared with the mean of three experimental repetitions, with error bars representing one standard deviation. In all comparisons, $t = 0$ corresponds to arrival of the incident/transmitted wave at the PT1 reference location. The numerical histories reproduce the principal experimental features visible in Figure 9, including the rapid pressure rise, the elevated pressure interval, and the subsequent decay. The plotted comparisons also indicate agreement in the vicinity of the peak end-wall response. However, the present manuscript does not tabulate numerical-versus-experimental errors in peak pressure, impulse, or arrival time; accordingly, the validation claim is limited here to the agreement demonstrated by the reported pressure-history comparisons.

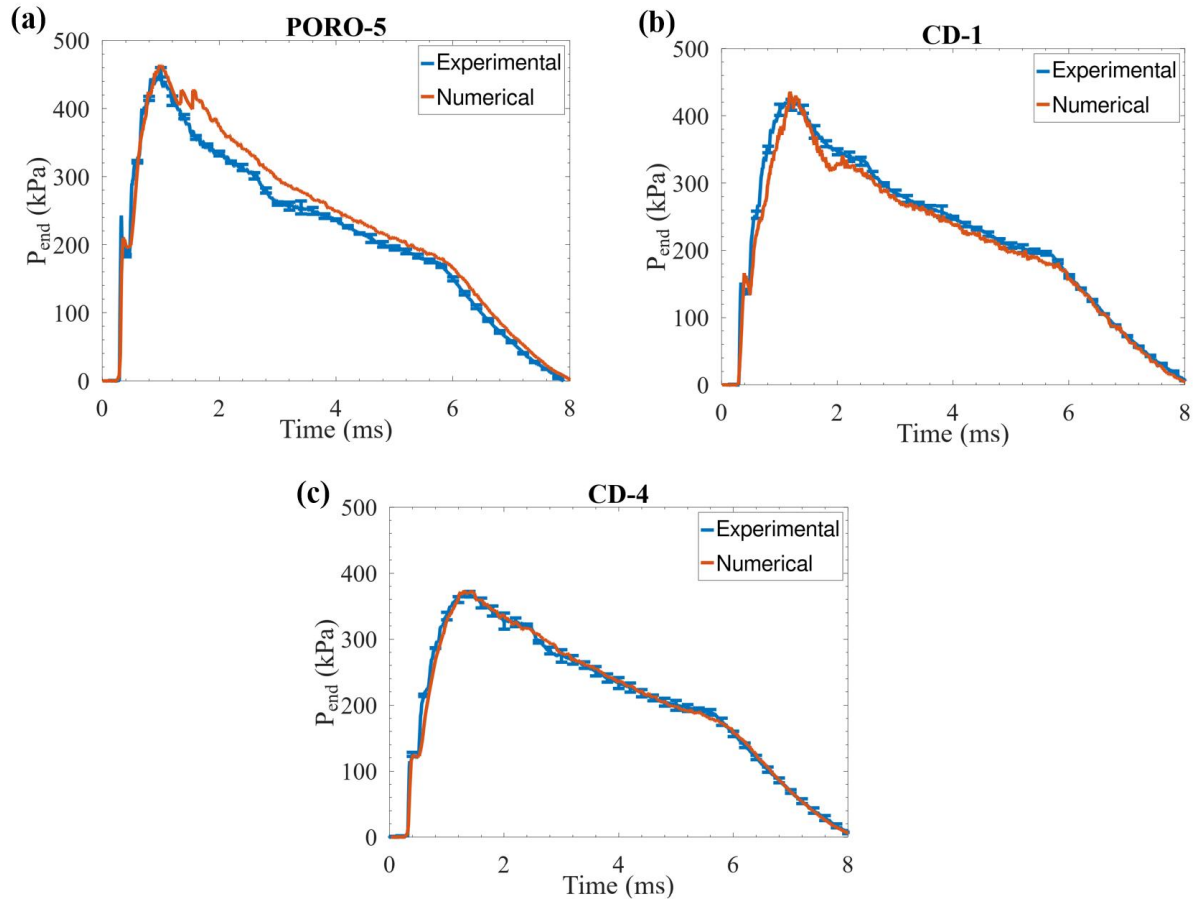


Figure 9. End-wall pressure time history comparison between numerical simulations and experiments for (a) PORO-5 with porosity continuously decreasing, (b) CD-1 with continuously converging orifices, and (c) CD-4 with diverging-converging orifices.

4 RESULTS AND DISCUSSION

The experimental results are presented to establish the baseline shock-wave behavior before evaluating the influence of porous plate array design parameters on attenuation performance. First, the baseline shock evolution is examined by comparing the blank shock tube with uniform-porosity plate arrays to quantify the effects of porosity on pressure attenuation and impulse reduction. Next, the influence of porosity distribution is investigated through arrays with increasing and decreasing porosity gradients while maintaining constant overall geometry. Finally, the effects of orifice geometry are evaluated by comparing converging, diverging, mixed converging–diverging configurations, and the stepped Helmholtz-inspired geometry. This progression isolates the contributions of porosity, porosity grading, and hole geometry to the overall blast mitigation performance of the porous plate arrays.

4.1 BASELINE SHOCK EVOLUTION AND EFFECT OF PLATE ARRAYS ON SHOCK ATTENUATION

Figure 10 presents the experimental end-wall pressure and cumulative impulse histories for the blank shock tube and the four uniformly porous plate arrays. Impulse is defined using the following:

$$I = \int_0^t P_{end}(t) dt \quad (7)$$

Impulse is affected by the properties of the plate array located upstream of the end-wall. The influence of uniform plate porosity on blast attenuation has been investigated previously, primarily for relatively low porosity ranges of approximately 10–30% [16]. In the present work, the baseline investigation is extended to a higher porosity range of 30–60%. These baseline results established a consistent reference for evaluating the effects of graded porosity distributions and alternative hole profiles presented in the following sections.

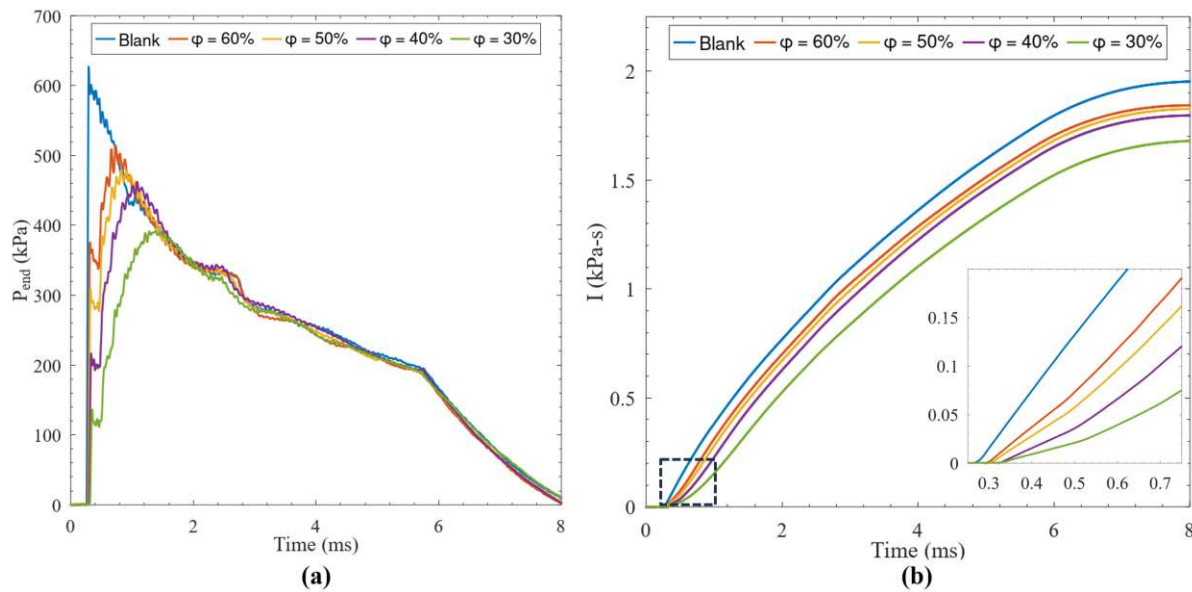


Figure 10. (a) End-wall time history for the uniform porosity arrays, and (b) cumulative impulse.

The cumulative impulse histories in Figure 10 exhibit the same overall trend as pressure histories. All porous plate arrays reduced the end-wall impulse relative to the blank configuration, with the greatest reduction occurring for the 30% porosity array. The cumulative impulse for the blank configuration was 1.95 kPa-s. Inclusion of the $\phi=60\%$ array reduced the impulse to 1.84 kPa-s, (approximately 6%). For the $\phi=30\%$ array, the impulse decreased to 1.68 kPa-s, (approximately 14%). The peak end-wall overpressure was 630 kPa, for the blank configuration. For the $\phi=60\%$ and $\phi=30\%$ arrays, the peak decreased to 515 kPa and 393 kPa, corresponding to reductions of approximately 18% and 38%, respectively. The measured end-wall pressure histories exhibit a slower post-peak decay than an ideal Friedlander waveform due to the sustained after-flow generated by the shock-tube facility. This sustained pressure contributes substantially to the cumulative impulse and may therefore result in smaller apparent impulse reductions than would occur for a more rapidly decaying free-field explosive blast. Accordingly, both peak end-wall pressure and cumulative impulse reductions are reported for all configurations to provide complementary measures of attenuation performance.

In addition to reducing the final impulse, the lower porosity arrays slowed the rate of impulse accumulation, indicating that the transmitted loading was distributed over a longer duration as evidenced in variations in impulse slope in the early time between 0.25 and 0.75 ms. While

higher porosity arrays produced smaller reductions in impulse, they also generated lower flow resistance and pressure losses across the plate array. This tradeoff between blast attenuation and flow restriction provided the motivation for the graded-porosity and alternative hole-profile configurations investigated.

The applied pressure history data for P_{applied} is shown in Figure 11, with the incident pressure equal to ~ 200 kPa for all cases. The blank configuration produced a reflected-pressure maximum of approximately 500 kPa, which arrived later than the reflections generated by the porous plate arrays. This delay occurred because the incident wave first traversed the plate-array region and the remaining standoff distance to the end-wall before reflecting and traveling back to PT1. The initial reflected pressure is shown to be lower for the high porosity cases, with the initial reflected pressure equal to ~ 325 kPa for the $\phi=60\%$ array while it is equal to ~ 450 kPa for the $\phi=30\%$ array. This is consistent with the greater blockage imposed by the lower porosity array and indicates that the lower porosity plate at the front of the array was loaded more heavily than the higher porosity plates.

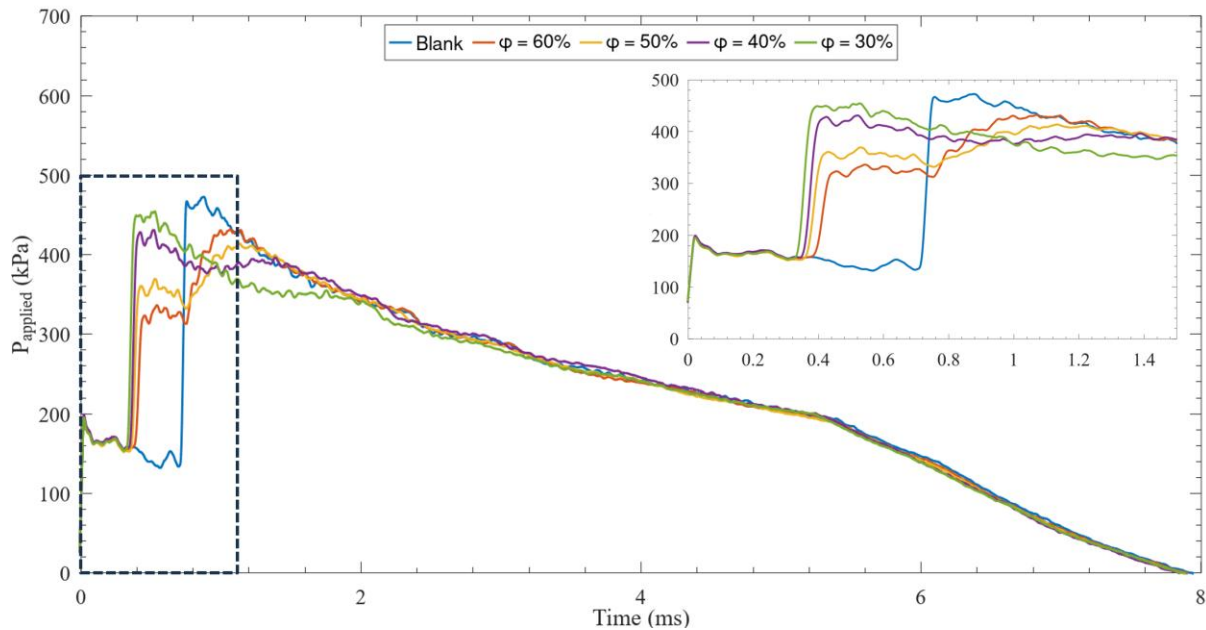


Figure 11. Applied pressure time history data for the uniform porosity plate arrays.

4.2 EFFECT OF POROSITY DISTRIBUTION

Following the evaluation of uniform-porosity arrays, the influence of porosity distribution along the length of the array was investigated. Previous studies have primarily focused on arrays with constant porosity, whereas grading the porosity provides an additional design parameter that may influence shock-wave transmission through successive reflections and localized pressure losses. To isolate the effect of porosity distribution, arrays with increasing and decreasing porosity were examined while maintaining the same overall porosity range and plate spacing as the uniform configurations. The results are compared to determine how the direction of the porosity gradient influences pressure attenuation and impulse reduction.

4.2.1 INCREASING AND DECREASING POROSITY GRADING

Array ID PORO-5 corresponds to the decreasing-porosity arrangement, in which the first plate has 60% porosity and the final plate has 30% porosity. PORO-6 reverses this sequence, placing

the 30% porosity plate first and the 60% porosity plate last. As reported in Figure 12 and Table 5, the maximum end-wall pressure is approximately 450 kPa for PORO-5 and 395 kPa for PORO-6. The peak end-wall pressure reductions were $\sim 28\%$ and $\sim 37\%$, while the reported impulse reductions are 14.1% and 14.4%, respectively. The cumulative-impulse reductions are therefore very similar for the two grading directions and are also close to the 14.0% reduction reported for the uniform 30% porosity array. Within the configurations tested, these data indicate that grading direction has a much stronger influence on peak end-wall pressure than on cumulative impulse. The similarity in impulse reduction to the uniform 30% case is consistent with an important role for the lowest-porosity plate, but the present data do not by themselves establish that minimum porosity uniquely governs impulse attenuation.

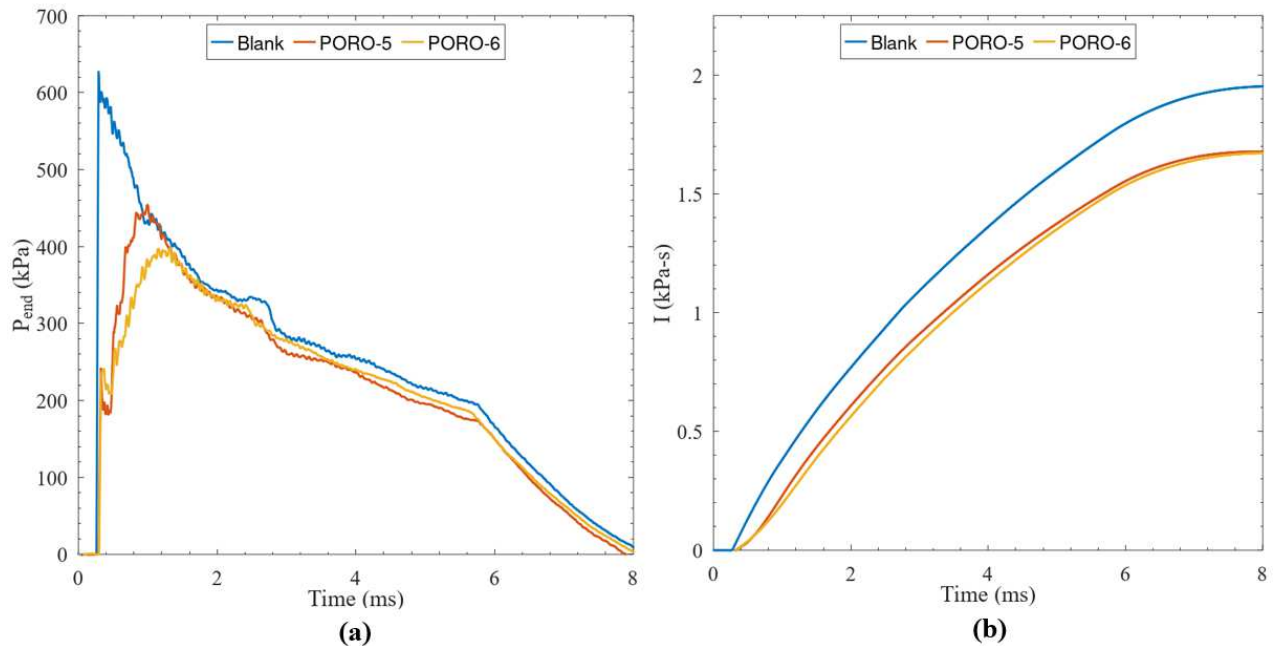


Figure 12. (a) End-wall pressure time history for the porosity graded arrays, and (b) cumulative impulse for the same arrangements.

Numerical schlieren contours for the PORO-5 and PORO-6 arrays are shown in Figure 13 and Figure 14. The dimensionless schlieren intensity is displayed over a range of 0 to 3.4, with increasing values indicating stronger density gradients associated with shock waves and other compressible-flow structures. In both figures, $t=0$ corresponds to the arrival of the incident shock (IS) at the first plate, with the shock propagating from left to right toward the end-wall. At $t=9 \mu\text{s}$, the incident shock has traversed the first plate, and the primary reflected shock (RS) is generated, propagating upstream toward the driver section. The increasing-porosity arrangement produces a stronger, more planar RS, whereas the decreasing-porosity arrangement exhibits greater shock curvature as the wave reflects from the individual plate blockages. The stronger initial reflection in PORO-6 limits the energy transmitted into the remainder of the array, resulting in weaker downstream wave propagation and a lower peak end-wall pressure compared with PORO-5. In contrast, the higher initial porosity of PORO-5 permits a stronger transmitted shock to enter the array before encountering progressively lower-porosity plates. As the porosity decreases through PORO-5, the increasing solid area of each successive plate causes a greater portion of the transmitted wavefront to reflect from the plate surface, produc-

ing the localized reflected-wave structures visible in the schlieren contours. These results indicate that placing the greatest flow restriction upstream, where the incident shock is strongest, is more effective at reducing peak end-wall pressure than introducing the same reduction in porosity progressively downstream.

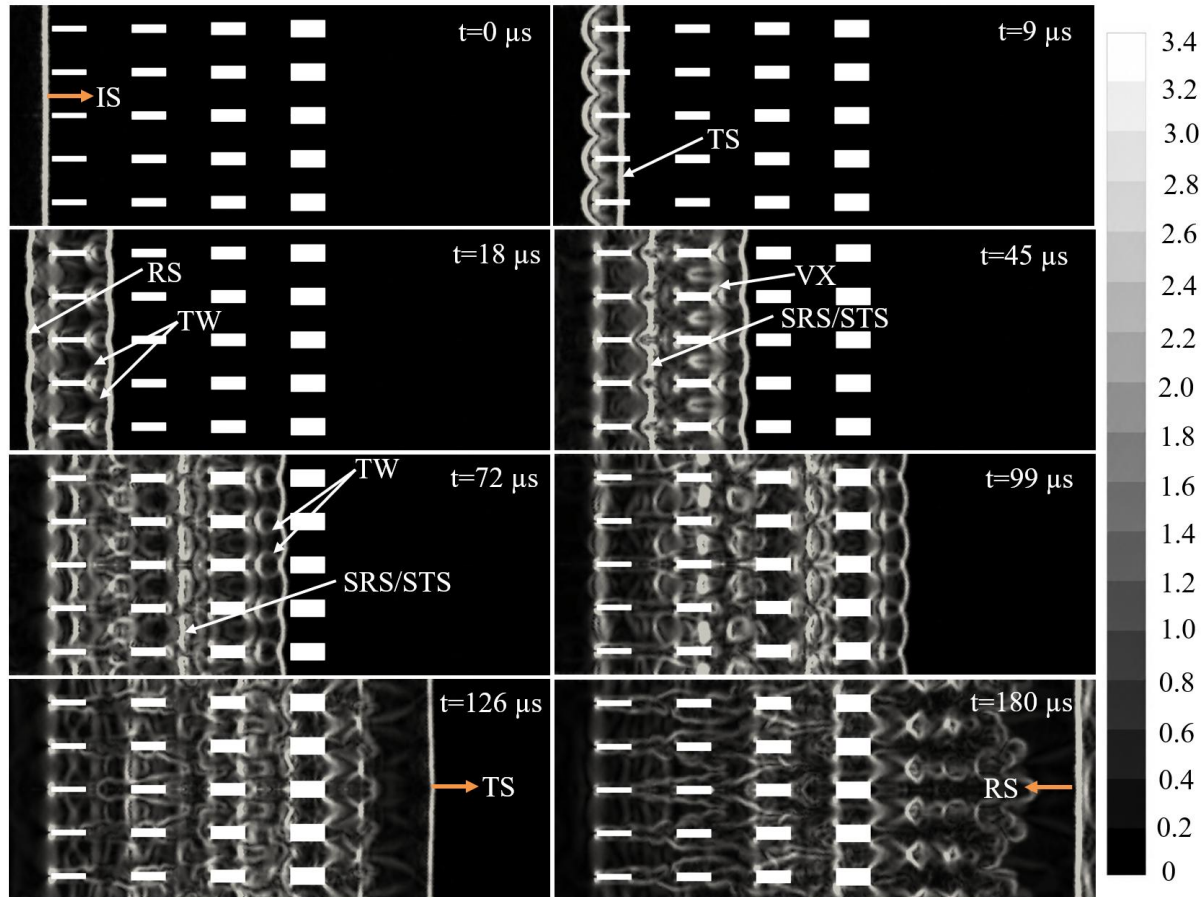


Figure 13. Numerical Schlieren contour plots for the PORO-5 arrangement of decreasing-porosity plate arrays.

Following transmission through the first plate, the transmitted shock (TS) exits the orifices and diffracts into the inter-plate region. The resulting transmitted wavefront becomes increasingly convex as it emerges from the lower-porosity plates because the smaller orifices increase lateral expansion of the jet exiting each plate before adjacent jets merge into a continuous wavefront. Consequently, the initial transmitted shock in PORO-6 exhibits greater curvature than that in PORO-5. Expansion of the transmitted wave upon exiting each plate also generates transverse wave structures (TW) and shear-layer roll-up, producing vortex structures (VX) downstream of the sharp orifice exits. As the transmitted shock progresses through the array, the vortex structures become progressively more pronounced in PORO-5 as the porosity decreases from plate to plate, whereas their relative strength diminishes in PORO-6 as the porosity increases.

At $t=45 \mu\text{s}$, the primary transmitted shock is located between the second and third plates. Between the first and second plates the secondary reflected shock (SRS) and secondary transmitted shock (STS) make contact, forming localized regions of high-density gradient associated

with repeated wave interactions. These collisions redistribute the transmitted wave energy between reflected and transmitted components and contribute to the progressive modification of the shock structure as it traverses the array. As the primary transmitted shock propagates through the array, a similar collision between the SRS and STS forms successively between each pair of plates, producing a repeating pattern of planar structures resulting from these shock interactions throughout the array. At $t=126\text{ }\mu\text{s}$, the individual transmitted shocks have merged into a single coalesced wavefront. Once the transmitted shocks coalesce into a single wavefront, the differences introduced by the individual plate interactions become less distinct. Consequently, although the early-time shock evolution differs considerably between PORO-5 and PORO-6, the later-stage propagation is comparatively similar, contributing to the nearly identical cumulative impulse measured at the end-wall. The transmitted shock in PORO-5 is located slightly farther downstream than in PORO-6, consistent with the slightly greater cumulative impulse measured for the decreasing-porosity configuration. At $t=180\text{ }\mu\text{s}$, the transmitted shock has reflected from the end-wall, generating a reflected shock with greater magnitude than the transmitted wave.

The schlieren visualizations show that the two grading directions produce different early-time wave-interaction patterns. In PORO-5, progressively smaller downstream openings are accompanied by repeated reflections and secondary transmitted structures throughout the array. In PORO-6, the lowest-porosity plate is encountered first and produces the strongest initial reflection, after which the downstream plates have progressively greater open area. These observations provide a physically consistent explanation for the lower peak end-wall pressure of PORO-6, but the schlieren fields alone do not uniquely quantify the contribution of each interaction to the final impulse.

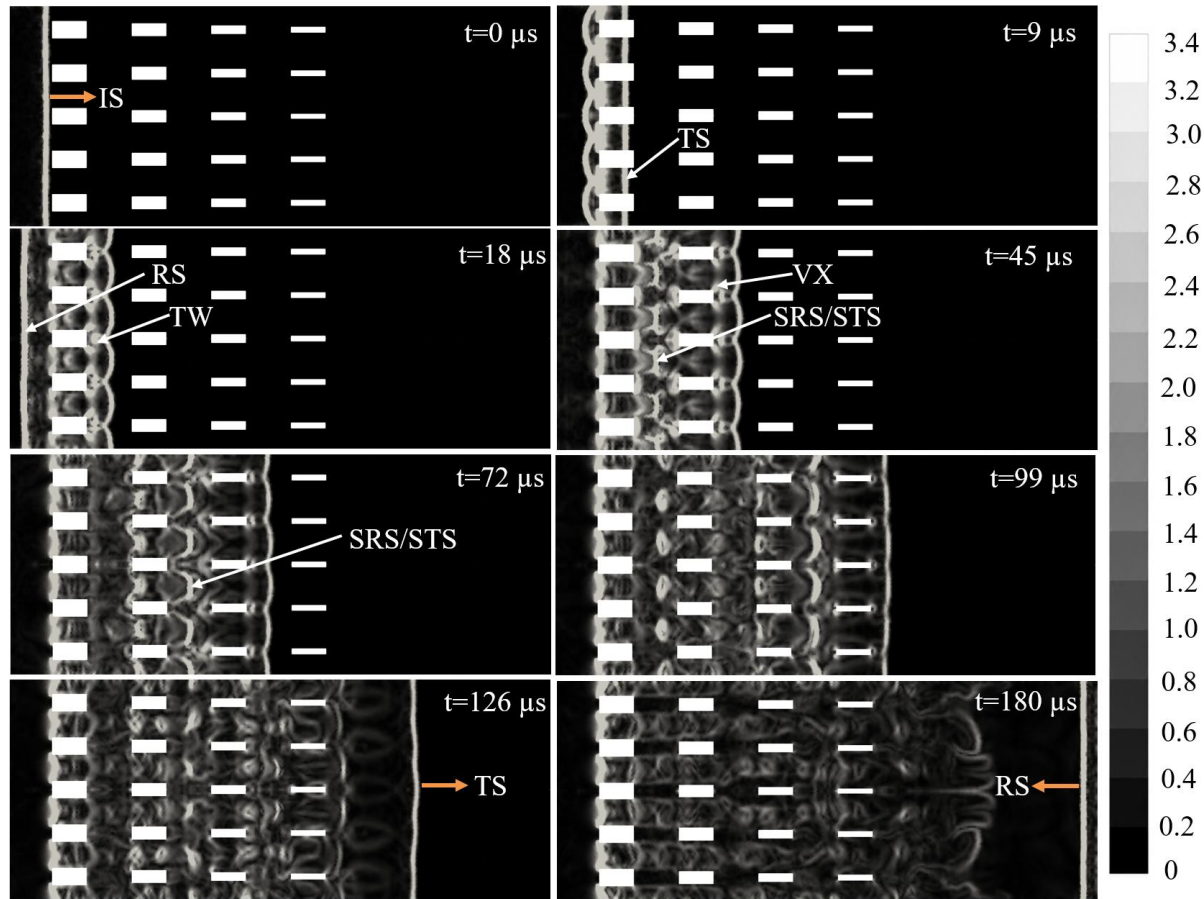


Figure 14. Numerical Schlieren contour plots for the PORO-6 arrangement of decreasing-porosity plate arrays.

4.3 EFFECT OF ORIFICE GEOMETRY

The second series of configurations examined the influence of internal orifice geometry on transmitted loading while maintaining the same plate count, plate thickness, and inter-plate spacing. In the preceding porosity study, cylindrical orifice diameters of 4.5 and 6.5 mm corresponded to uniform plate porosities of 30% and 60%, respectively. For the shaped orifices, the local open-area ratio varies through the plate thickness and is therefore described by its progression from the upstream to downstream face rather than by a single porosity value. The converging and diverging orifices transition continuously from 60% to 30% and 30% to 60%, respectively. The converging-diverging orifice transitions from 60% at the inlet to a 30% throat at the plate mid-plane and back to 60% at the outlet, while the diverging-converging geometry follows the opposite 30%–60%–30% progression. The stepped expansion-chamber geometry also follows a 30%–60%–30% progression, with 4.5 mm inlet and outlet sections separated by a 6.5 mm constant-diameter expansion chamber. Thus, the shaped configurations use the same characteristic open-area ratios as the straight-orifice plates while varying their axial distribution through the plate thickness. The comparisons below therefore focus on the measured performance of the specified geometries without assuming that taper effects are isolated from every other local area-distribution effect.

4.3.1 CONVERGING AND DIVERGING

Continuously converging and diverging orifices (CD-1 and CD-2) were compared to determine how reversing the taper changes transmitted loading and wave evolution. The two profiles use

the same pair of limiting diameters but reverse their orientation relative to the incident shock: CD-1 contracts from the larger inlet toward the smaller outlet, whereas CD-2 expands from the smaller inlet toward the larger outlet. Accordingly, this comparison captures the combined effect of taper orientation, entrance/exit area distribution, and the resulting internal shock evolution; it does not isolate taper direction alone. The subsequent CD-3, CD-4, and HELM-1 comparisons provide additional evidence for distinguishing entrance-area effects from the influence of the internal passage profile.

Figure 15 compares the end-wall pressure histories and cumulative impulses for the converging (CD-1) and diverging (CD-2) configurations. Peak end-wall pressures of approximately 422 kPa and 330 kPa were measured for CD-1 and CD-2, respectively. The corresponding cumulative impulses were 1.73 and 1.54 kPa-s, representing reductions of 11.1% and 21.2% relative to the blank configuration. Additionally, a reduction in peak end-wall pressure of ~33% and ~48% was observed for the CD-1 and CD-2 cases. The superior attenuation observed for the diverging configuration suggests that taper direction alters how the transmitted shock interacts with subsequent plates.

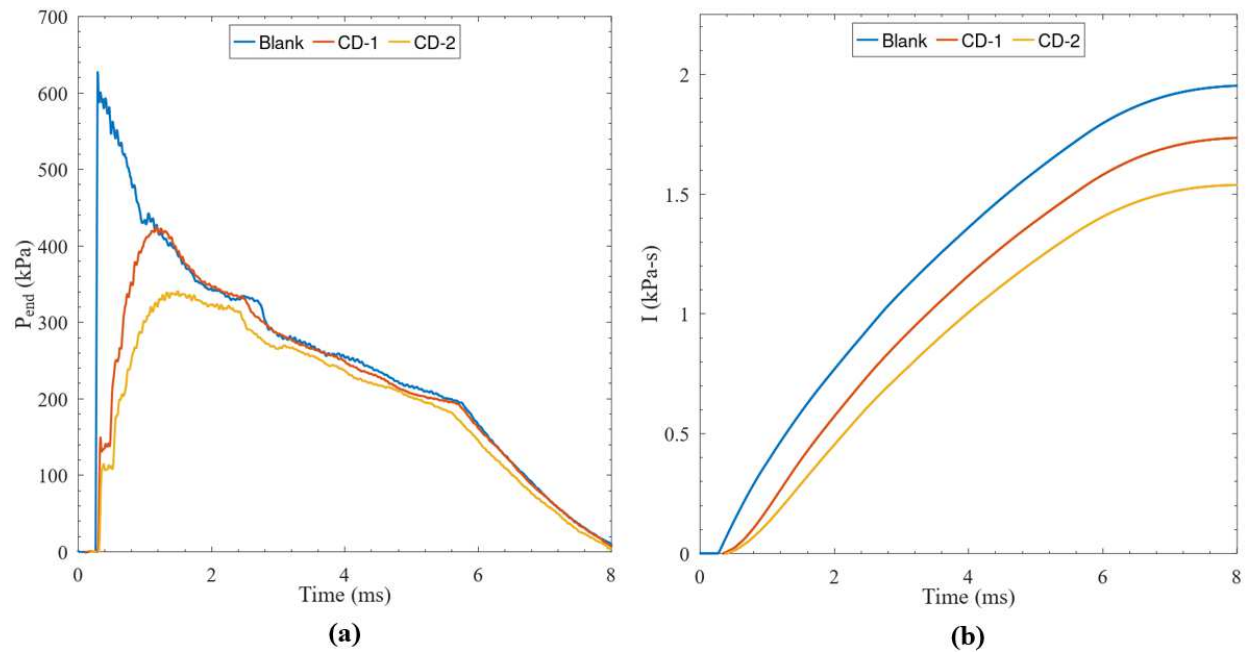


Figure 15. (a) End-wall pressure time history for the continuously converging (CD-1) and diverging (CD-2) arrays, and (b) cumulative impulse for the same arrangements.

Figure 16 and Figure 17 provide numerical schlieren contours for the converging (CD-1) and diverging (CD-2) plate arrays over the first 180 μ s. Like the porosity graded arrays, the incident shock reaches the first plate at $t=0$ μ s.

At $t=18$ μ s, the reflected shock is visible propagating upstream from the first plate in both arrays. Distinct differences in the internal flow structure are also evident. For CD-1, localized regions of high density-gradient magnitude emerge immediately downstream of the plate exit, forming a narrow central jet (JT) bounded by regions of rapid lateral expansion (EX) and transverse flow. In contrast, CD-2 exhibits no distinct jet immediately downstream of the orifice.

Instead, the region of maximum density-gradient magnitude remains within the diverging passage while the transmitted shock expands smoothly as it exits the orifice into the inter-plate region.

SRS and STS waves are observed between the first and second plates for both geometries at $t=45\ \mu\text{s}$. Upon intersecting near the centerline, they merge to form high density-gradient structures. This process repeats throughout the array and is clearly visible at $t=72\ \mu\text{s}$ and $t=99\ \mu\text{s}$. In CD-1, the STS precedes the SRS prior to collision, and the resulting merged structure is predominantly planar. Conversely, the interaction in CD-2 produces a convex reflected structure, indicating that the orientation of the tapered orifice substantially alters the evolution of these secondary wave interactions.

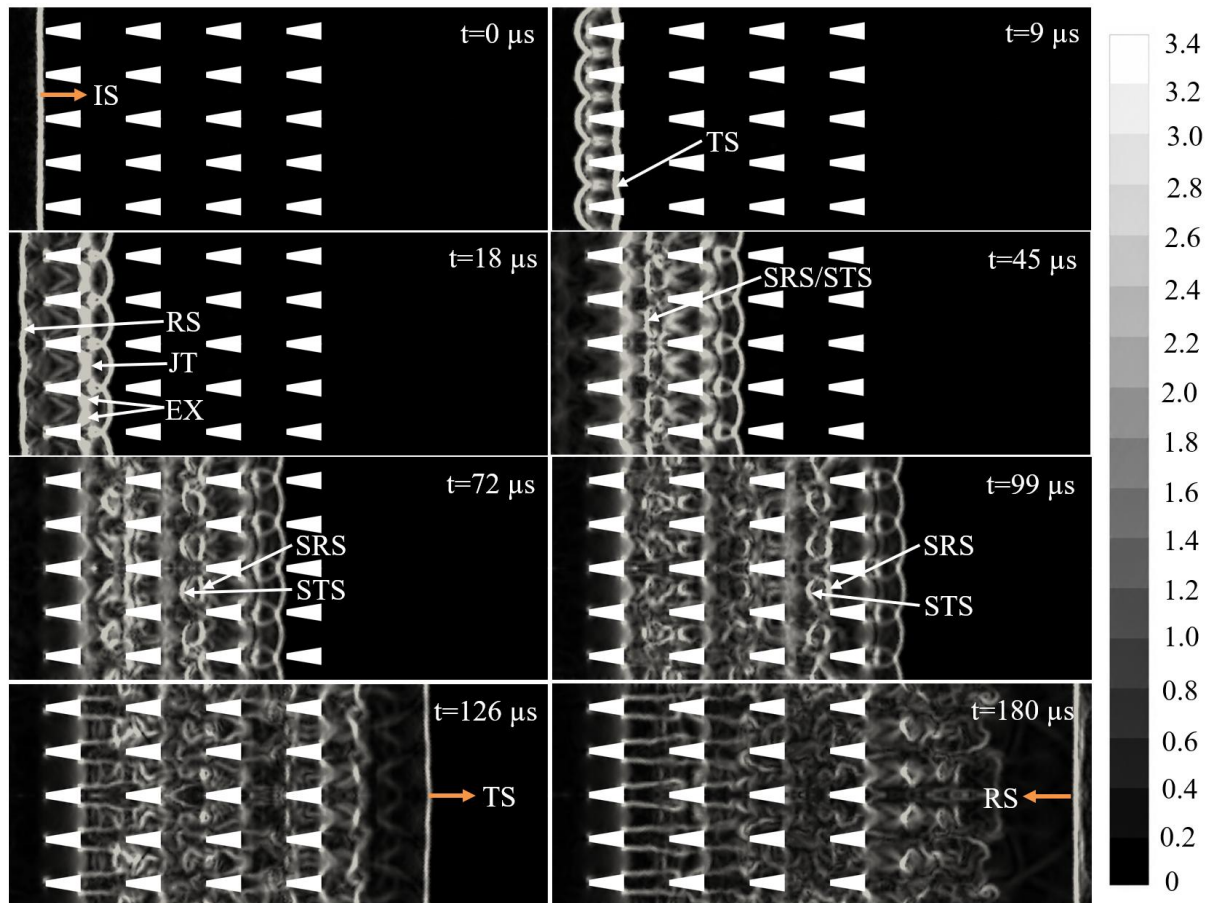


Figure 16. Numerical Schlieren contour plots for the CD-1 arrangement of continuously converging plate arrays.

A persistent region of elevated density-gradient magnitude remains immediately upstream of the first plate in CD-1 throughout and is still visible at $t=180\ \mu\text{s}$. This stationary compression region is attributed to the converging entrance geometry, where the smaller inlet diameter continuously impedes the incoming flow and maintains a localized compression region upstream of the plate.

At $t=126 \mu\text{s}$, the individual transmitted shocks have merged to form a single coalesced transmitted shock in both configurations. However, the transmitted shock in CD-2 lags noticeably behind that of CD-1. By $t=180 \mu\text{s}$, the transmitted shock in CD-1 has already been reflected from the end-wall and begun propagating upstream, whereas the transmitted shock in CD-2 has not yet reached the end-wall. This difference in arrival time demonstrates that the continuously diverging orifices reduce transmitted shock propagation velocity, consistent with the lower end-wall pressures and impulse measured experimentally.

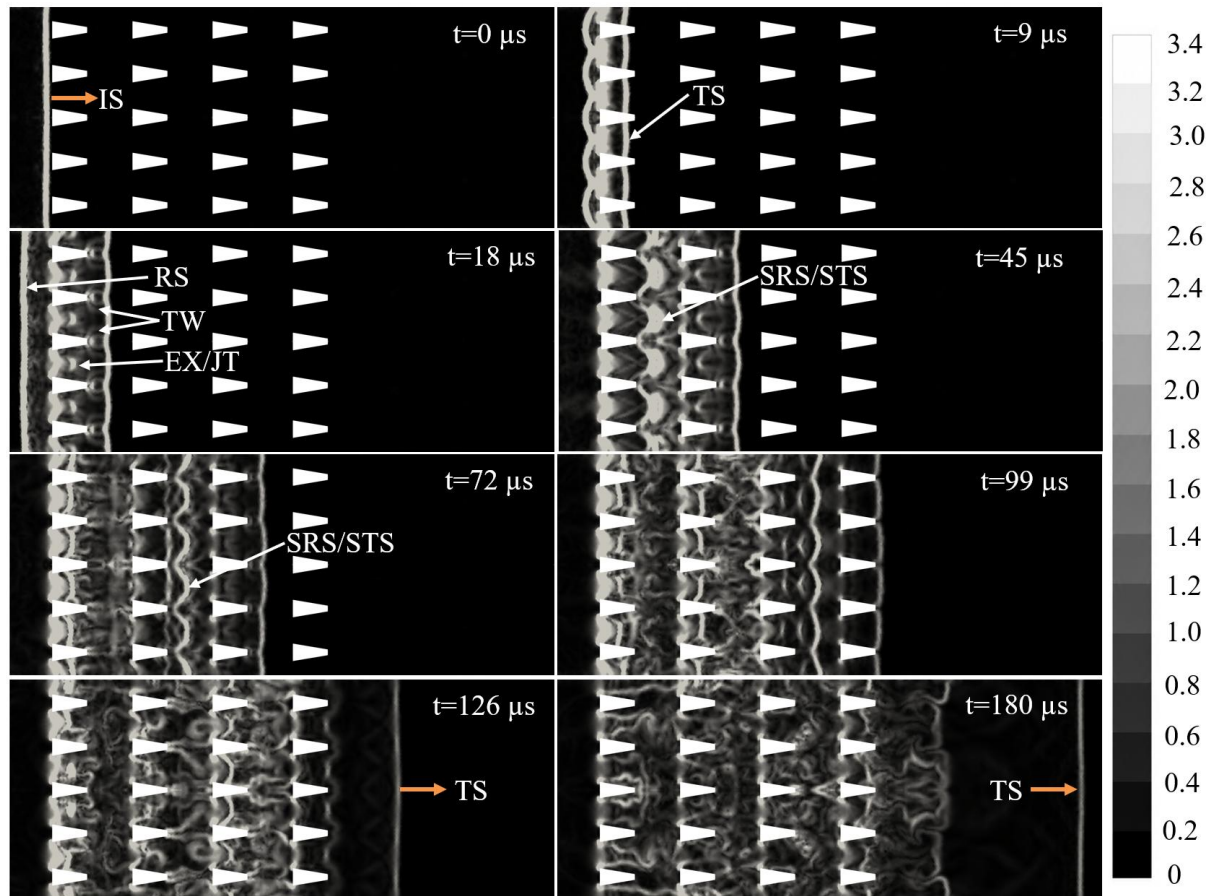


Figure 17. Numerical Schlieren contour plots for the CD-2 arrangement of continuously diverging plate arrays.

Figure 18 and Figure 19 present enlarged numerical schlieren contours of the first plate for the CD-1 and CD-2 geometries. The enlarged views and smaller time steps isolate the wave interactions responsible for the differing attenuation mechanisms observed throughout the plate array. At $t=6 \mu\text{s}$, the reflected shock is much stronger for CD-2. Vortex structure formation is also seen at the orifice entrance for both cases, although these structures are stronger for CD-2. For CD-1 the weaker reflected shock has significant transverse velocity inside the orifice, behind the transmitted wave. Because the entrance diameter is larger for this case, adjacent RS waves do not make contact until $t=9 \mu\text{s}$. At this point in time, the initial regular reflection (RR) has become a Mach reflection (MR) and a triple-point (TP) forms where the two RS and single TS waves meet near the outlet of the orifice. Conversely, for the diverging orifices the smaller entrance diameter results in the transverse components of the RS making contact earlier and a high-density gradient region is present at the orifice entrance at $t=9 \mu\text{s}$.

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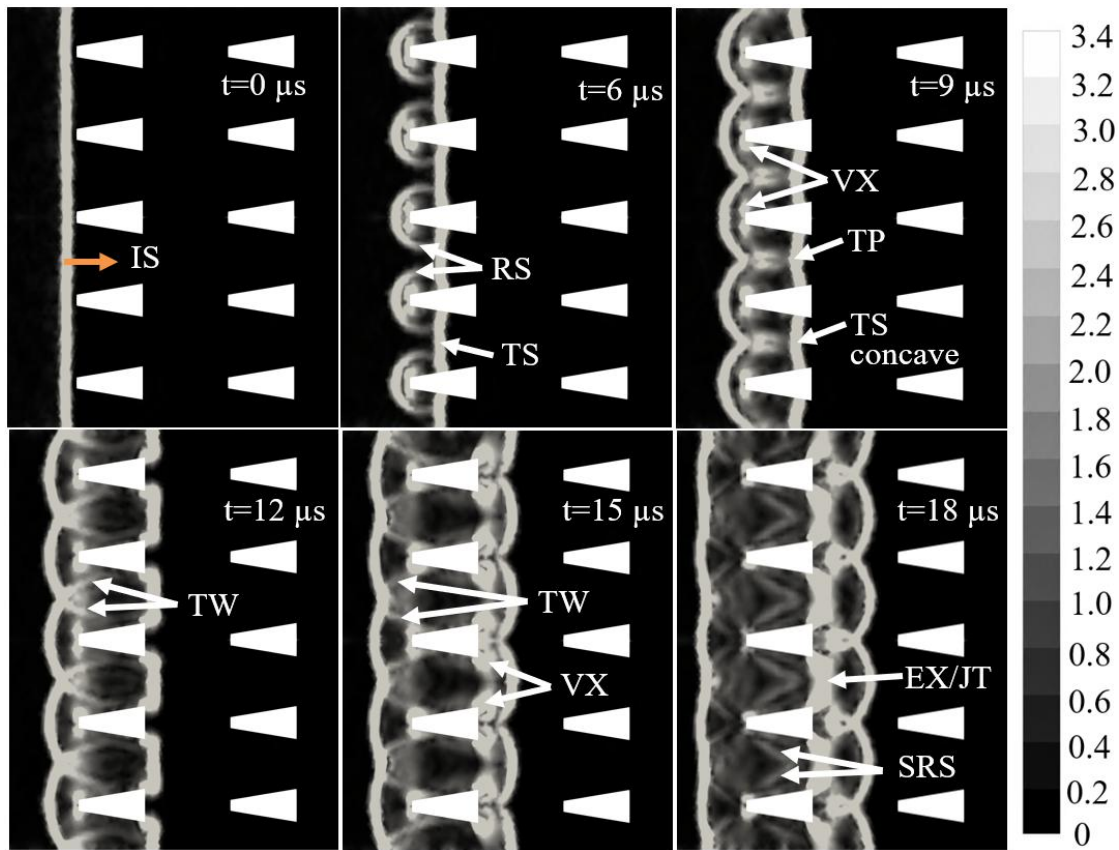
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Figure 18. Numerical Schlieren images focusing on shock interaction with the first plate array for the CD-1 arrangement of continuously converging plate array.

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Between $t = 12 \mu\text{s}$ and $t = 18 \mu\text{s}$, the transmitted shock evolves differently in CD-1 and CD-2. In CD-1, strong jetting persists downstream of the plate, with concentrated shear-layer and vortex structures near the orifice exit and a high-density-gradient region associated with rapid transverse expansion and axial jetting behind the leading transmitted shock. In CD-2, a similarly concentrated downstream jet is not apparent at the exit; instead, the transmitted structure expands through the diverging passage, and a secondary transmitted shock develops behind the leading front. Taken together with the measured reductions in peak pressure and impulse, these fields are consistent with the hypothesis that the smoother expansion in CD-2 changes how the transmitted wave encounters the next plate and increases subsequent reflection. The present schlieren fields support this interpretation qualitatively, but they do not independently quantify the partition of wave energy between reflection, transmission, and vortical motion.

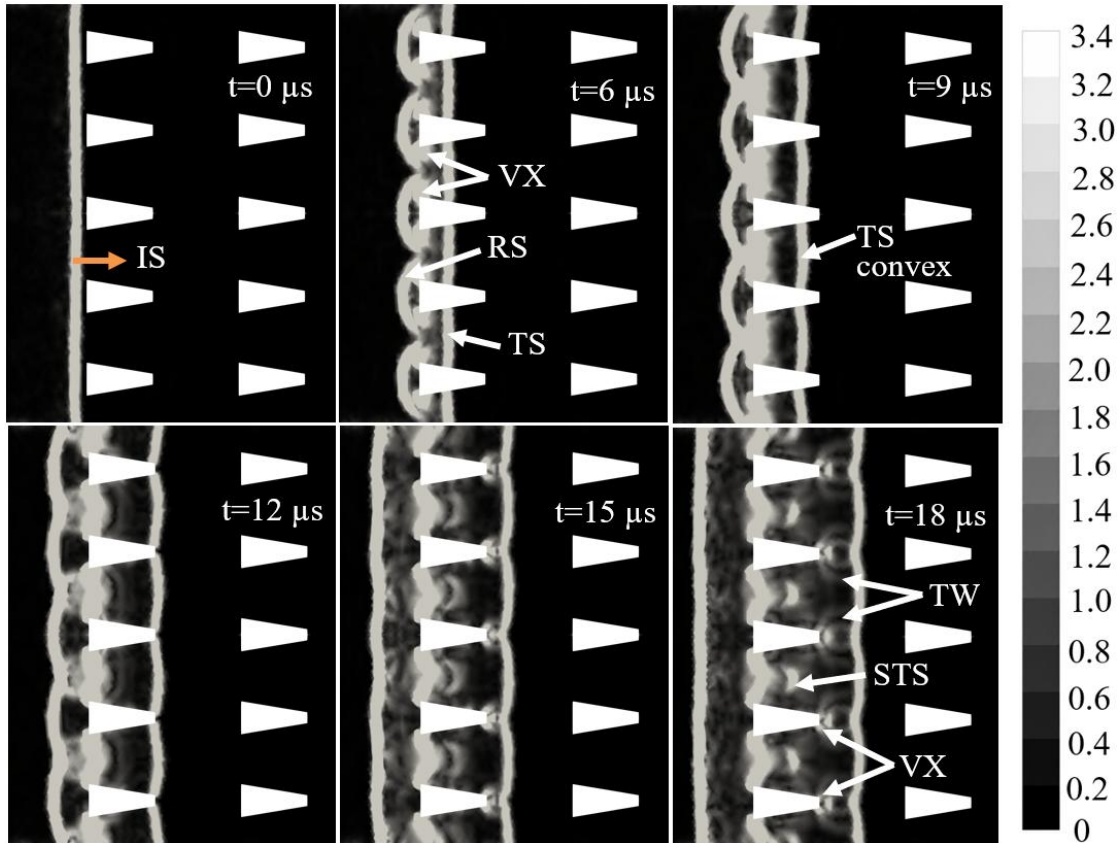


Figure 19. Numerical Schlieren images focusing on shock interaction with the first plate array for the CD-2 arrangement of continuously diverging plate array.

4.3.2 MIXED CONVERGING, DIVERGING, AND STEPPED EXPANSION-CONTRACTION

The substantially greater attenuation observed for the continuously diverging orifices raises the question of whether its improved performance results primarily from the smaller entrance diameter presented to the incident and transmitted shock or from the wave evolution produced within the diverging passage. Although the numerical schlieren contours indicate that taper direction alters the transmitted shock structure and subsequent wave interactions, the continuously converging and diverging geometries also present different diameters to the incident shock at the plate entrance and to the transmitted shock at the plate exit. Consequently, the relative influence of the entrance condition and the internal passage geometry cannot be isolated from the CD-1 and CD-2 comparison alone.

To further assess these effects, three additional orifice geometries were investigated: a converging-diverging profile (CD-3), a diverging-converging profile (CD-4), and a stepped expansion-contraction profile (HELM-1). Each configuration incorporates both an expansion and a contraction within a single orifice while maintaining constant plate porosity and minimum throat diameter. Comparisons among these geometries and the continuously tapered configurations therefore provide additional insight into the relative effects of entrance diameter, taper sequence, and internal wave evolution.

Like the continuously converging and diverging arrangements, CD-3, CD-4, and HELM-1 reduced both the maximum end-wall pressure and cumulative impulse relative to the blank configuration. As shown in Figure 20, the peak end-wall pressure decreased to 381 kPa for CD-3, 371 kPa for CD-4, and 349 kPa for HELM-1, corresponding to reductions of 39%, 41%, and 44%, respectively. The cumulative impulses were 1.61 kPa-s for both CD-3 and CD-4 and 1.59 kPa-s for HELM-1, corresponding to reductions of 17.4%, 17.4%, and 18.6%, respectively.

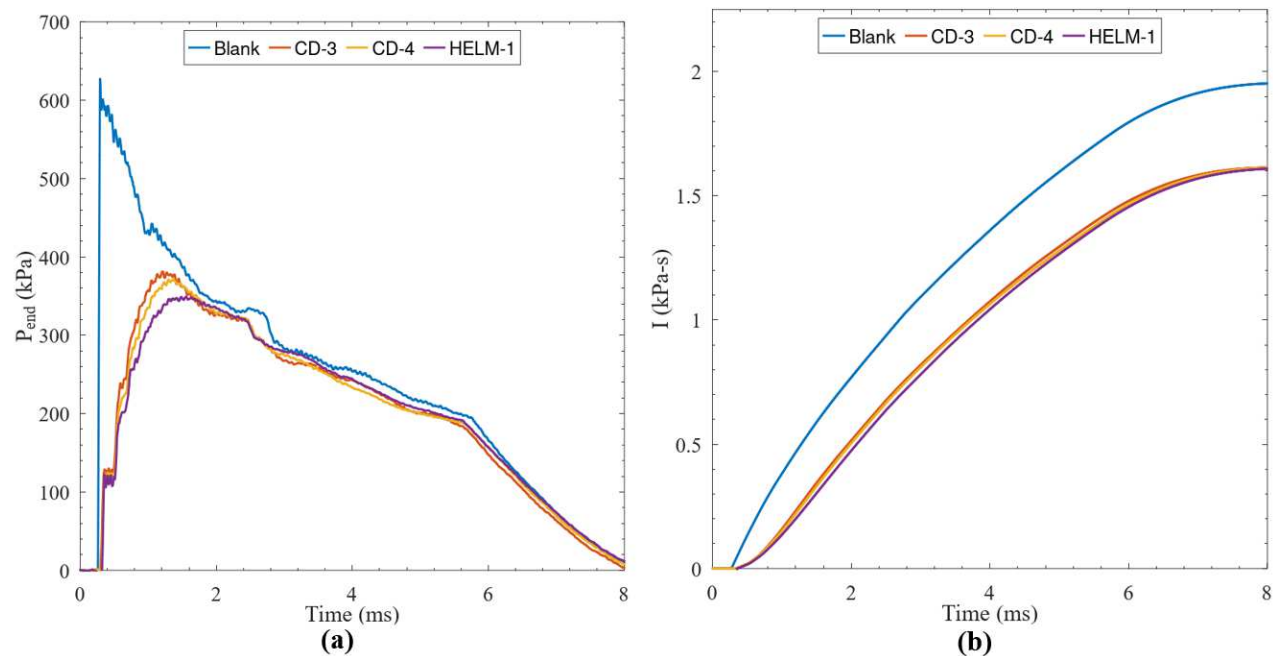


Figure 20. (a) End-wall pressure time history for the converging-diverging (CD-3), diverging-converging (CD-4), and stepped expansion-contraction (HELM-1), (b) cumulative impulse for the same arrangements.

Focused numerical schlieren contours were examined over the first 18 μs following arrival of the incident shock at the first plate. These images isolate the early wave interactions occurring within and immediately downstream of the shaped orifices. Schlieren contours up to end-wall reflection are not shown for these cases as trends and observations generally follow trends identified in the converging and diverging orifice figures.

For CD-3, shown Figure 21, the relatively large entrance diameter allows the incident shock to penetrate farther into the orifice while generating a reflected shock with a substantial transverse component. The transverse portions of the reflected shocks trail the transmitted shock and propagate toward the solid regions separating adjacent orifices. By $t=9 \mu\text{s}$, RS fronts traveling predominantly in the transverse direction interact, producing a Mach-reflection structure and an associated triple point. Pronounced vortical structures are also visible at $t=9 \mu\text{s}$ near the axial midpoint of the plate, corresponding to the transition from the converging to the diverging portion of the orifice. At the same time, the transmitted shock begins to expand through the diverging section, while a narrow axial jet develops near the orifice exit. This combination of wave expansion and jetting produces a strongly nonplanar transmitted front.

At $t=12\ \mu\text{s}$, a transverse SRS wave becomes visible within the converging portion of the passage. The SRS subsequently propagates upstream and begins to emerge from the entrance of the orifice at $t=15\ \mu\text{s}$ and $t=18\ \mu\text{s}$. Strong axial jetting remains evident at these later times near the converging-diverging transition. Downstream of this transition, a convex secondary transmitted shock forms behind the leading TS and propagates toward the plate exit.

After emerging from the plate, the individual transmitted shocks produced by adjacent orifices expand laterally and begin to coalesce. Transverse wave structures trail the coalescing TS, particularly in the wakes of the solid ligaments separating neighboring orifices. Thus, the CD-3 response is characterized by an early transverse reflected-shock interaction, internal vortex formation at the minimum-area location, sustained axial jetting, and the development of a distinct convex STS behind the primary transmitted front.

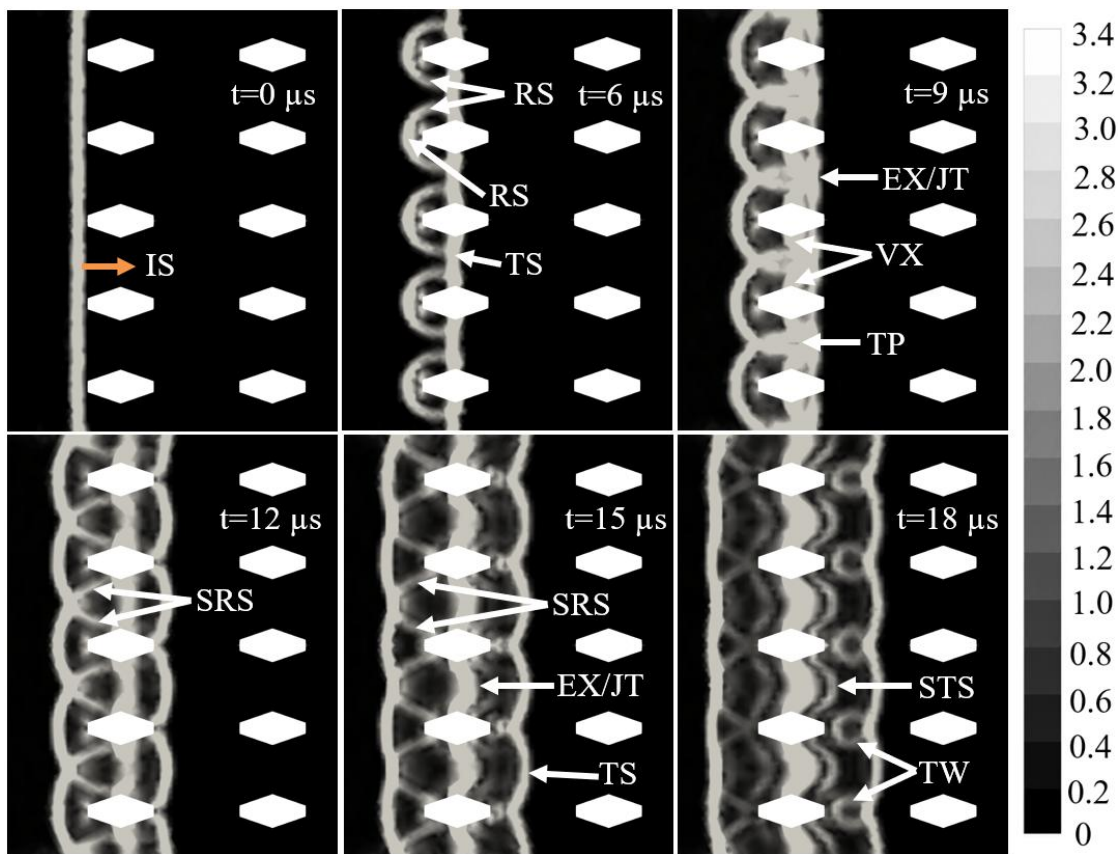


Figure 21. Numerical Schlieren images focusing on shock interaction with the first plate array for the CD-3 arrangement of the converging-diverging plate array.

Numerical schlieren images for the diverging-converging plate array are shown in Figure 22. The smaller entrance diameter of CD-4 produces a more rapid interaction between the transverse portions of the reflected shocks. These fronts have already interacted by $t=6\ \mu\text{s}$, earlier than observed for CD-3. Vortical structures form near the inlet of the diverging section and are particularly apparent at $t=9\ \mu\text{s}$. These structures are stronger and more concentrated than those observed near the entrance of CD-3.

The primary transmitted shock progresses through the passage and reaches the plate exit by approximately $t=12 \mu\text{s}$. It is followed by reflected compression waves generated as the expanding flow encounters the downstream converging section. These reflected waves possess transverse components directed toward the orifice centerline, resulting in recompression of the flow downstream of the diverging–converging transition.

Additional vortical structures develop near the orifice exit and are visible at $t=12 \mu\text{s}$ and $15 \mu\text{s}$. The primary TS emerges from the plate at $t=15 \mu\text{s}$, and by $t=18 \mu\text{s}$ it has separated from the trailing vortical region. A secondary transmitted shock forms immediately downstream of the diverging–converging transition and remains behind the primary TS. This STS is bordered on its upstream side by weak-gradient regions associated with transverse wave motion and the recompressing internal flow.

Compared with CD-3, the CD-4 geometry therefore produces earlier interaction of the reflected-shock fronts, stronger inlet vortices, and a secondary transmitted shock associated primarily with recompression in the converging section rather than expansion downstream of a throat.

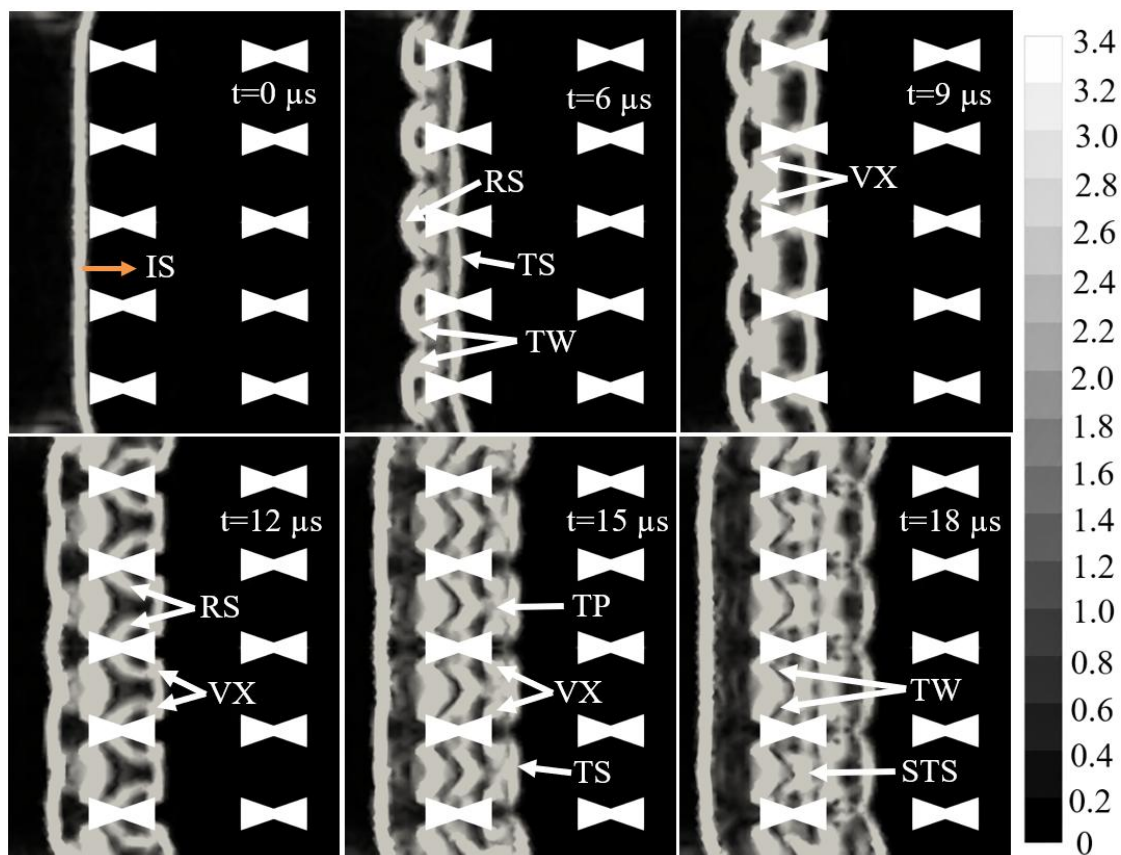


Figure 22. Numerical Schlieren images focusing on shock interaction with the first plate array for the CD-4 arrangement of the diverging-converging plate array.

For HELM-1, the numerical Schlieren images, shown in Figure 23 indicate that the transmitted shock has entered the expanded chamber by $t=6 \mu\text{s}$. Strong transverse flow develops throughout this region as the shock diffracts past the entrance shoulders and expands into the enlarged section. Vortical structures are visible near the chamber inlet at $t=9 \mu\text{s}$, resembling those produced near the entrance of the CD-4 passage. The TS front has reached the downstream end of the expansion chamber by $t=12 \mu\text{s}$. Interaction with the stepped contraction generates a visible secondary reflected shock that propagates back into the chamber. At $t=15 \mu\text{s}$, expansion from the upper and lower chamber shoulders, combined with axial jetting through the center of the contraction, produces a pronounced V-shaped region of high density-gradient magnitude. An SRS wave also becomes visible near the orifice centerline immediately upstream of the exit at this timestep. The shoulders of the enlarged chamber appear to generate approximately planar SRS fronts. These structures become increasingly obscured after $t=15 \mu\text{s}$, however, by the complex afterflow, axial jet, and developing STS.

Replacing the continuous converging section of CD-4 with the stepped contraction of HELM-1 changes the local reflected-wave structure but does not produce a large qualitative change in the dominant first-plate interactions visible over the first $18 \mu\text{s}$. Experimentally, HELM-1 nevertheless produces greater peak-pressure and impulse attenuation than CD-3 and CD-4. The approximately planar reflected structures generated near the downstream end of the expansion chamber may contribute to this difference, but the present schlieren contours do not isolate their contribution quantitatively. Accordingly, the HELM-1 result is treated as an observed performance difference accompanied by a plausible wave-structure interpretation rather than as proof of a single dominant attenuation mechanism.

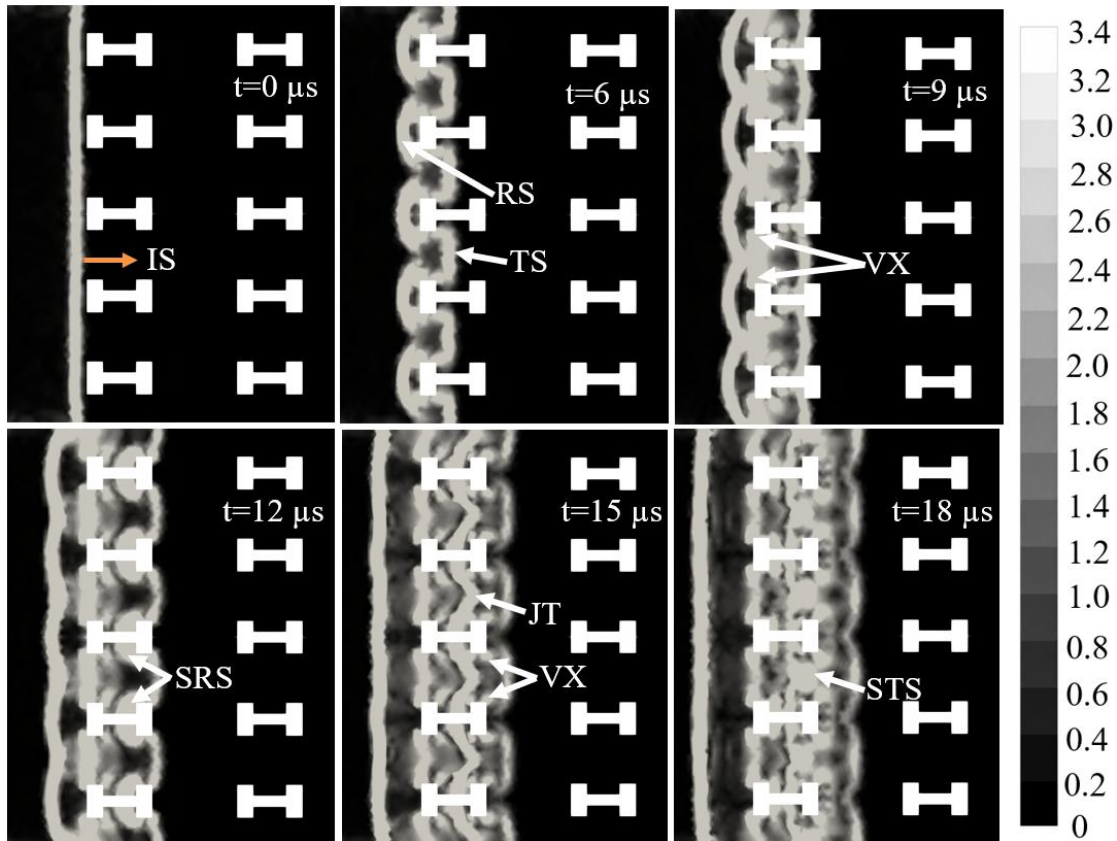


Figure 23. Numerical Schlieren images focusing on shock interaction with the first plate array for the HELM-1 arrangement of the stepped contraction-expansion plate array.

The mixed and stepped geometries provide additional insight into the attenuation mechanism responsible for the superior performance of the continuously diverging orifice. Although CD-4 and HELM-1 both retain the small entrance diameter of CD-2, neither reproduces the same reduction in peak pressure or cumulative impulse. Likewise, introducing a downstream diverging section in CD-3 improves attenuation relative to the continuously converging geometry, but still falls short of the continuously diverging configuration. These results indicate that the improved performance of CD-2 cannot be attributed solely to entrance diameter or the presence of local expansion within the passage.

Instead, the schlieren contours suggest that the continuous divergence throughout the full plate thickness produces a fundamentally different wave evolution. In CD-2, the transmitted shock undergoes a gradual and nearly continuous lateral expansion as it traverses the orifice, producing a relatively planar transmitted front at the plate exit with minimally concentrated axial jetting. In contrast, CD-3 exhibits strong jetting originating near the converging-diverging transition, while CD-4 and HELM-1 generate recompression within the downstream converging or stepped contraction. These localized acceleration and recompression regions promote vortex formation, secondary shock generation, and increased flow non-uniformity before the transmitted shock exits the plate.

Consequently, the transmitted wavefields emerging from CD-3, CD-4, and HELM-1 are more spatially nonuniform in the reported schlieren contours than the field emerging from CD-2. These configurations also provide less measured attenuation than CD-2. The combined observations support an association between the comparatively smooth, continuously diverging passage and improved attenuation in the present array geometry. They do not, however, establish a unique causal pathway; confirming the relative roles of reflection, jet alignment, secondary-shock generation, and vortical motion would require additional quantitative flow diagnostics such as pressure, velocity, Mach-number, or flux-based comparisons.

4.4 OVERALL ATTENUATION COMPARISON

Table 5 summarizes the measured attenuation performance of all porous plate arrays investigated in the present study. The comparison includes the peak end-wall pressure, cumulative impulse, and the corresponding reductions relative to the blank configuration. The table provides a direct comparison of the effects of porosity, porosity grading, and internal orifice geometry on blast-wave attenuation.

Array ID	Description	Peak P_{end} (kPa)	Peak P_{end} Reduction (%)	Impulse (kPa-s)	Impulse Reduction (%)
Blank	No array	630	—	1.95	—
PORO-1	Uniform 60%	515	18.2	1.84	5.6
PORO-2	Uniform 50%	481	23.6	1.83	6.4
PORO-3	Uniform 40%	463	26.4	1.8	8
PORO-4	Uniform 30%	393	37.6	1.68	14
PORO-5	Decreasing Poro.	450	27.6	1.68	14.1
PORO-6	Increasing Poro.	395	36.5	1.67	14.4
CD-1	Converging	422	33	1.73	11.1
CD-2	Diverging	330	47.6	1.54	21.2
CD-3	Converging-Diverging	381	39.4	1.61	17.4
CD-4	Diverging-Converging	371	41.1	1.61	17.4
HELM-1	Stepped	349	44.6	1.59	18.6

Table 5. Comparison of overall end-wall pressure and impulse reduction for each of the plate arrays studied.

5 SCOPE AND LIMITATIONS

The conclusions of this study are limited to the investigated shock-tube conditions, four-plate arrays, plate thickness and spacing, and the specific porosity and orifice geometries considered. Experiments were conducted at a nominal incident shock Mach number of 1.62; therefore, the extent to which the observed attenuation trends and relative performance of the configurations persist at substantially different incident shock strengths remains to be established. Additionally, the shock-tube facility produces sustained post-shock flow and a slower pressure decay than an ideal free-field blast waveform, which influences the measured cumulative impulse and should be considered when extrapolating the results to explosive blast loading.

The numerical model neglects viscosity and turbulence and therefore does not explicitly capture viscous or turbulent energy-dissipation mechanisms within and downstream of the orifices. While the model reproduces the principal pressure response and provides insight into compressible wave propagation through the arrays, the numerical schlieren contours are used primarily to interpret the reflection, transmission, and diffraction processes responsible for the observed attenuation trends. Quantitative attribution of attenuation to individual wave interactions, jetting, or vortical mechanisms cannot be established from density-gradient visualizations alone. Future work should investigate a broader range of incident shock strengths and geometric parameters, including passage length and orifice taper angle, and incorporate quantitative flow-field diagnostics to further resolve the mechanisms governing attenuation. More complex passage geometries should also be investigated, including tortuous-path inserts analogous to acoustic labyrinths, designed to promote repeated internal reflection, diffraction, and disruption of transmitted shock-wave propagation.

6 CONCLUSION

This study combined shock-tube experiments with three-dimensional compressible-flow simulations to examine how porosity distribution and internal orifice geometry affect blast-wave transmission through four-plate porous arrays. The experiments establish the attenuation performance of the tested configurations, while the numerical density-gradient fields provide complementary insight into the associated wave evolution.

Three findings are supported by the measured data. First, reducing uniform plate porosity from 60% to 30% increased attenuation: relative to the blank case, the reported peak end-wall pressure reduction increased from 18.2% to 37.6%, while the reported impulse reduction increased from 5.6% to 14.0%. For the graded arrays, reversing the sequence so that the 30% porosity plate was encountered first reduced the reported peak end-wall pressure from approximately 450 to 395 kPa, whereas the reported cumulative-impulse reductions remained nearly unchanged at 14.1% and 14.4%. Thus, within the tested grading sequences, plate order strongly affected the peak transmitted load but had comparatively little effect on cumulative impulse.

Second, the shaped-orifice arrays produced substantial differences in attenuation. Among all tested configurations, the continuously diverging array (CD-2) produced the lowest reported peak end-wall pressure, 330 kPa, and the lowest reported cumulative impulse, 1.54 kPa-s. Using the reductions reported in Table 5, these values correspond to 47.6% peak-pressure attenuation and 21.2% impulse attenuation relative to the blank configuration. The mixed and stepped profiles also outperformed the continuously converging profile, but none matched CD-2 under the tested conditions. These results identify internal passage geometry as a consequential design variable in addition to nominal open area.

Third, the numerical simulations reproduce the principal features of the measured end-wall pressure histories for the representative validation cases and reveal systematic differences in shock diffraction, reflection, secondary-wave interaction, and jet development among the array geometries. The continuously diverging passages are associated with smoother lateral expansion and delayed downstream shock propagation, whereas compound and stepped passages generate more localized recompression, jetting, and secondary structures. These observations

provide a physically consistent interpretation of the experimental ranking, but the density-gradient fields should be regarded as mechanistic evidence rather than a quantitative decomposition of attenuation.

Overall, the results demonstrate that both porosity distribution and internal passage geometry can be used to modify blast-wave transmission through rigid porous plate arrays. For the geometry and loading condition tested here, continuous divergence provided the strongest attenuation of the evaluated profiles, while porosity grading primarily changed peak loading rather than cumulative impulse. Future work should determine whether these rankings persist across incident shock strength, taper angle, passage length, plate spacing, and alternative definitions of shaped-orifice open area, and should use quantitative flow-field metrics to test the mechanisms inferred from the numerical schlieren fields.

7 DECLARATION OF COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

8 ACKNOWLEDGEMENTS

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10 AUTHOR CONTRIBUTIONS

Philip Keppel: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration. Helio Matos: Conceptualization, Methodology, Writing - review & editing, Funding acquisition. Arun Shukla: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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