AFRL-RZ-WP-TP-2009-2247

SCHLIEREN IMAGING OF A SINGLE-EJECTOR, MULTI-TUBE PULSED DETONATION ENGINE (Postprint)

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Innovative Scientific Solutions Inc.

JANUARY 2009

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2009	Conference Proceedings Postprint	03 December 2007 – 01 December 2008

4. TITLE AND SUBTITLE
SCHLIEREN IMAGING OF A SINGLE-EJECTOR, MULTI-TUBE PULSED DETONATION ENGINE (Postprint)

5a. CONTRACT NUMBER
IN HOUSE

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62203F

6. AUTHOR(S)
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5d. PROJECT NUMBER
3048

5e. TASK NUMBER
04

5f. WORK UNIT NUMBER
304804PD

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Innovative Scientific Solutions Inc.
Dayton, OH, 45440

Combustion Branch (AFRL/RZTC)
Turbine Engine Division
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command, United States Air Force

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-RZ-WP-TP-2009-2247

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Propulsion Directorate
Wright-Patterson Air Force Base, OH 45433-7251
Air Force Materiel Command
United States Air Force

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/RZTC

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-RZ-WP-TP-2009-2247

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT
Single-ejector, multi-tube pulsed detonation engine configurations are examined utilizing high speed Schlieren and coherent structural velocimetry. The mechanisms of ejector augmentation are evident in secondary air entrainment and induced flow across the ejector lip. An axisymmetric ejector with both a linear array and a more compact box array of detonation tubes was examined. Good secondary entrainment and subsequent ejector flow was observed, supporting previous results indicating off-axis effects are relatively insignificant to ejector thrust augmentation. A linear ejector with linear detonation tubes revealed limited secondary flow engagement with the ejector lip, likely due to structural ribs.

15. SUBJECT TERMS
Pulse Detonation Engine, Schlieren Imaging, Coherent Structural Velocimetry

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT:	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON (Monitor)
a. REPORT	b. ABSTRACT	c. THIS PAGE			1LT Levi M. Thomas, USAF
Unclassified	Unclassified	Unclassified	SAR	20	19b. TELEPHONE NUMBER *(Include Area Code)* (937) 255-6814

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Schlieren Imaging of a Single-Ejector, Multi-Tube Pulsed Detonation Engine

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Single-ejector, multi-tube pulsed detonation engine configurations are examined utilizing high speed schlieren and coherent structural velocimetry. The mechanisms of ejector augmentation are evident in secondary air entrainment and induced flow across the ejector lip. An axisymmetric ejector with both a linear array and a more compact box array of detonation tubes was examined. Good secondary entrainment and subsequent ejector flow was observed, supporting previous results indicating off-axis effects are relatively insignificant to ejector thrust augmentation. A linear ejector with linear detonation tubes revealed limited secondary flow engagement with the ejector lip, likely due to structural ribs.

Nomenclature

d	driver diameter
D_{ej}	ejector diameter
D^{*}_{ej}	ejector equivalent-area diameter (2-D ejector)
ϕ	equivalence ratio
ff	fill fraction
H_{ej}	ejector throat height (2-D ejector)
igd	ignition delay- time between valve closing and spark deposit
L_{ej}	ejector length
pf	purge fraction
R_{in}	ejector inlet radius
W	ejector width (2-D ejector)
x	ejector distance downstream from detonation tube exit
y	distance from detonation tube centerline

Introduction

Previous studies have shown the potential of an ejector to almost double the thrust of a pulsed detonation engine (PDE) tube [1-3]. Axial misalignment of the detonation tube and ejector was shown to have little or no effect on augmentation to a y/d of 1.14[4]. However when multiple detonation tubes are bundled together and directed at a single ejector, it was found that the augmentation levels dropped significantly. It was hypothesized that interaction between a starting vortex and the induced flow in the ejector by an adjacent tube was causing the decrease in multi-tube performance. In this study, Schlieren imaging of the PDE exhaust entering the ejector is used to examine the negative tube-tube interactions to determine methods to mitigate the reduction in performance for multi-tube, single ejector, PDE operation.

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Experimental Setup

The thrust stand and research pulsed detonation engine located at the Pulsed Detonation Research Facility in the Air Force Research Laboratory were used for this study. The PDE utilizes automotive valving to feed up to four detonation tubes. The damped thrust stand was setup to measure PDE thrust alone for baseline tests or total thrust from ejector and PDE. This experimental setup has been described in detail previously[5]. Unless otherwise noted, experiments were performed with stoichiometric hydrogen air, 10 Hz per detonation tube, 3.5" diameter detonation tubes, purge fraction of 0.5, 75" detonation tube length, with a 28" Schelkin-like spiral to promote deflagration-to-detonation transition. Three ejector configurations will be examined.

In multi-tube operation, the fill and/or purge from an adjacent tube can influence the flow into the ejector. Shown below in fig. 1 is a schematic of the timeline of the PDE for two complete cycles. While tube 1 is firing, tube 3 is filling, tube 4 is finishing the purge period and tube 2 is idle.

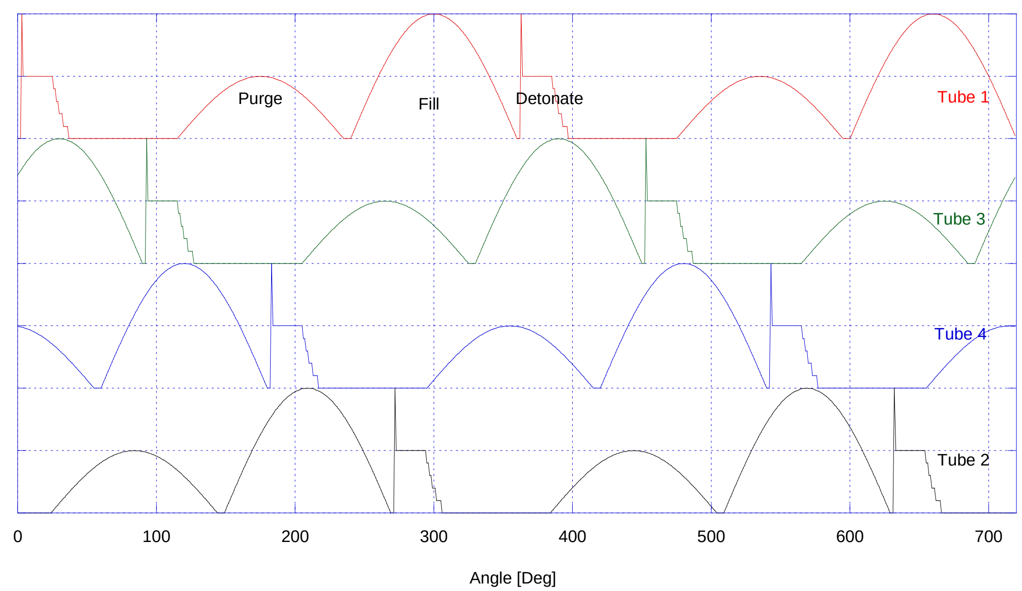


Figure 1 Schematic of the timeline for two complete cycles of the PDE. Notice the four detonation tubes are 90 degrees offset and the firing order is 1-3-4-2.

A. Schlieren Setup

Shown below in fig 2, is a schematic of the light source and spherical mirror arrangement. Due to PDE vibration concerns the light source and camera are folded by flat mirrors to be as distant from the PDE is possible. Images were process using standard PIV cross-correlation software with 50% overlap. The camera frame rate was 4700 frames per second or 213 μs between frames and an image resolution of 447 μm/pixel.

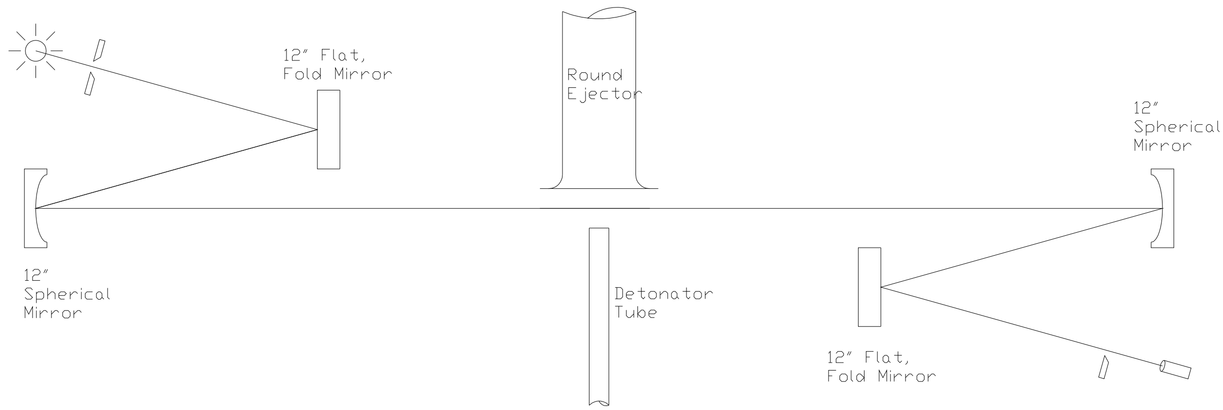
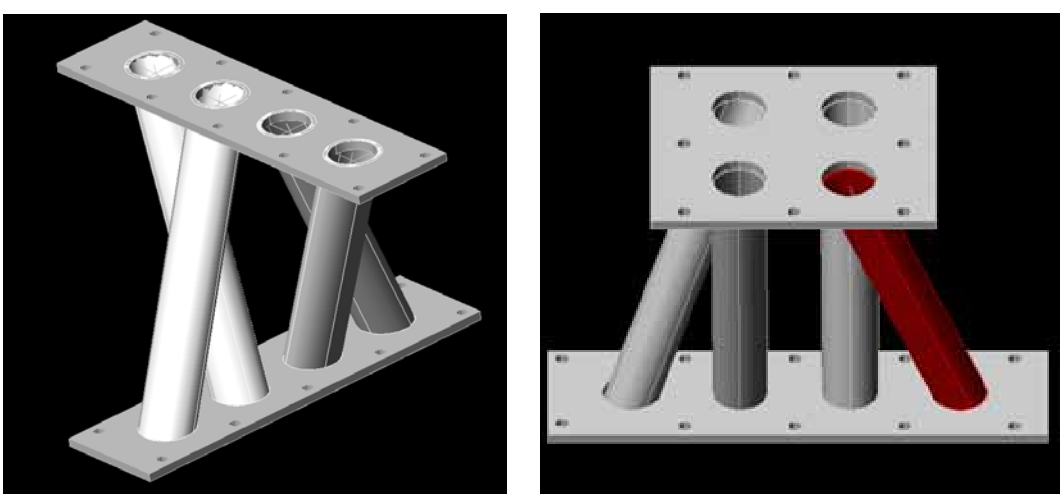


Figure 2 Schematic of Z-type schlieren mirror arrangement with fold mirrors used in this experiment.

The detonator tube array is typically horizontal, and imaging through three exhaust plumes give little information on the effect of the off-axis detonator tubes. An adaptor was constructed to rotate the tube array to vertical so that the effect of the detonator tube location relative to the edge of the ejector could better be visualized. In Fig 3a, an image of the adaptor used to rotate the detonation tubes from a horizontal array to a vertical array is shown. Interestingly, the length and angle of all four tubes connecting the horizontal flange to the vertical flange are identical. In this arrangement, only three detonator tubes could be located within the diameter of the ejector and the fourth outside tube was not used. Figure 3b, shows an adaptor to fit all four detonation tubes within the perimeter of the round ejector. The length and angle of the tubes connecting the two flanges are not identical but similar. The tube inner diameter in Fig 3 is 2.06" and the distance from flange to flange is 12" . Detonation tubes 60" long and 3.5" in diameter were fabricated so that the exit of the detonation tube was approximately 72" and little adjustment of the mirrors was required.



a b

Figure 3 Adaptors used to a) rotate tube array from horizontal to vertical and, b) to adjust the array so all tubes are within the perimeter of the ejector.

B. Round Ejector, Linear Tube Array

In this experiment, three detonation tubes were directed into the inlet of a single, round, 13" diameter ejector, The ejector to detonation tube diameter ratio, D_{ej}/d was 3.86, and x/d varied from 0 to 5, although, all of the imaging was done at x/d of 2. The ejector L_{ej}/D_{ej} was 5.7 and the inlet radius to ejector diameter was 0.66. The ejector hardware available was a straight walled ejector with a rounded inlet. A tapered diffusion section was not available but was found previously to nearly double ejector augmentation[3].

The detonation tubes were 72" long with a volume of 580 in^3. The centerline spacing between the 3.5" diameter detonation tubes was 4", therefore tubes 1 and 3 were 4" or y/d of 1.14 off axis. A schematic of the detonation tube arrangement is shown in fig. 4 and a picture of the hardware is shown in fig 5. The adaptor to rotate the array from horizontal to vertical is not shown in this schematic, but an image is shown in fig 3a. The conditions were identical to those of the off-axis ejector experiment previously conducted with each tube firing at a frequency of 10 Hz, ignition delay of 0 ms and an equivalence ratio of one[4]. The valves in this engine were operated by a cam shaft and therefore the relative timing between tube firing was fixed by the rotational speed of the cam shaft. This was a four tube engine and the firing order was 1, 3, 4, 2 (effectively: 1, 3, 4, with 2 skipped for this configuration). At 10 Hz, there was 25 ms between each tube firing. Since tube two was not used, there were 50 ms between the initiation of a detonation in tube 4 and that in tube 1. Schlieren images collected show the unused tube, 2, the top corner of the ejector and part of tube 4.

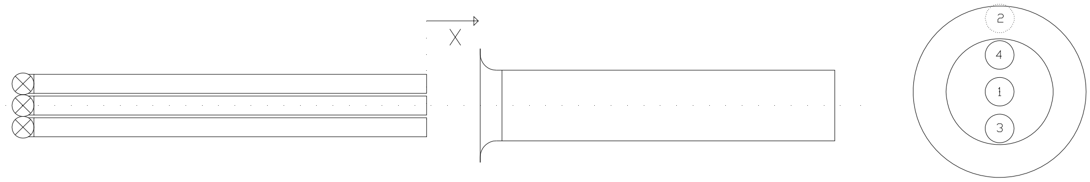
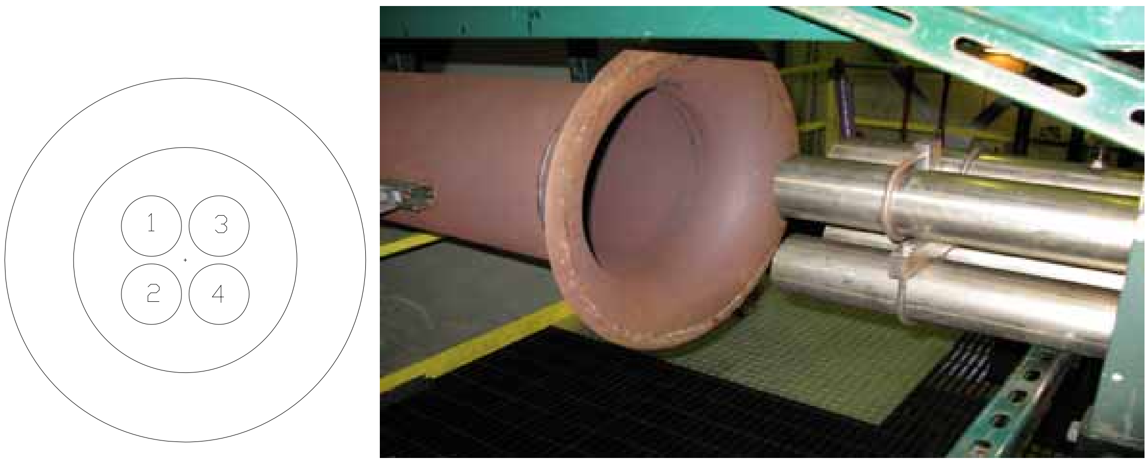


Figure 4. Schematic of multi-detonation tube single round ejector configuration

Figure 5 A picture of the round ejector and vertical tube array.

C. Round Ejector, Box Tube Array

In this configuration, four detonation tubes were arranged to be quasi-symmetric about the ejector axis. The tubes are closer to the center of the ejector than the outboard tubes of the linear tube array. The detonation tube volume was again 580 in^3, and the same round ejector was used. The tube arrangement and a picture of the ejector and detonation tubes is shown in fig 6.



a) **b)**

Fig 6 Box configuration, a) tube arrangement as viewed from the tailpipe and, b) picture of the ejector inlet and detonation tubes.

D. Linear Ejector, Linear Tube Array

Although a round ejector has certain advantages, a linear arrangement of detonation tubes may be more desirable in application. In this experiment, four detonation tubes were directed into the inlet of a linear ejector. The ejector mouth was 22" wide and 7" high. The radius of the inlet lip was 1" giving an inlet radius to ejector height ratio of 0.133. The ejector was tapered by a half angle of four degrees from inlet to exit. The centerline spacing between the detonation tubes was 4" and two different sets of detonation tubes were used. Both sets of detonation tubes were 3.5" in diameter. The first set was used to image the flow into the ejector as displayed in the "Side View" of fig. 7 and had a tube volume of 650 in^3. The second set of tubes was used to image the flow into the ejector as displayed in the"Top View" of fig. 7 and had a tube volume of 580 in^3. The discrepancy in tube volume is due to keeping the overall length of the detonation tubes 72" (to minimize mirror adjustments) and the adaptor shown in fig. 3a used to rotate the tube array from horizontal to vertical. The dimensionless ratios of ejector height to driver diameter tested were 2.1, and Lej/d was 6.3. A schematic showing the tubes as they relate to the ejector in the vertical configuration is shown in fig. 8a and a picture is shown in fig. 8b.

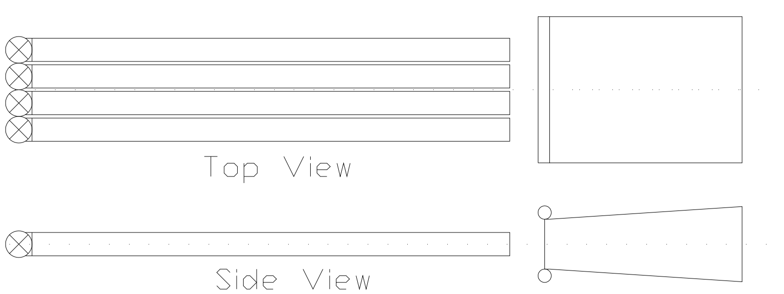
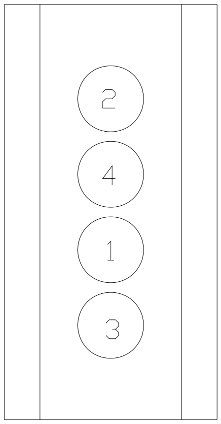
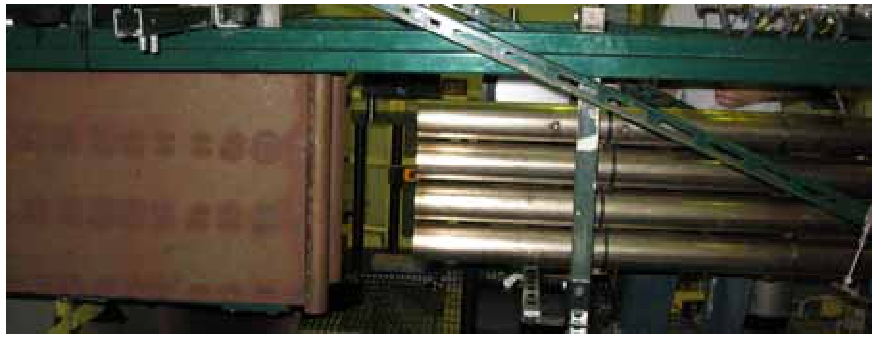


Figure 7 Schematic of PDE-linear ejector configuration with 3.5" detonation tubes.





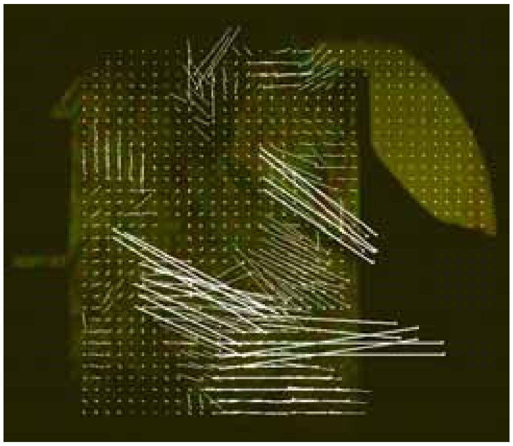
a) b)

Fig 8 The linear ejector in the vertical arrangement, a) tube numbering as viewed from the tailpipe, and b) picture of linear ejector inlet and tube detonation tubes.

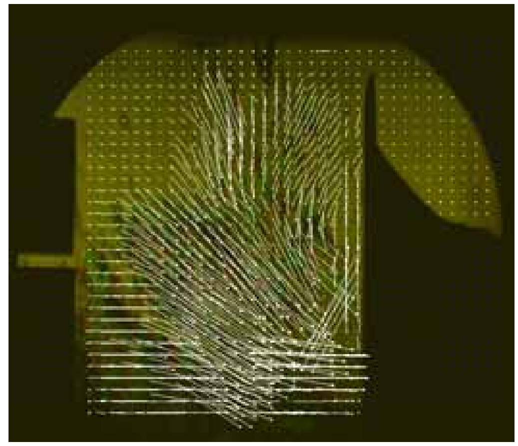
Experimental Results and Discussion

A. Round Ejector, Linear Tube Array, single tube operation

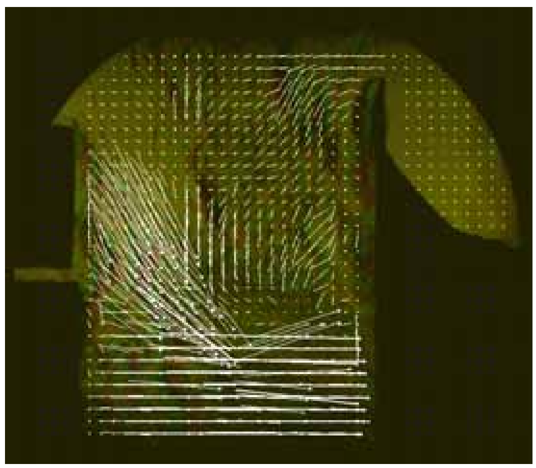
Previously, it has been shown that detonation tubes located off of the centerline of the ejector can produce augmentation ratios as large as a detonator tube located on the centerline. During multi-tube operation, however, there has been shown to be a slight decrease in the augmentation ratio[4]. Schlieren images of the flow field 10 ms after the exiting shock wave collided with the ejector showed the greatest amount of induce flow into the ejector. These images are shown in fig. 9 for a single detonation tube interacting with the ejector. Figure 9a is the uppermost tube, Figure 9b is the central tube and 9c is the lowest tube. The tube centered on the ejector (fig 9b) shows the most induced flow and coherent flow pattern. The top and bottom tube must be engaging the ejector on either side locally producing higher velocity. The suction pressure on the lip of the ejector is proportional to the square of the velocity, so the off axis tubes may produce higher velocities over reduced areas.



a



b

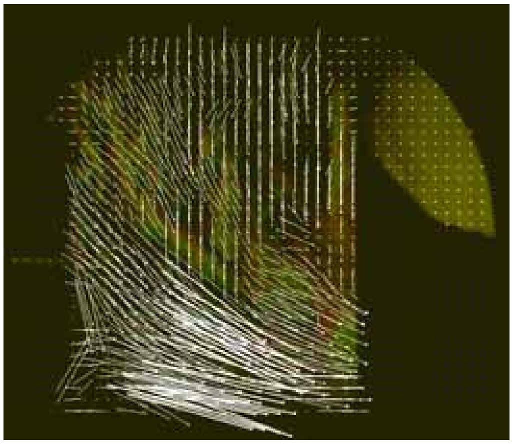


c

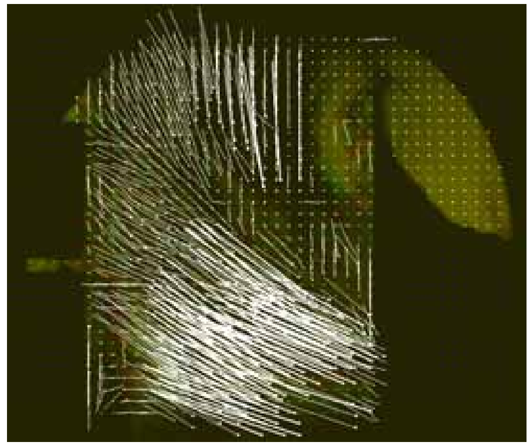
Figure 9 Flow field approximately 10 ms after the shock interacted with the ejector. Only one detonation tube is being used a) detonation tube at the top of the ejector (note: the highest tube in the view is not being used), b) tube centered on the ejector (actual tube is not in the view), c) detonation tube at the bottom of the ejector (tube is not in the view).

B. Round Ejector, Linear Tube Array, Multi-tube operation

The flow field for multi-tube operation appears to be more coherent than single tube operation, see fig 10. The images are again arranged from uppermost detonation tube to lowermost from fig. 10a to c respectively at 10 ms after the shock wave interacted with the ejector. It appears that the flow from the previous firing tends to center the flow induced flow on the ejector, compare fig. 9 with 10. The center tube, fig 10b, still appears to have the most coherent flow field and the largest induced flow on the upper lip of the ejector. Based on these images, the multi-tube operation would be expected to have greater augmentation than single tube operation.



a)



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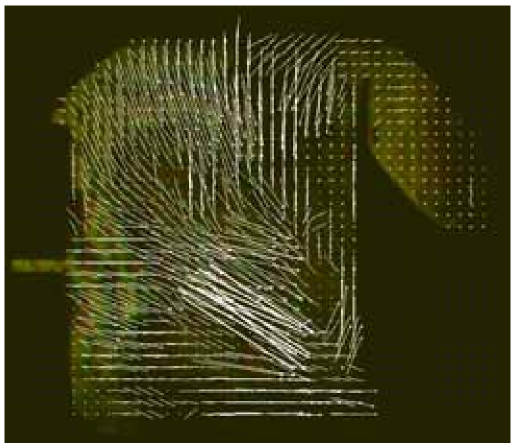


c)

Figure 10 Flow field approximately 10 ms after the shock interacted with the ejector. Three tubes firing order is : tube centered on ejector, tube lowest on ejector and tube at the top of the ejector. (The uppermost tube in the image is not active and there is a ¼ cycle pause between the tube at the top of the ejector firing and the center tube firing) a) detonation tube at the top of the ejector, b) tube centered on the ejector (actual tube is not in the view), c) detonation tube at the bottom of the ejector (tube is not in the view).

Figure 11, shows component velocities in the vicinity of the upper lip of the ejector as a function of time. In figure 11a, only one detonation tube fires, and the velocity toward the ejector oscillates with a period of about 10 ms. The Positive x component and negative y component indicate the velocity vector is to the right and downward into the ejector. Counting the first, noisy flow into the ejector at about 10 ms there are 4 oscillations that occur prior to the purge gas exiting the detonation tube. In fig 11b, two tubes are firing 180 degrees out of phase and the flow oscillations into the ejector are almost damped out when the next tube fires. The first tube fires at 2 ms, the second fires at 52 ms and the first fires again at 102 ms. For four tube operation, the flow at .025 ms and .075 ms will be interrupted by the next detonation, potentially reducing the augmented thrust produced by a single tube.

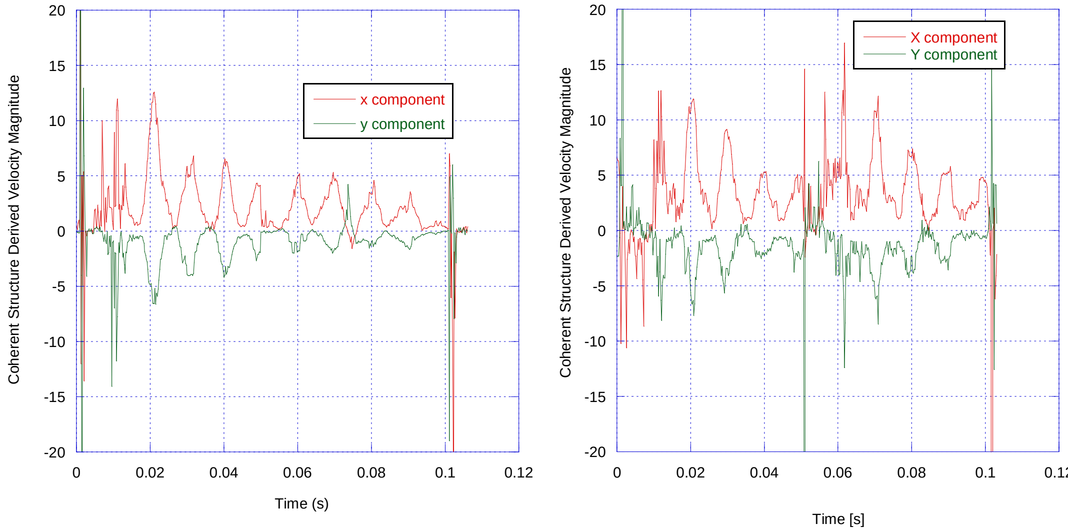
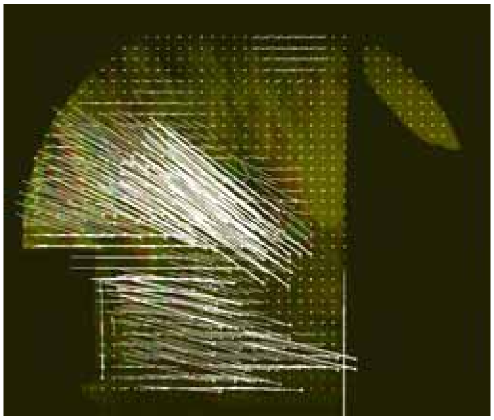


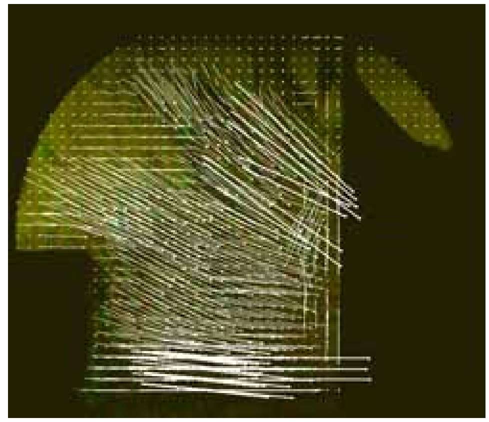
Figure 11. Velocity components toward the ejector inlet as a function of time, a) single tube operation. b) two tubes firing 180° out of phase.

C Round Ejector, Box Array, Multi-tube Operation

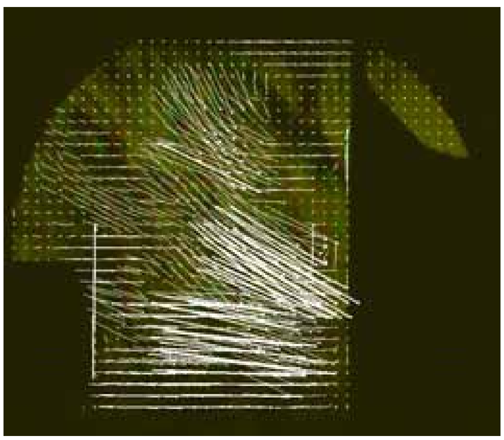
The box configuration schlieren imaging and analysis is shown in figure 12. Although the lower tubes are not visible in the field-of-view, strong secondary entrainment is evident, indicating high entrainment ratio. Although lip velocity is only visible in frames b. and d. for the images shown, this not likely truly indicative of the actual flow as lack of focused structure near the ejector lip likely resulted in poor CSV results in this region. Based upon the consistent secondary flow entrainment visible in all four frames, it is more likely that the lip flows result in significant ejector thrust augmentation, as evident in thrust augmentation results.



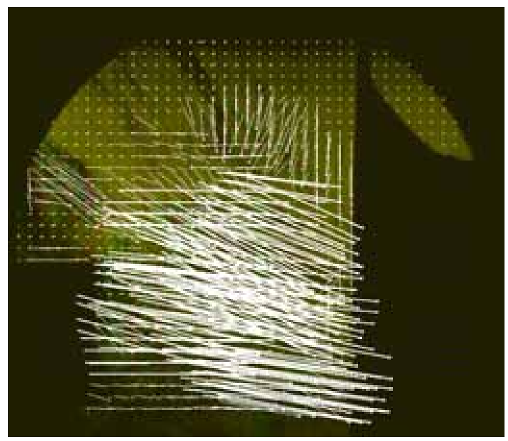
a) Tube 4



b) Tube 2



c) Tube 1

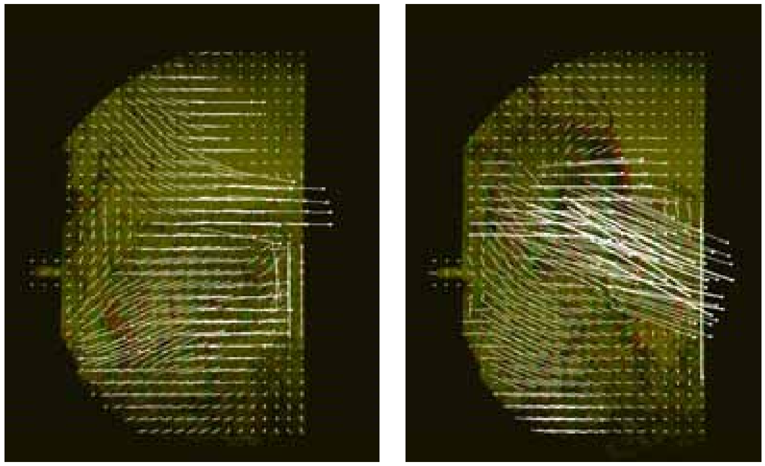


d) Tube 3

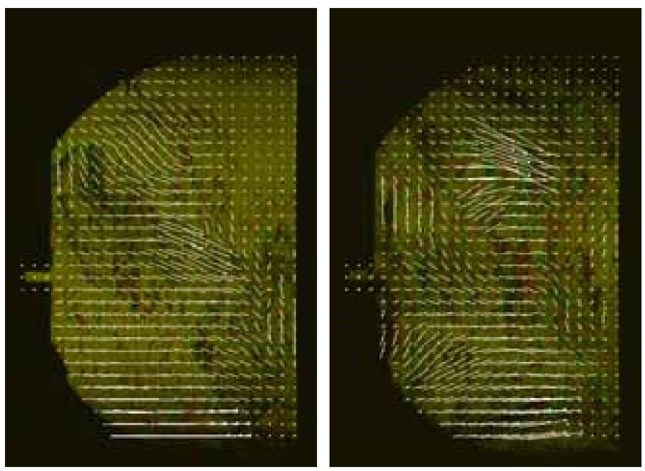
Figure 12 Flow field approximately 10 ms after the shock interacted with the ejector. Box configuration, all four tubes firing a) Tube 4, lower right , b) tube 2, lower left, c) Tube 1, upper right, d) Tube 3 upper right. Firing order is 4-2-1-3.

D. Linear Ejector Linear Array, Multi-Tube Operation

Imaging of the linear ejector in the vertical plane is shown in figure 13. Tube 2 and 4 (the upper two) are visible on the left side of the image. Entrainment from the upper tube (frame a) appears to be symmetric. The primary flow from tube 1 is evident in the lower row of flow vectors of frame b. Tube 3 is not evident in frame c, appearing below the imaging field, but secondary airflow entrainment can be observed. Tube 4 looks much as tube 2 did, with symmetric entrainment. Although secondary airflow entrainment is evident in the frames shown, the flow field vectors indicate the majority of the flow is toward the primary jet and upstream of the ejector lip. Only frames a. and b. show significant lip velocities, and those vectors are localized to a short section of ejector width. This is believed to be due to the ribs in ejector which likely interfered with vertical entrainment (up/down in fig 13) capacity of the linear ejector and correlates with the low thrust augmentation ratio observed for the linear ejector.



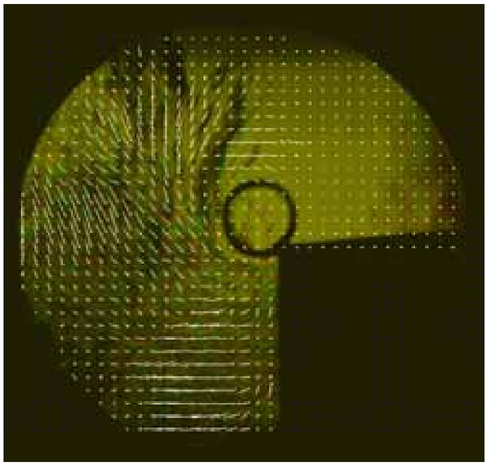
a) Tube **b) Tube 1**

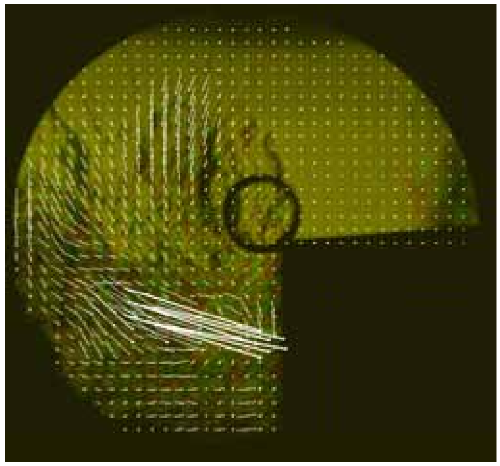


c) Tube 3 **d) Tube 4**

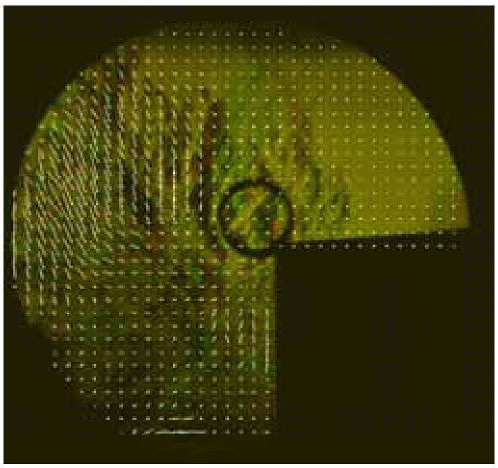
Figure 13 Flow Field approximately 10ms after shock interacted with ejector. Linear ejector, vertical configuration a) Tube 2, b) Tube 1, c) Tube 3, d) Tube 4

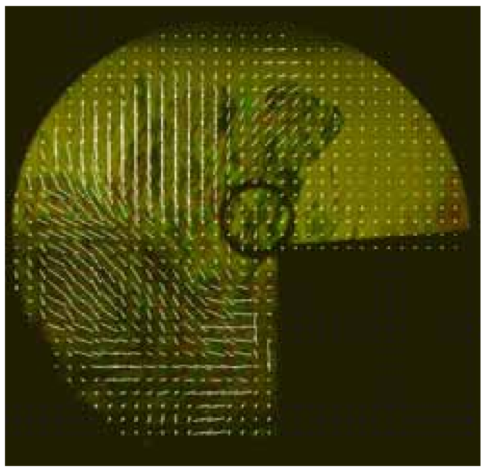
Due to the deep field of view, imaging of the linear ejector in the horizontal plane encompassed all four tubes and spanned the ejector width. For this reason, it was not possible to resolve the firing order with respect to imaging as there is no visual frame of reference. This is evident in the schlieren visible within the ejector lip of figure 14. Although it is clear that mass is entrained in these images, separation is apparent at above the lip, particularly in image a. and c. These frames suggest that the lip radius could be larger, possibly resulting in greater thrust augmentation.





a) 1st firing in sequence **b) 2nd firing in sequence**





c) 3rd firing in **d) 4th firing in sequence**

Figure 14 Flow Field approximately 10ms after shock interacted with ejector. Linear ejector, horizontal configuration, each tube firing shown sequentially (1-3-4-2 firing order, timing unknown).

Summary and Conclusions

Schlieren imaging and Coherent Structural Velocimetry was performed on a variety of single ejector, multi-PDE tube geometries. Both linear arrays of detonation tubes and a more tightly configured box array resulted in significant secondary entrainment and ejector lip flow, with resultant ejector thrust augmentation. Previously obtained poor thrust augmentation results from a linear ejector with linear PDE tube driver configuration was supported by the current results: excessive separation at the lip and limited engagement of secondary airflow, likely caused by flow limitations from the structural ribs.

Acknowledgments

The authors gratefully acknowledge the contributions of Will McCudy, Curt Rice, Dave Burris, Dave Baker and Jeff Stutrud for their help in enabling this research. For their leadership and guidance, we also thank Dr Robert Hancock and Dr Mel Roquemore. Support for this work was provided by Dr. Julian Tishkoff at AFOSR.

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