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Experimental and Computational studies are conducted to investigate the use of miniature actuator bumps (MABs) for nozzle jet vectoring. The control concept features asymmetric deployment of MABs around the nozzle throat to s*ubsonically* skew the sonic plane and shift the throat for jet vectoring. Cold-flow jet studies are conducted to investigate the effects of actuator parameters (deployment height, location, and shape) on pitch vector control for axisymmetric and non-axisymmetric nozzles. Experiments are conducted in a Jet Facility at the University of Toledo and CFD simulations are conducted using a full, 3-D Navier-Stokes flow solver on select nozzle geometries. Measurements indicate that the thrust vector control can be achieved with small actuator deployment heights, and that the sensitivity is increased when the actuator is used near the nozzle throat. Also, MAB control is more effective for two-dimensional nozzles – a result that is consistent with earlier studies conducted using fluidic actuators. The underlying mechanism of *subsonic* flow turning holds for a range of stagnation pressure and throat conditions. Thrust vectoring using the MAB concept offers distinct advantages over traditional control approaches by way of reducing the weight and cost of the control actuation system through proper design and integration of a microelectromechanical systems (MEMS) actuation device for MAB deployment.

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On the Use of Miniature Actuator Bumps (MABs) for Nozzle Thrust Vectoring

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Experimental and Computational studies are conducted to investigate the use of miniature actuator bumps (MABs) for nozzle jet vectoring. The control concept features asymmetric deployment of MABs around the nozzle throat to *subsonically* skew the sonic plane and shift the throat for jet vectoring. Cold-flow jet studies are conducted to investigate the effects of actuator parameters (deployment height, location, and shape) on pitch vector control for axisymmetric and non-axisymmetric nozzles. Experiments are conducted in a Jet Facility at the University of Toledo and CFD simulations are conducted using a full, 3-D Navier-Stokes flow solver on select nozzle geometries. Measurements indicate that the thrust vector control can be achieved with small actuator deployment heights, and that the sensitivity is increased when the actuator is used near the nozzle throat. Also, MAB control is more effective for two-dimensional nozzles—a result that is consistent with earlier studies conducted using fluidic actuators. The underlying mechanism of *subsonic* flow turning holds for a range of stagnation pressure and throat conditions. Thrust vectoring using the MAB concept offers distinct advantages over traditional control approaches by way of reducing the weight and cost of the control actuation system through proper design and integration of a microelectromechanical systems (MEMS) actuation device for MAB deployment.

I. Introduction

THE potential payoffs for Thrust Vectoring Control (TVC) in the areas of propulsion and air vehicle control are quite well known. The intrinsic advantages of TVC systems over conventional aerodynamic control systems include pitch and yaw control in post-stall conditions and increased agility of air vehicles, and reduced cost, weight, and complexity of the control actuation system. An extensive body of work in the design and testing of mechanical (jet vanes and tabs) and fluidic (liquid and gas injection) TVC methods exists in the open literature.[1–5] The studies reveal that the mechanical TVC systems are highly effective in pitch vector control, but impose significant weight and cost penalties with added design complexity to the system in order to accomodate the structural components associated with the jet vane/tab control system. On the other hand, the fluidic TVC systems offer signigicant savings in weight, cost and complexity, but are limited to approximately ±15 deg in pitch vector control as compared to ±90 deg in the case of best

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mechanical TVC designs. Also, the effects of thrust vectoring vary across different nozzle designs and the method of control used.

Many research programs in the late 1960' and 1970' have focused on the development of unconventional TVC systems and complementary nozzle designs (axisymmetric, nonaxisymmetric) to improve the structure and propulsion efficiencies of fighter aircraft. The findings from the nozzle design studies show that the axisymmetric nozzles are structurally very efficient and require less cooling (hence low maintenenace), and that the nonaxisymmetric nozzles offer improved TVC capabilities but with added mechanical complexity. It is learned that a universal approach for TVC which can be claimed 'best' for all applications does not exist, and that identifying an optimal TVC technique largely depends on the targeted application and the constraints of its propulsion system.

Our approach is aimed at realizing a low-cost TVC system for small propulsion systems with stringent volume and cost constraints. The ultimate goal of the idea pursued here is the design and integration of MEMS based TVC system that fits well within the constraints of a small propulsion system. To this end, experimental and computational studies are conducted to investigage the feasibility of a new unconventional technique that uses miniature actuator bumps (MABs) for nozzle thrust vectoring. The TVC technique used is clasically referred to as the *throat shifting method* which involves the skewing of sonic plane at the nozzle throat by altering the flow *subsonically* upstream using small-scale perturbation. Figure 1 shows an illustratrion of this concept. The skewed sonic plane changes the shock and expansion wave patterns in the divergent section of the nozzle, resulting in a vectored flow. Of primary interest are the effects of MAB deployment height, shape and location on pitch vector angle, and the sensitivity of these effects for different nozzles (2-D, 3-D, axisymmetric and nonaxisymmetric). Some pseudo 2-D nozzles and the use of postexit attachments are also examined to enhance the effects of MAB control on pitch vector control. Thrust vectoring using the MAB concept offers distinct advantages over traditional control approaches by way of reducing the weight and cost of the control actuation system through proper design and integration of a microelectromechanical systems (MEMS) actuation device for MAB deployment.

A. Two-Dimensional (2-D) Nozzle

A two-dimensional nozzle, designed using a Method of Characteristics (MOC) approach that provides maximum thrust and uniform flow at the nozzle exit for a given nozzle area, is used for this study. Figure 1 shows the schematics and pictures of the nozzle design. The stagnation pressure chamber is 2-inch in height, 2-inch in width, and 12-inch in length. The nozzle is designed to provide a perfectly-expanded condition at a stagnation pressure of 60 psia with an area ratio of 1.35:1. The nozzle is fabricated using two symmetrical halves of converging and diverging sections using a NC machine. Other parts of the nozzle assembly include a pressure chamber and an adapter to enable a continuous supply of pressurized air into the nozzle inlet. A total of 12 pressure ports, 6 on top and 6 on bottom, are used to measure static pressures inside the divergent section of the nozzle. An approach to enhance the effect of MAB for TVC using a postexit attachment is investigated as well. To model the effects of a postexit attachment, the 1.35:1 area ratio 2-D nozzle, which is a perfectly-expanded configuration for the stagnation pressure of 60 psi, is modified to a 1.21:1 area ratio nozzle–a slightly under-expanded configuration–using a 70 deg divergent section, shown schematically in Figure 2.

B. MAB Control on a 2-D Nozzle

The MAB control is implemented using thin wires ranging from 0.003 to 0.0065-inch in diameter inside the inner wall of the nozzle. These control devices are tested at multiple locations, all between the throat and exit sections of the nozzle, as shown in Figure 3. The results include (i) pictures taken using a shadowgraph apparatus which shows shock patterns and the vectoring of jet downstream of the nozzle exit, and (ii) static pressure distribution along the divergent section of the nozzle in the form normalized pressure (ratio of static pressure to the stagnation pressure). In all the pressure plots, open circles indicate a baseline (MAB-*off*) case and shaded squares indicate a controlled (MAB-*on*) case. For controlled cases, MABs are placed only on the upper surface of the nozzle, as illustrated in Figure 3. Actuator parameters examined in the 2-D nozzle study include: size (different diameter wires) and location (between nozzle throat and exit sections). Actuators 1-6 refers to the actuator location on the top side of the nozzle (internal) wall, as shown in Figure 3. The merit of performance used is the pitch thrust vector angle.

Figures 4 and 5 show static pressure distribution for the baseline and controlled cases, respectively, for different actuator locations. The shadowgraph images shown in Figures 6-8 show comparisons of the baseline (MAB-*off*) with controlled (MAB-*on*) cases for different actuator size, location, and stagnation pressure conditions. When the MAB is deployed, the small geometrical asymmetric near the nozzle throat causes an asymmetric pressure loading between the nozzle top and bottom surfaces which disturbs the standing sonic plane and skews the plane of symmetry. This effect is translated into the supersonic (divergent) section of the nozzle which ultimately results in a vectored jet at the the nozzle exit. The results in Figure 4 and 5 indicate that the effects of MAB are largest when used near the aerodynamic minimum area (throat) of the nozzle and is progressively reduced as the actuator is moved away from the throat. Also, the effect caused by the larger actuator (MAB of 0.0065-inch diameter) is essentially the same as the effect caused by the smaller actuator (MAB of 0.003-inch diameter) for all exit Mach numbers, which clearly indicate that that there is an optimum setting; see Figure 7. In effect, in some cases (e.g., for exit M = 1.2 and MAB-1) the pitch control effect from the 0.003-inch MAB is stronger than the 0.0065-inch MAB. It is expected that increasing the actuator size causes a corresponding decrease in the *skewed* throat area, which impacts the thrust negatively. Hence, a trade off between the level of thrust vectoring achieved and the loss is thrust efficiency is necessary.

Figure 6 shows shadowgraph pictures of the flow emanating from the 2-D nozzle under baseline (MAB-*off*) and controlled (MAB-*on*) cases for different exit Mach numbers. The actuator used in these cases MAB-1 is located at x/L of -0.2, just upstream of the nozzle throat. It is found that a bistable shock pattern is formed in the transonic flow conditions. At such conditions, when the MAB is placed at an optimal location, it stabilizes the shock stream and the resulting jet in one direction. For all the cases, the jet is vectored in the same direction as the control implemented, that is, if the MAB is actuated on top, the jet emanating from the exit is vector on the up direction. The pitch vector angle caused by the small actuator (MAB of 0.0035-inch diameter) varies from 2 to 8 deg for different locations and exit Mach numbers examined; see Figures 6 and 7. Figure 8 shows enlarged pictures from a baseline case and the best control-*on* case at the same condition. Figure 9 shows an overlay of the results from the TVC experiments conducted on 2-D nozzle using MABs. The highlighted region (MABs-1, 2 and 3 for $M > 1$) shows the most effective conditions for TVC using the MABs.

The influence of adding a postexit attachment on a 2-D nozzle is studied using a highly divergent exit section. The original nozzle is modified to accomodate a 70 deg divergent section from $x/D = 0.62$ to the exit, as shown in Figure 2. The area ratio (A/A_t) at x/D of 0.62 is 1.16, which corresponds to a design Mach number of 1.48 and a corresponding exit-to-total pressure ratio of 0.28. The shadowgraph images of flows at different exit pressures from this configuration are shown in Figure 10. In all baseline cases, the flow separates from the nozzle wall downstream of $x/D = 0.62$. The nozzle behaves approximately as the Mach 1.4 nozzle with a 70 deg diverging section case. When a MAB of 0.003-inch diameter is placed at $x/D =$ -0.2, the jet vectors towards the side with the control in a similar fashion as the original nozzle. The control is effective over pressure ratios for conditions ranging from high subsonic, over expansion, and under expansion. Moreover, the degree of vectoring is visually larger than corresponding cases of the original nozzle configuration. This is evident particularly for cases with low exit-to-total pressure ratio.

Figure 11 shows the pressure difference between the top and bottom surfaces of the nozzle. Just as the original nozzle, there exists a natural asymmetry (without control) which may have been caused due to the small imperfections in the nozzle and/or the conditioning of the inflow. The 0.003-inch diameter actuator is effective in overcoming this natural asymmetry and produces a normal force away from the side with the control. The magnitude of control increases with the total pressure. In comparison with the original nozzle, the control is more effective especially at lower exit-to-total pressure ratios. This result is consistent with the flow visualization results. As demonstrated in the examples in Figure 11, along the length of the original nozzle, the control can produce pressure levels that are higher or lower than the side with no control. For the case with a diverging exit section, however, the control produces a consistently lower pressure on the side with the control along the entire nozzle. Similar effects are obtained using a larger actuator (MAB of 0.006-inch diameter); see Figure 12.

Experimental and Computational studies to investigate the effects of MAB control on pseudo 2-D and 3-D nozzles using a different MAB shape are in progress. Most of the cold-flow jet experiments are completed, and results are being processed. The final paper will include a complete description of all the nozzles (2-D, 3-D, pseudo 2-D, axisymmetric and non-axisymmetric) tested and experimental and computatational results on the effects of MAB control for TVC using the throat shifting method.

II. Acknowledgment

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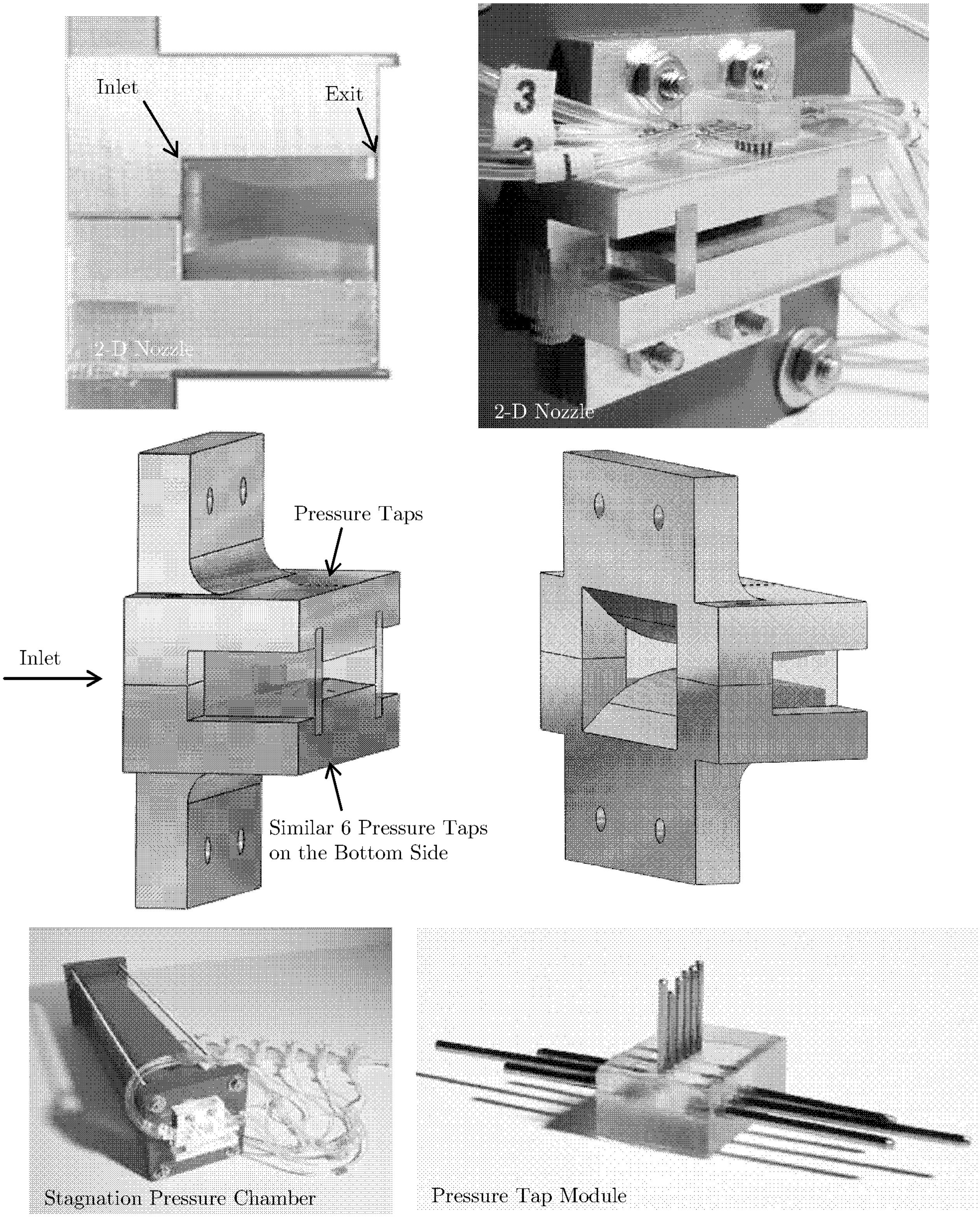


Figure 1. Illustrations of the 2-D nozzle used in this study.

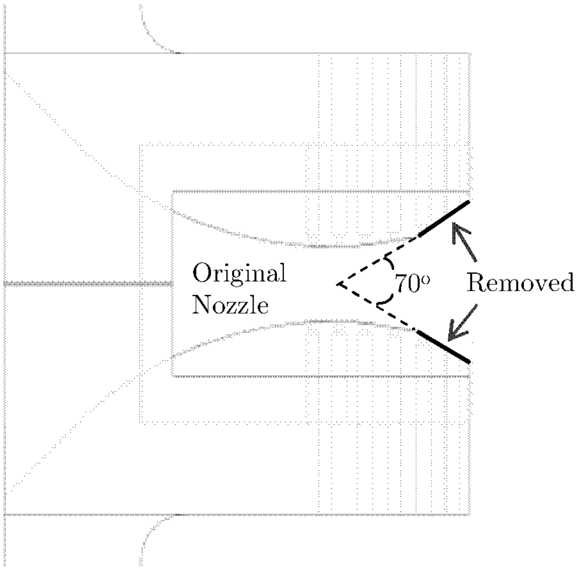
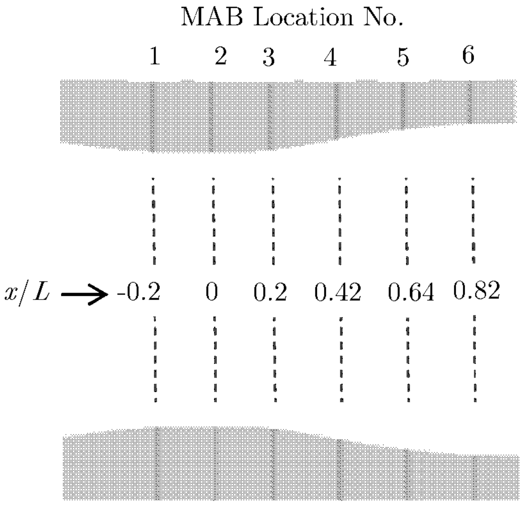


Figure 2. Schematic of the modified 2-D nozzle geometry to include a 70 deg divergent section at the nozzle exit.



$x/L = 0$ (nozzle throat)
$x =$ distance measured from throat to exit
$L =$ length of the divergent section

MAB	x/L
1	-0.20
2	0.00
3	0.20
4	0.42
5	0.64
6	0.82

Figure 3. Different Miniature Actuator Bump (MAB) locations tested on a 2-D nozzle.

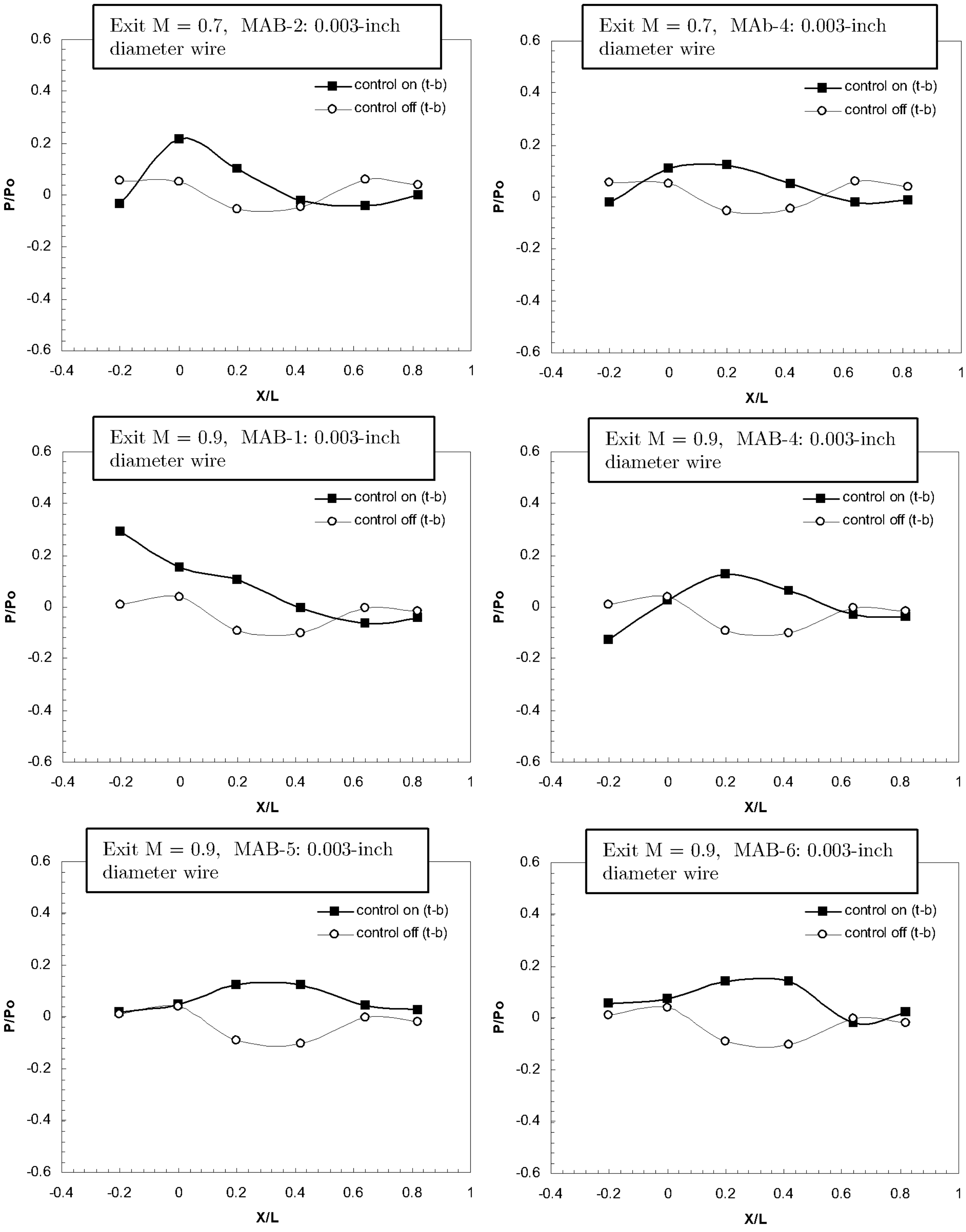


Figure 4. Results from TVC experiments on a 2-D nozzle: static pressure distribution inside the nozzle for MAB-*off* and MAB-*on* cases at different exit Mach numbers; MAB used is a 0.003-inch diameter wire.

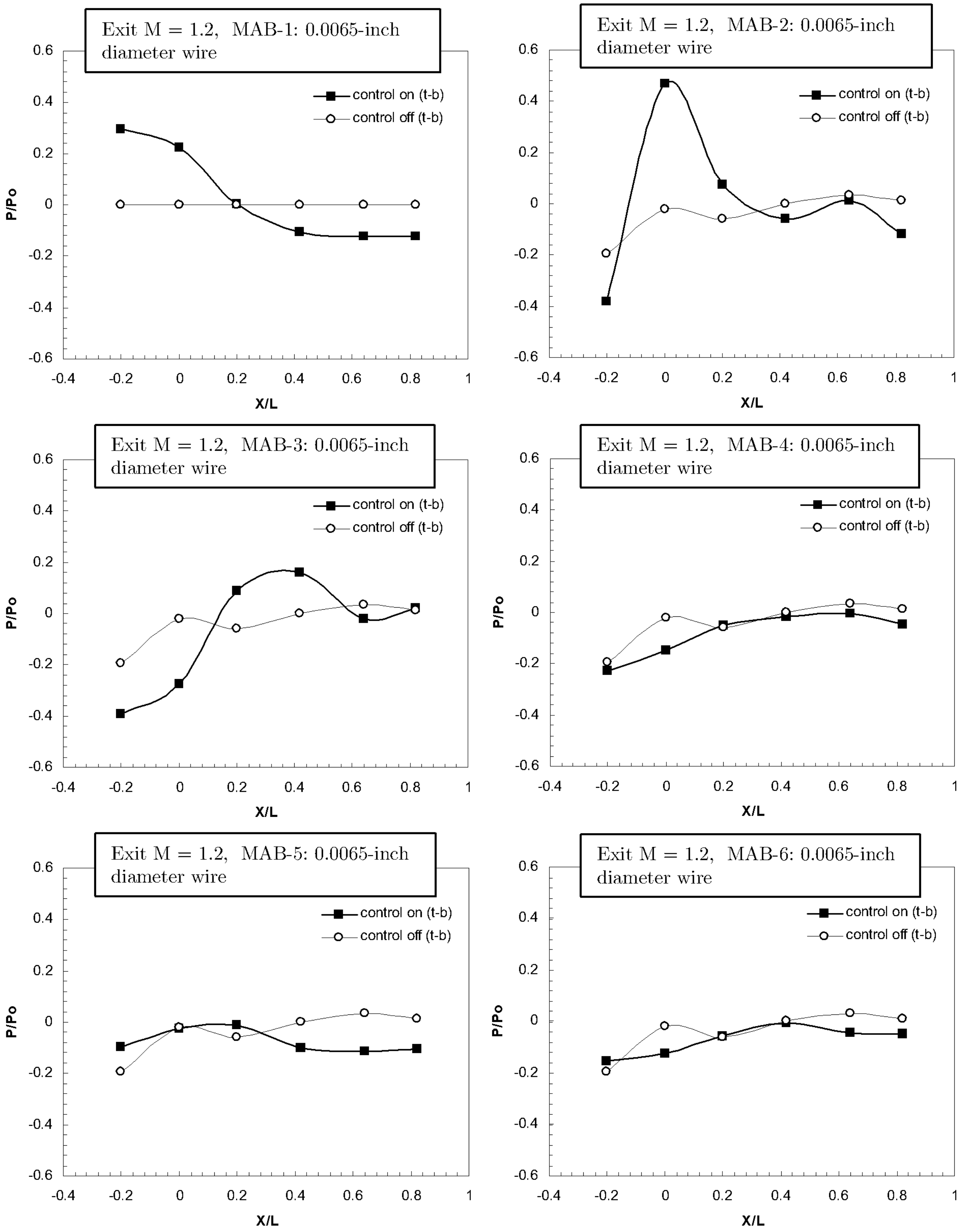
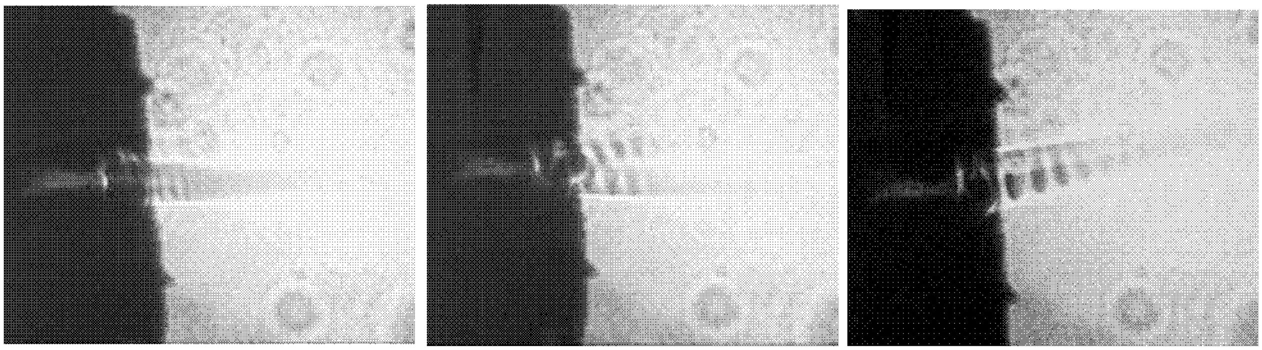
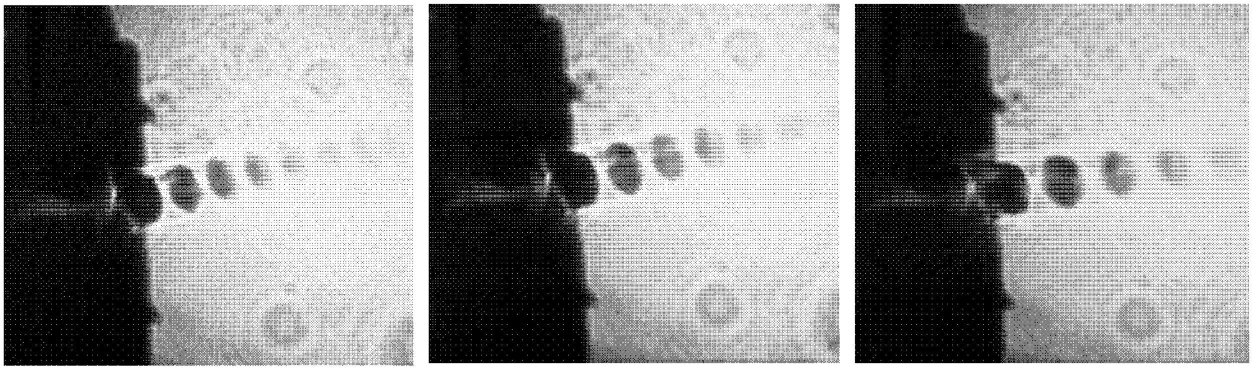


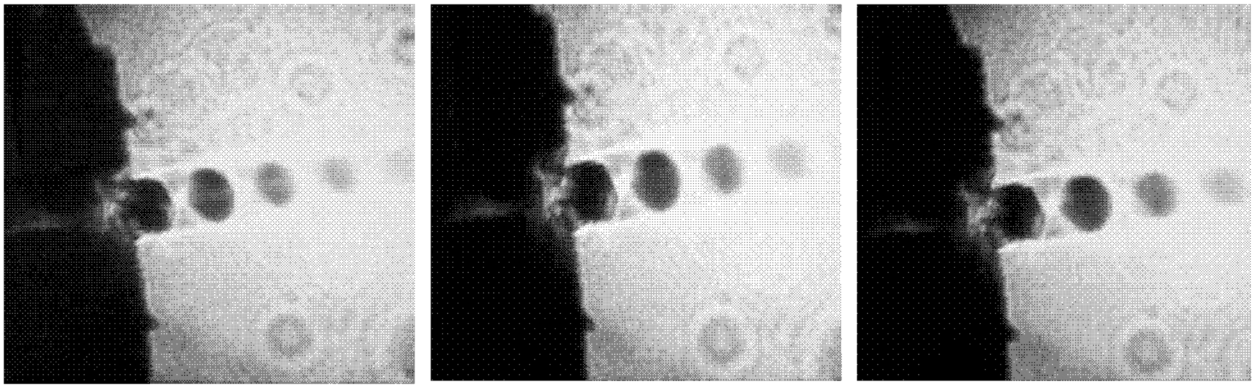
Figure 5. Results from TVC experiments on a 2-D nozzle: static pressure distribution inside the nozzle for MAB-*off* and MAB-*on* cases at different exit Mach numbers; MAB used is a 0.0065-inch diameter wire.



Exit M = 0.98; MAB-*off* Exit M = 1.0; MAB-*on* Exit M = 1.11; MAB-*on*

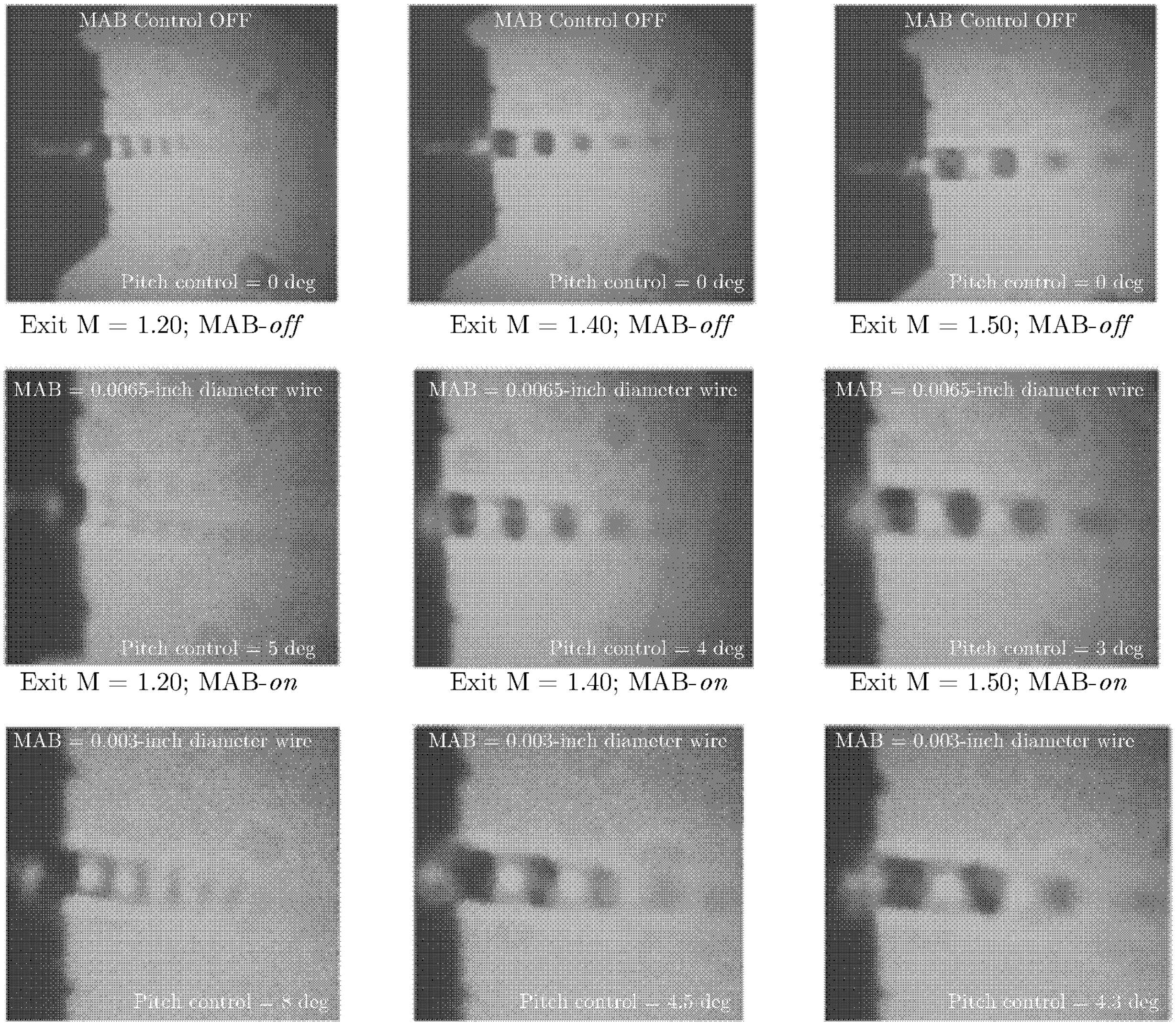


Exit M = 1.25; MAB-*on* Exit M = 1.3; MAB-*on* Exit M = 1.38; MAB-*on*



Exit M = 1.42; MAB-*on* Exit M = 1.43; MAB-*on* Exit M = 1.47; MAB-*on*

Figure 6. Results from TVC experiments on a 2-D nozzle: shadowgraph pictures showing shock structures downstream of nozzle exit for MAB-*off* and MAB-*on* cases at different exit Mach numbers; MAB used is a 0.003-inch diameter wire.



Exit M = 1.20; MAB-*off* Exit M = 1.40; MAB-*off* Exit M = 1.50; MAB-*off*

Exit M = 1.20; MAB-*on* Exit M = 1.40; MAB-*on* Exit M = 1.50; MAB-*on*

Exit M = 1.20; MAB-*on* Exit M = 1.40; MAB-*on* Exit M = 1.50; MAB-*on*

Figure 7. Results from TVC experiments on a 2-D nozzle: shadowgraph pictures showing shock structures downstream of nozzle exit for MAB-*off* and MAB-*on* cases at the exit Mach number of 1.2; MAB-1 used in the middle row pictures is a 0.0065-inch diameter wire, and MAB-1 used in the bottom row pictures is a 0.003-inch diameter wire.

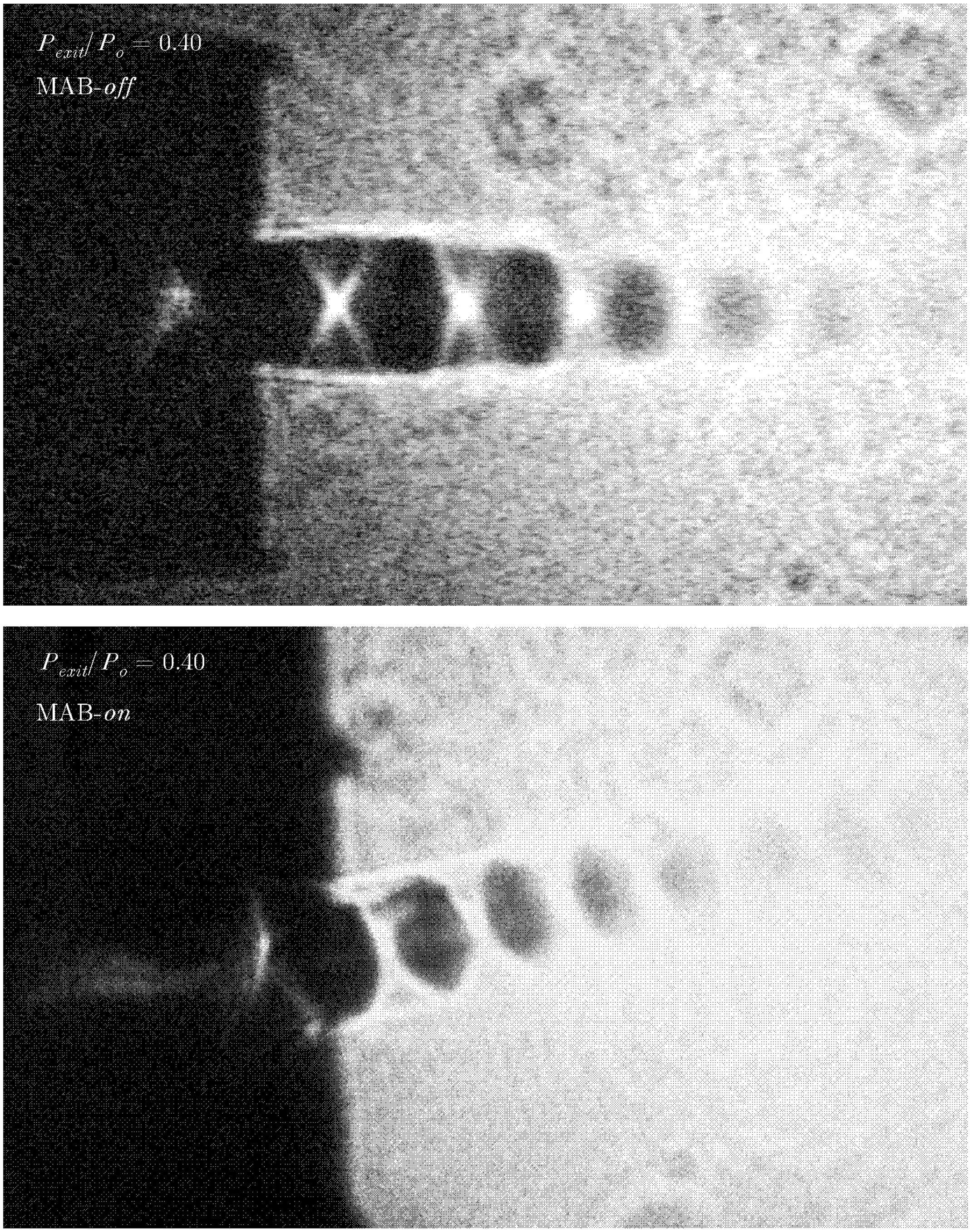


Figure 8. Shadowgraph pictures showing the best TVC effect using MABs on a 2-D nozzle. MAB-1 used is a 0.003-inch diameter wire. The jet is vectored due to *subsonic* skewing of the sonic plane towards the side of the control input (top).

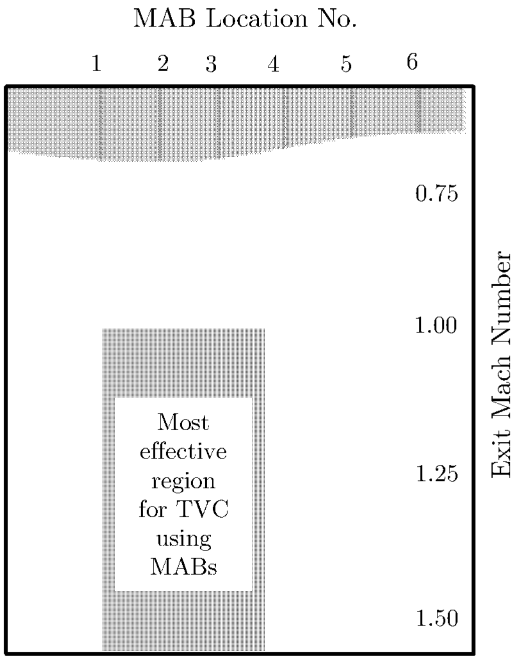
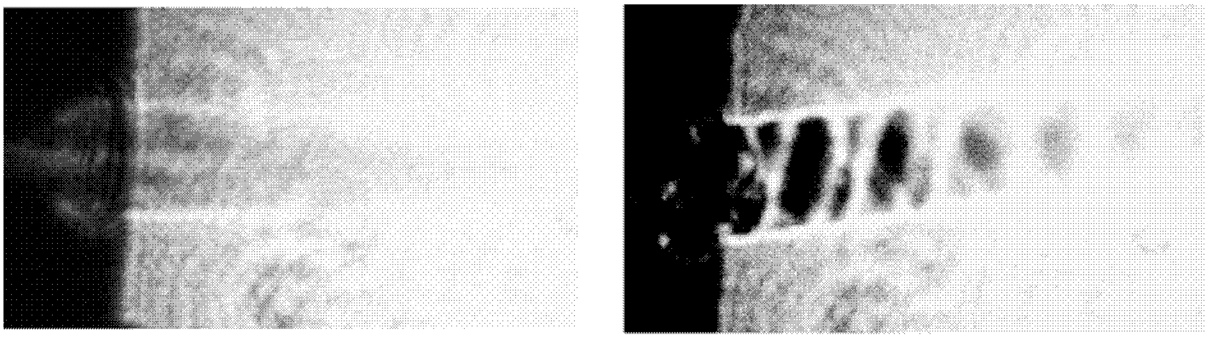
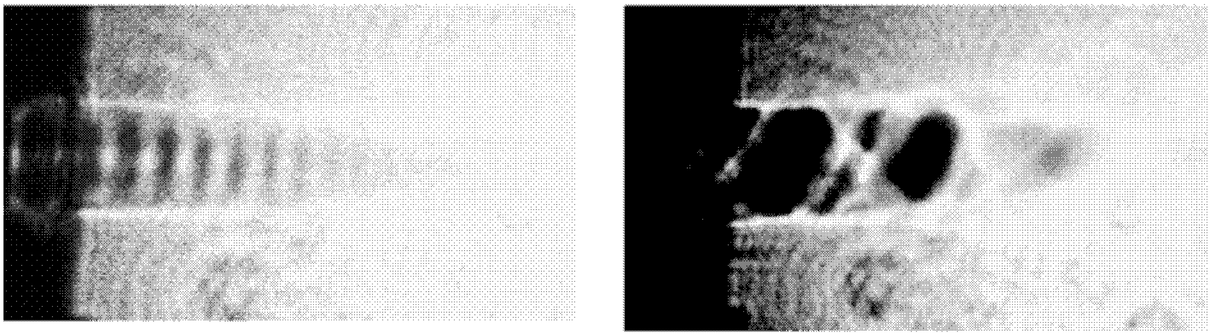


Figure 9. Summary of TVC results using MABs on a 2-D nozzle.



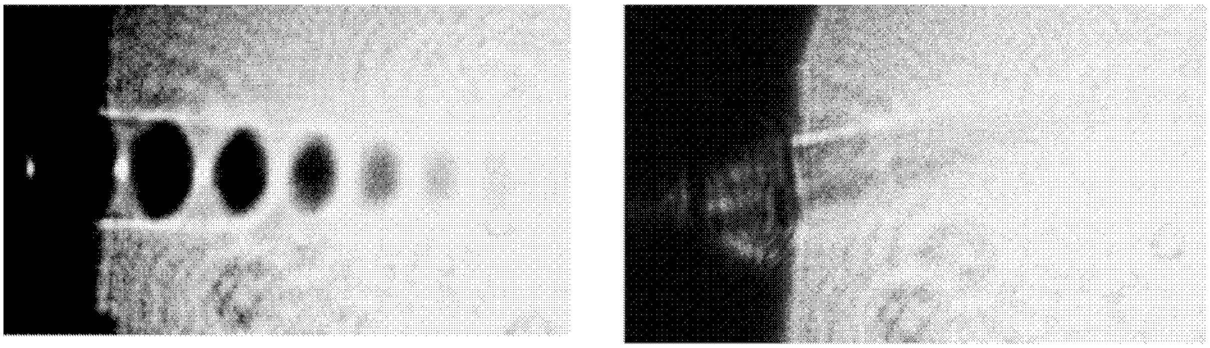
(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.56$; MAB-*off*

(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.56$; MAB-*on*



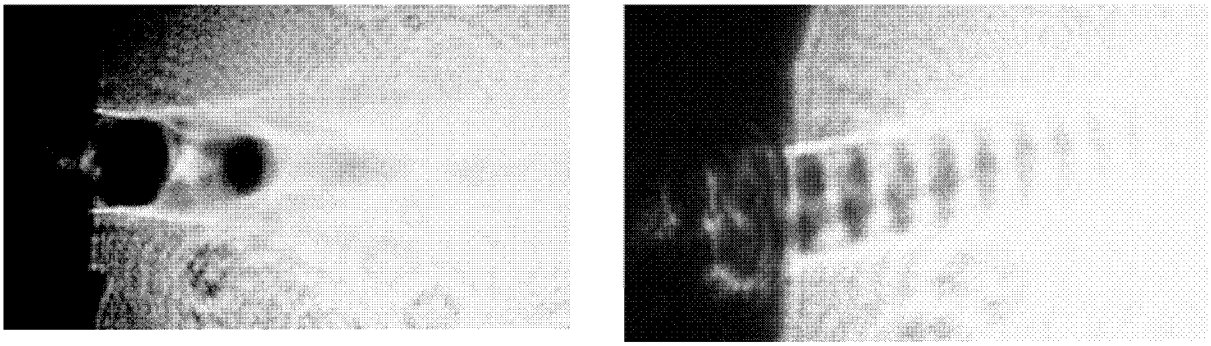
(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.48$; MAB-*off*

(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.48$; MAB-*on*



(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.40$; MAB-*off*

(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.40$; MAB-*on*



(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.25$; MAB-*off*

(a) $\mathrm{P}_{\mathrm{exit}}/P_o = 0.25$; MAB-*on*

Figure 10. Results from TVC experiments on a 2-D nozzle: shadowgraph pictures showing shock structures downstream of nozzle exit for MAB-*off* and MAB-*on* cases at different exit Mach numbers for the 2-D nozzle with a 70 deg divergent postexit configuration; MAB-1 used is a 0.003-inch diameter wire.

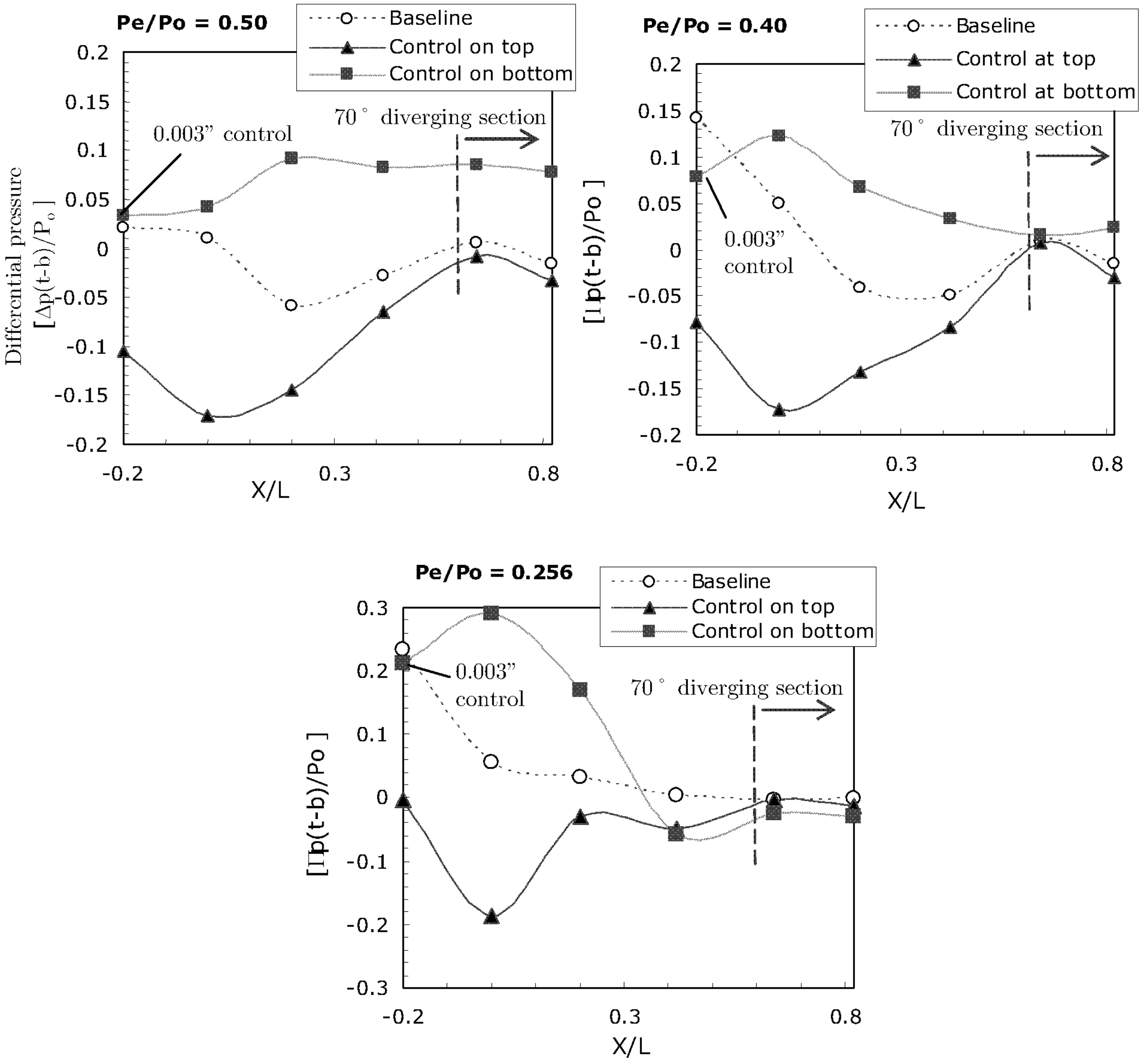


Figure 11. Pressure differential between the top and bottom surfaces of the nozzle divergent section when MAB-1 control is applied using a 0.003-inch diameter wire.

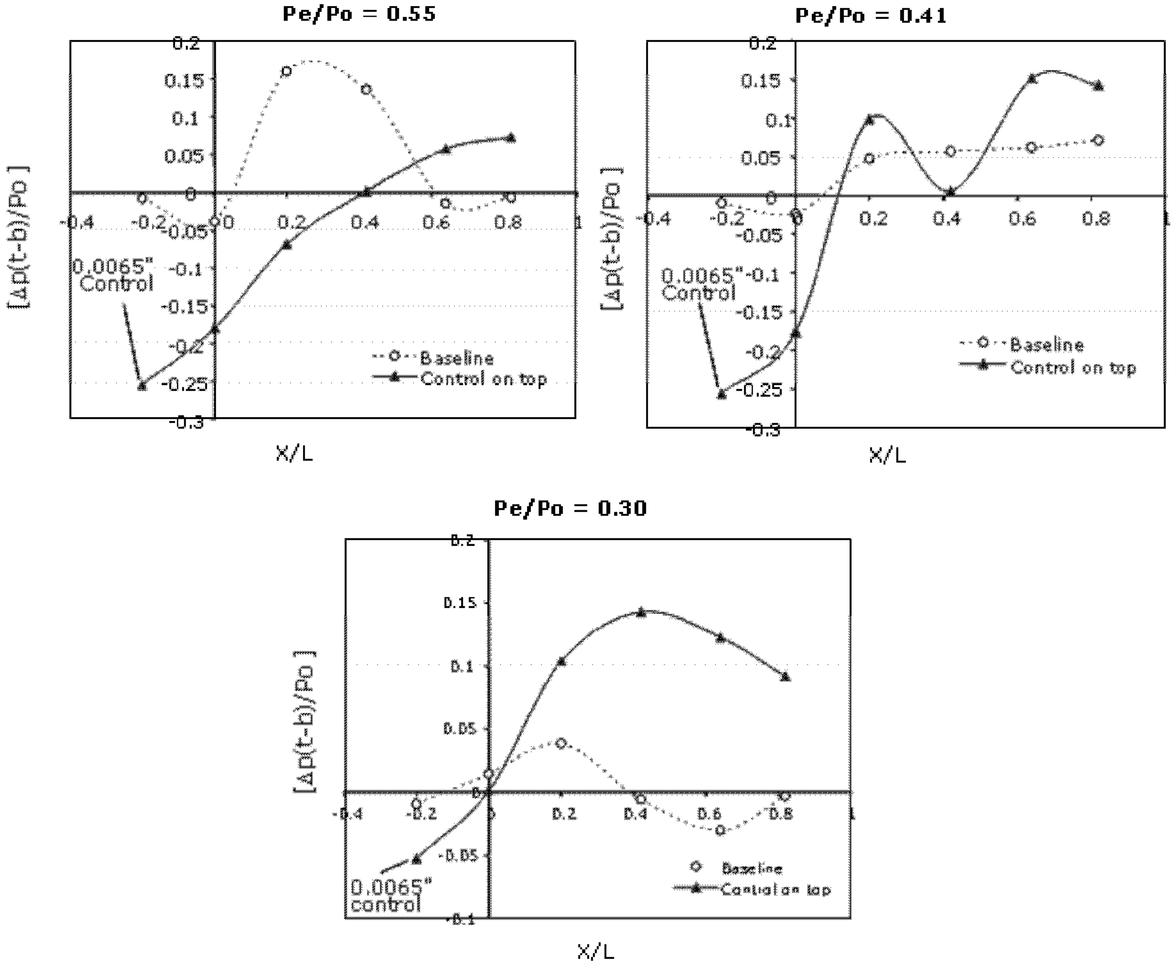


Figure 12. Pressure differential between the top and bottom surfaces of the nozzle divergent section when MAB-1 control is applied using a 0.006-inch diameter wire.