NOZZLE AFTBODY DRAG REDUCTION USING FLUIDICS

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ABSTRACT

High transonic drag is an issue that must be considered in the design of supersonic flight vehicles. Generally, aftbody drag is maximum at flight Mach numbers near 1.0. This study has shown numerically that fluidic injection can be used to decrease nozzle aftbody drag, thereby increasing nozzle performance under transonic conditions. The fluidic injection is used to separate the flow expanding over the external flap, increasing the static pressure and decreasing the aftbody drag. The amount of flow injected was identified as a critical performance parameter while injection pressure was found to have only secondary effects. Use of multiple injection locations provided greater drag reduction for a given amount of injection flow. However, the location of these injectors must be considered.

NOMENCLATURE

A	Area
C_d	Discharge Coefficient
C_{Fg}	Thrust Coefficient, gross
C_{Fn}	Thrust Coefficient, net
Cp	External Flap Pressure Coefficient
$F_{P,Ideal}$	Ideal Thrust, Nozzle
M	Mach Number
NPR	Nozzle Pressure Ratio
SPR	Injector (Secondary) Pressure Ratio
p	Static Pressure
Pt	Total Pressure
q	Dynamic Pressure
W	Mass Flow
Lext	External Flap Length

Subscripts

∞	Freestream Conditions
8	Station 8, Nozzle Throat
9	Station 9, Nozzle Exit
Inj	Injector

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INTRODUCTION

The nozzle designer is confronted with the task of maximizing nozzle performance while minimizing aftbody drag. Unfortunately, improving one often comes at the sacrifice of the other. This is especially true for supersonic vehicles operating at off-design, transonic conditions. Aftbody drag reaches its maximum value at transonic flight Mach numbers, as illustrated in Figure 1. This high drag creates a performance "pinch" point that must be overcome for the vehicle to accomplish its mission.

Previous nozzle investigations have applied fluidic injection to control the throat and exit area to optimize nozzle performance, provide thrust vectoring, and avoid the use of heavy variable geometry. This current work applies fluidic injection to control the flow over the external flap of a two-dimensional nozzle to reduce the high aftbody drag that occurs at transonic Mach numbers.

Generally, fluidic injection studies have focused on the use of fluidic injection in the nozzle as a means of providing thrust vectoring. Although the primary focus of the present study is not thrust vectoring, the knowledge obtained from these earlier studies on the interaction of the fluidic jet into the main stream is directly applicable.

Wing[1], Wing and Giuliano[2], and Giuliano and Wing[3] investigated fluidic injection from a slot in the divergent section to form oblique shocks for the purpose of thrust vectoring. Wing found that as injection flow increased, the separation region moved upstream into a region of lower Mach number flow. The reduced Mach number resulted in an increase in the oblique shock angle and increased vectoring. Later Waithe and Deere[4] were successful at increasing vectoring capability through the use of multiple injection ports without increasing the secondary flow, which would have decreased thrust performance.

Deere et. al.[5] later used fluidic injection to induce separation in recessed cavities in the divergent section a two-dimensional nozzle. Vectoring was achieved through the pressure differential on the nozzle walls.

Fluidic injection has also been applied in earlier studies to improve nozzle performance. Gamble and Haid[6] applied fluidic injection to improve off-design performance in a hypersonic vehicle (X-43) operating at low Mach numbers. Results of this study indicate that significant improvement in nozzle performance may be achieved by separating the over-expanded flow from the external ramp of the single expansion ramp nozzle. Multiple approaches that employ fluidic injection were investigated with two-dimensional CFD. Significant improvements in nozzle performance were obtained by separating the flow from the SERN ramp with oblique shocks generated through fluidic injection. Performance analysis based on the turbojet cycle resulted in a net thrust increase of 3% and Trust Specific Fuel Consumption improvement of 1%, validating the feasibility of the design.

The present study improves thrust performance by reducing aftbody, or boattail, drag. Fluidic injection is employed to induce a separation in the flow along the external flap. The study considers the effects of injector pressure and flow rate as well as the number and placement of the injectors. Two-dimensional Computational Fluid Dynamics (CFD) was used to show significant drag reductions.

APPROACH

Nozzle Description

The two-dimensional baseline nozzle selected for this study is shown in Figure 2. The flight point selected for the analysis is Mach 1.2 at an altitude of 34,687 feet. A typical turbojet cycle with NPR of 6.3 is assumed. The nozzle is configured to have an expansion ratio, A_9/A_8, equal to the design expansion ratio of 1.52. The resulting boattail angle is 15.8°.

Three fluidic injectors were located along the external flap of the nozzle as shown in Figure 3. The location of the injectors was fixed during the study. However, the areas were varied to control the flow rate while assuming that the injectors were choked at all times. The injectors were removed in cases where no flow was required.

Computation Method

The production code of the NPARC Alliance, WIND, was selected for this study. The code has been used successfully for simulating separation in transonic flows for convergent-divergent nozzles. DalBello et. al. [7,8] found the internal and external performance and pressure distribution predicted by WIND for an over-expanded axisymmetric nozzle compared well to experimental data. Engblom[9] used WIND to predict SERN performance on the NASP model 5B and compared predictions to experimental data. Excellent agreement was obtained between the predicted static pressure contours from the CFD and experimental results and overall performance predictions were considered adequate.

Computational Domain

The computational domain is shown in Figure 4 and Figure 5. The freestream was extended 30 throat heights downstream of the nozzle exit and 20 throat heights in the upstream and normal directions. The two-dimensional nozzle was considered symmetric about the nozzle centerline, so a reflection boundary was used at the line of symmetry. The y+ values along the internal and external walls were approximately one.

Flow Solver

WIND Version 5.0 was chosen for the flow simulations. The default second-order Roe upwind scheme with modification for stretched grids and second-order time marching were used to solve the Reynolds-Averaged Navier-Stokes equations.

Turbulence Model

Mentor's Shear Stress Transport (SST) model was chosen for its history of matching experimental data[7,8] of internal and external nozzle flows. The y+ values of about one for the walls allowed modeling without the use of wall functions.

Boundary Conditions

The boundaries were defined for high-speed free-stream flow. Characteristic boundary conditions were used along the free stream in-flow boundaries and a constant pressure outflow boundary was used at the free stream outlet. The nozzle and injection inlets were defined by constant total pressure and temperature. A viscous boundary condition was applied to the walls.

The gas exiting the nozzle and the injector was assumed to be air and ideal. The specific heat and thermal conductivity were held constant. The viscosity was based on Sutherland's Law.

Computational Matrix

The study was divided into two parts. The first part focused on understanding the effects of a single injector. The injector used for these investigations was located at the midpoint of the external flap. The injection pressure ratio, SPR, was varied from 0.5 to 1.5. The injector operated choked at all SPR. The throat area was varied to obtain injection rates between 0.25% and 3.0% of W_8. The matrix of runs for the single injector is shown in Table 1.

Table 1: Single Injector Matrix

Case	SPR	W_{inj}/W_8
1	0.5	0.25 %
2	0.5	0.5 %
3	0.5	1.0 %
4	1.0	0.5 %
5	1.0	1.0 %
6	1.0	2.0 %
7	2.0	0.75 %
8	2.0	1.5 %
9	2.0	3.0 %

The second part of the study focused on the effects of multiple injectors. Two additional injector configurations were investigated. The first added an injector at the leading edge of the flap, just downstream of the hinge point, for a total of two injectors. The second added a third injector just upstream of the trailing edge. The various pressure ratios and injection rates for the multiple injection cases were selected based on the results of the single injector investigation. The matrix of runs for the multiple injectors is shown in Table 2.

Table 2: Mulitple Injector Matrix

Case	#Injectors	SPR	W_{inj}/W_8
1	2	0.5	0.5 %
2	2	1.0	1.0 %
3	2	0.5	1.0 %
4	2	1.0	2.0 %
5	3	0.5	0.75 %
6	3	1.0	1.5 %

RESULTS

The thrust coefficient, C_{Fn}, was used to compare the thrust improvement between the baseline case and each of the fluidic injection cases. It was defined as follows:

$$C_{Fn} = \frac{F_{Actual} - F_{Drag} - F_{Inj,x}}{F_{Ideal}}$$

where, F_{Actual} is the thrust produced by the nozzle, F_{Drag} is the resulting drag force on the external flap (including both pressure and viscous drag), $F_{inj,x}$ is the x component of the injector stream thrust, and F_{Ideal} is the thrust that would be produced if the exhaust flow was expanded ideally to ambient (freestream) pressure.

The results of the single injector matrix are shown in Figure 6. The C_{Fn} increases steadily with injector flow. This is consistent with the findings of Wing[1], who found that the separation region grew with injection flow. The SPR, however, did not have as great of an effect on thrust coefficient. The results at SPR of 0.5 and 1.0 fall on top of one another. At SPR of 1.5, the thrust coefficient is a close match at lower injection rates, but is slightly lower at higher injection rates.

Figure 7 shows the pressure coefficient, Cp, along the external flap for the single injector cases at SPR of 1 as well as the baseline. The Cp is defined as

$$C_p = \frac{p - p_\infty}{q_\infty}$$

where p is the static pressure on the flap, p_∞ is the freestream static pressure, and q_∞ is the freestream dynamic pressure. The low pressure on the external flap due to the expansion wave of the hinge point is seen for the baseline. A small separation region is seen towards the trailing edge where the pressure coefficient increases. This separation region grows as injection is added and increased. A second separation region also forms just upstream of the injector that also grows as the injection rate increases. Downstream of the injector, a low-pressure region is formed by re-expansion of the gases. This is most severe at the lower injection rates where the pressure contours return to the baseline. However, at the injection rate of 2.0% the downstream separation region has grown just up to the injector, relieving this low-pressure region.

It should be noted that, although the performance at an SPR of 1.0 and W_{inj}/W_8 of 0.5% closely matched the performance at SPR of 0.5 and W_{inj}/W_8 of 0.5%, the downstream separation locations were significantly different. In fact, the separation location for the SPR=1.0 case was closer to that for the SPR of 0.5 and W_{inj}/W_8 of 0.25%. The reason for this is unknown, and further investigation is needed.

Figure 8 and Figure 9 show the Mach contours for the baseline and single injector case at SPR=1.0 and 2.0% injection. The low Mach number region starting just upstream of the injector identifies the separation region. This can be seen to grow from the baseline case to the injection case.

The results from the single injector indicate that injector flow is critical in separating supersonic expanding flow from an external nozzle flap. Injection pressure had only a secondary effect. The second part of this study looks into improving performance through multiple injectors. The injection rates and pressure ratios in Table 2 were selected based on the findings with the single injector.

The C_{Fn} obtained for the various configurations are shown in Figure 10 as a function injection rate. No improvement was obtained with the addition of the second injector at the leading edge of the flap. However, significant improvement was seen with the addition of the third injector at the trailing edge.

The addition of the second injector increased the size of the original separation region and the downstream separation region as shown in Figure 11. High and low pressure regions due to separation upstream and expansion downstream of the additional injector are also seen. These expanded high-pressure regions balanced out the additional flow, explaining the similar performance between the single and two-injector configurations.

The addition of the third injector resulted in a performance improvement over the previous two configurations. Figure 12 shows the C_p distribution for the three-injector configuration. The distribution shows significant increases in the size and pressure of the downstream separation region. This suggests that injectors should be placed to augment the adverse pressure gradient that causes the boundary layer to separate from the external flap. This is supported by Figure 13 which compares single, two, and three-injector configurations at an SPR of 0.5 and W_{inj}/W_8=0.25% per injector. These distributions show a strong correlation between performance improvement and the growth of the downstream separation region. The greatest improvement came with the addition of the injector in the separation region.

CONCLUSIONS

This study has shown numerically that fluidic injection can be used to increase nozzle thrust-minus-drag performance at transonic conditions by decreasing the aftbody drag. This was accomplished by separating the expanding flow from the nozzle external flap. The amount of flow injected was identified as the critical parameter. Injection pressure was found to only have secondary effect.

Multiple injection locations were found to provide greater benefit for a given amount of injection flow. Location of these injectors must be considered. The findings here suggest that growing the separation region from the trailing edge of the flap will lead to the greatest performance improvement with the least amount of flow injected.

FUTURE WORK

Future work should focus on developing methodology for determining the injector configuration that will provide the greatest performance improvement with the least amount of injected flow. This should be followed by a system wide investigation on performance. Since the effectiveness of the fluidic injection is not a strong function of the injection pressure, a variety of sources should be considered, including; ram air, fan bleed, compressor bleed, and diverting primary flow from the nozzle. Finally, the computational fluid dynamics should be calibrated against test data.

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[7] DalBellao, T.W., Georgiadis, N.J., Yoder, D.A. and Keith, T.G., "Computations of Internal and External Axisymmetric Nozzle Aerodynamics at Transonic Speeds". NASA/TM-2003-21273.

[8] DalBellao, T.W., Georgiadis, N.J., Yoder, D.A. and Keith, T.G., "Computational Study of Axisymmetric Off-Design Nozzle Flows". AIAA-2004-0530, January 2004.

[9] Engblom, W.A., "Numerical Prediction of SERN Performance Using WIND Code". AIAA-2003-4410, July 2003.

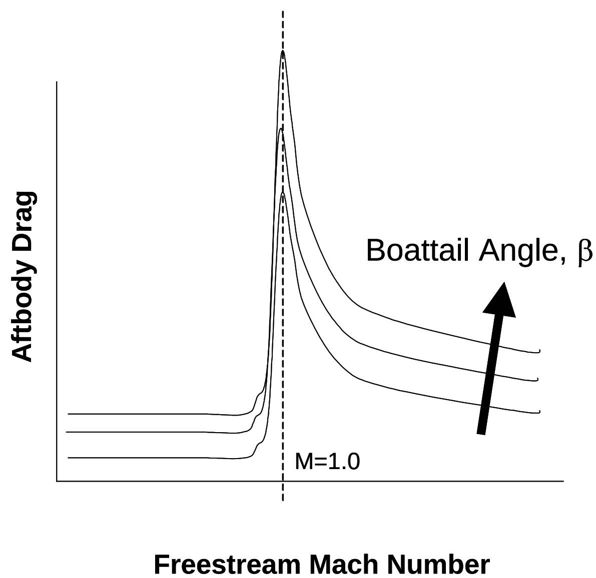

Figure 1 - Aftbody Drag Peaks for Transonic Mach Numbers

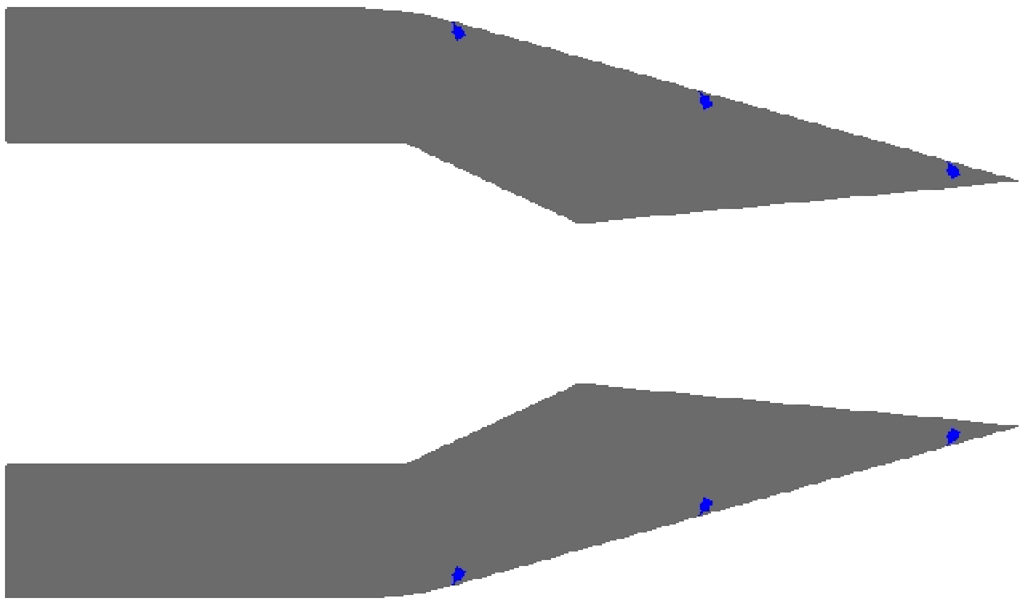

Figure 2: Baseline Nozzle

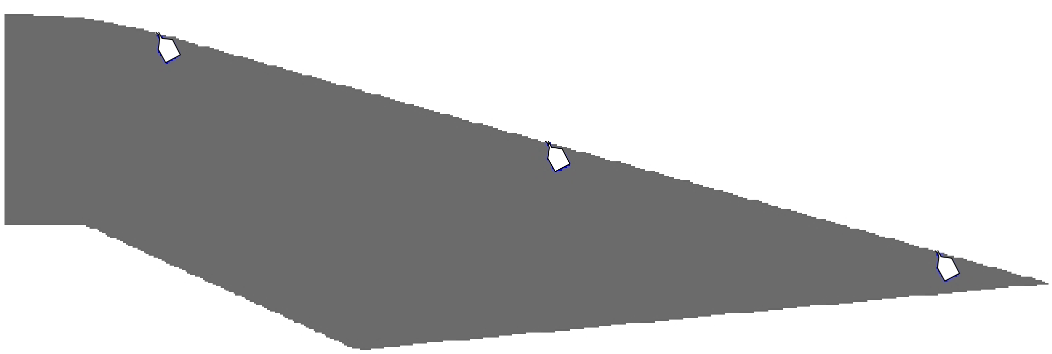

Figure 3: Fluidic Injector Locations Along Nozzle External Flap

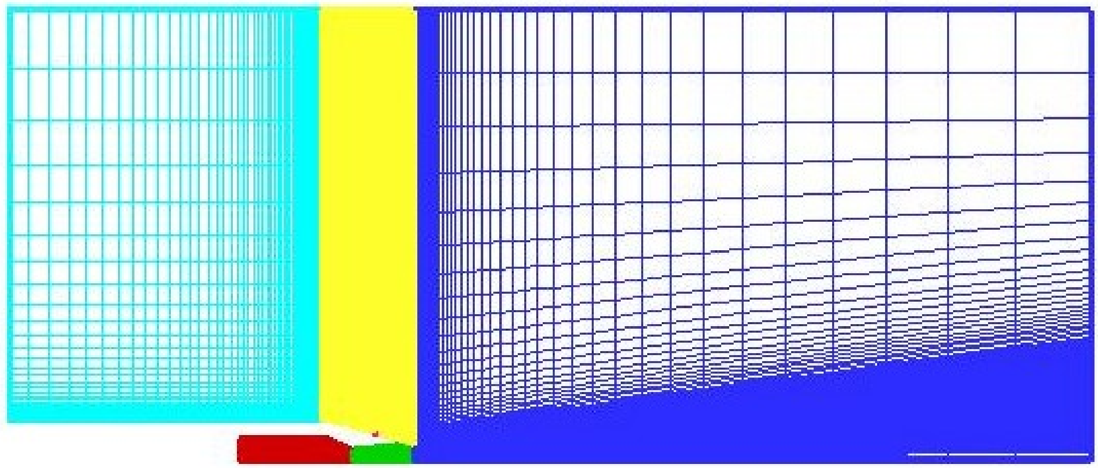

Figure 4: Overall Computational Domain

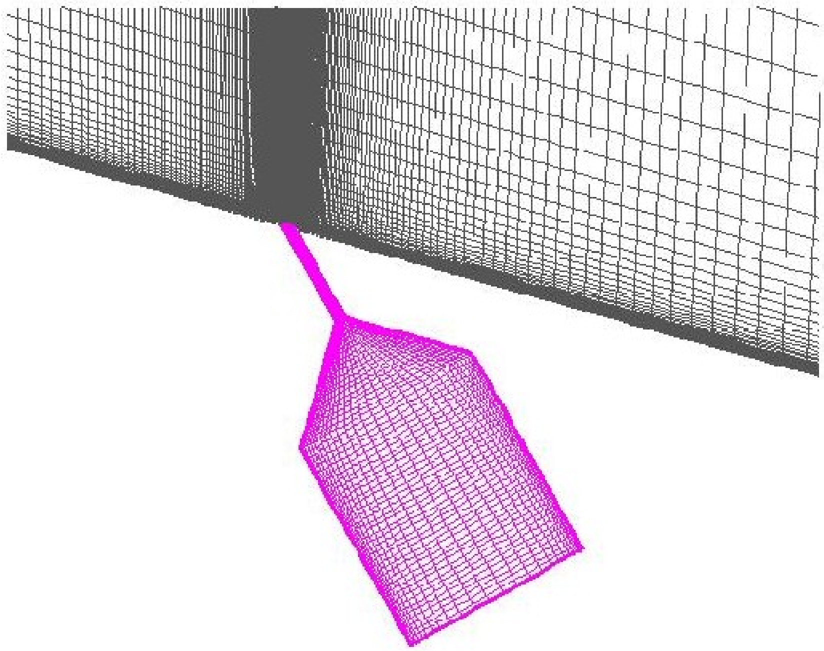

Figure 5: Computational Domain Around Injectors

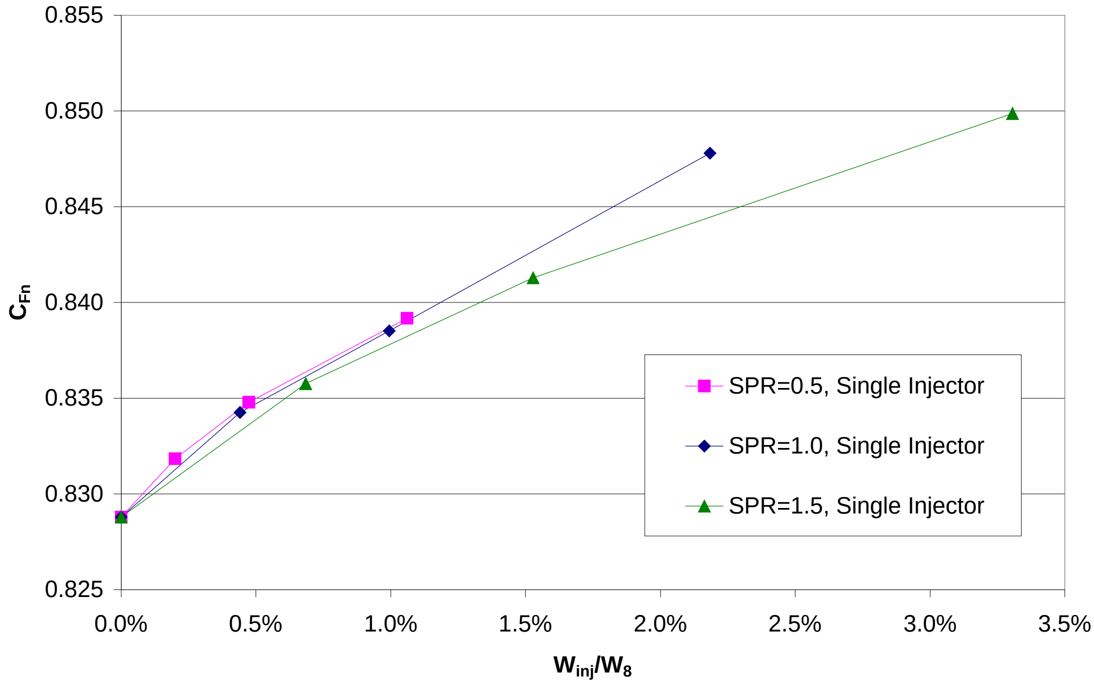

Figure 6: Thrust Coefficient Verse Injection Rate for Single Injector

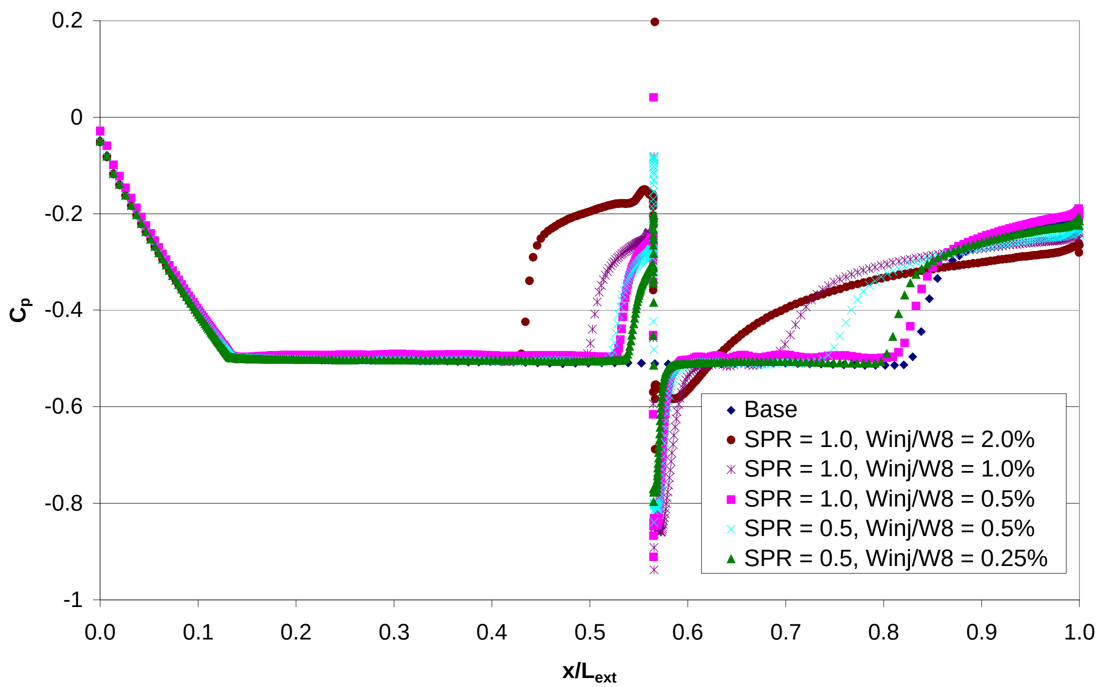

Figure 7: Pressure Distribution on External Flap for Single Injector

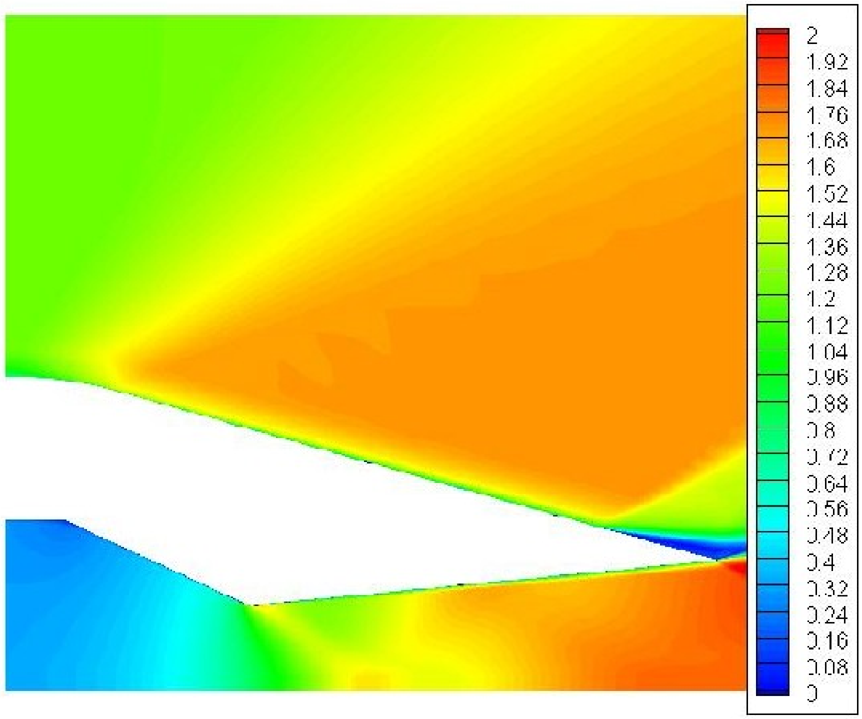

Figure 8: Baseline Mach Contours

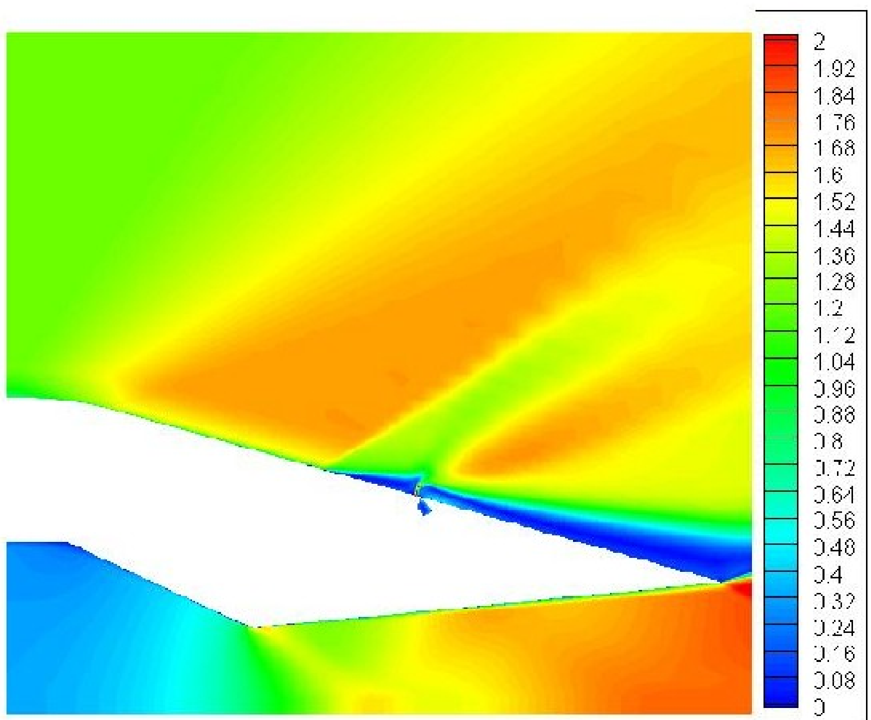

Figure 9: Mach Contours for Single Injector at SPR = 1, W_{inj}/W_8 = 2.0%

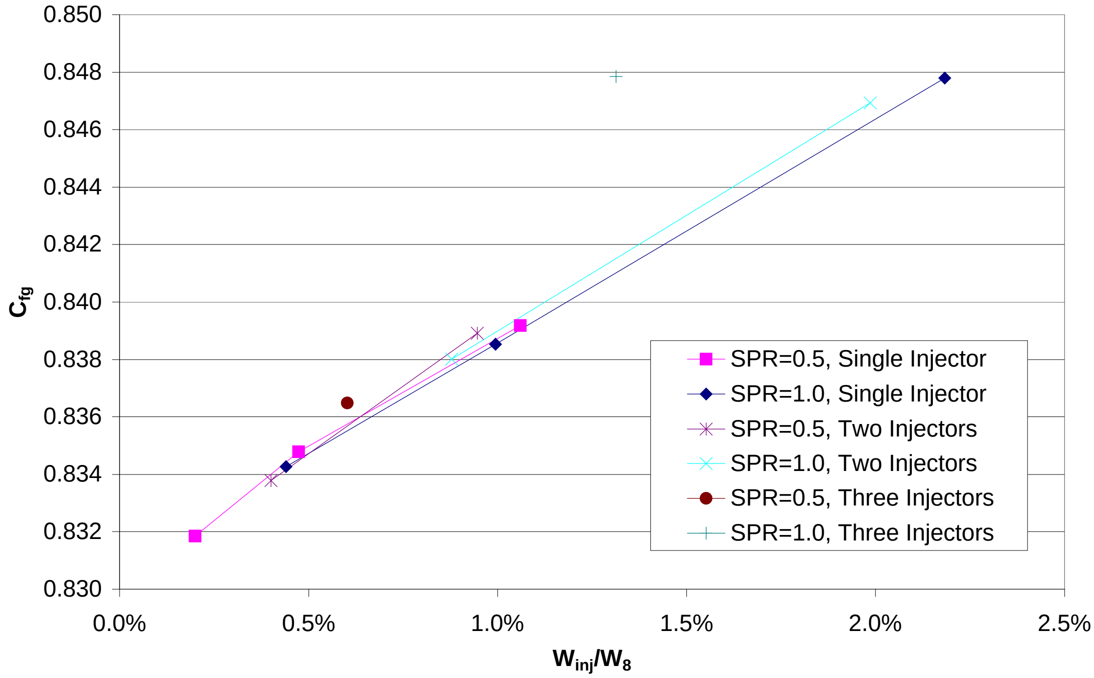

Figure 10: Thrust Coefficient for Single and Multiple Injectors

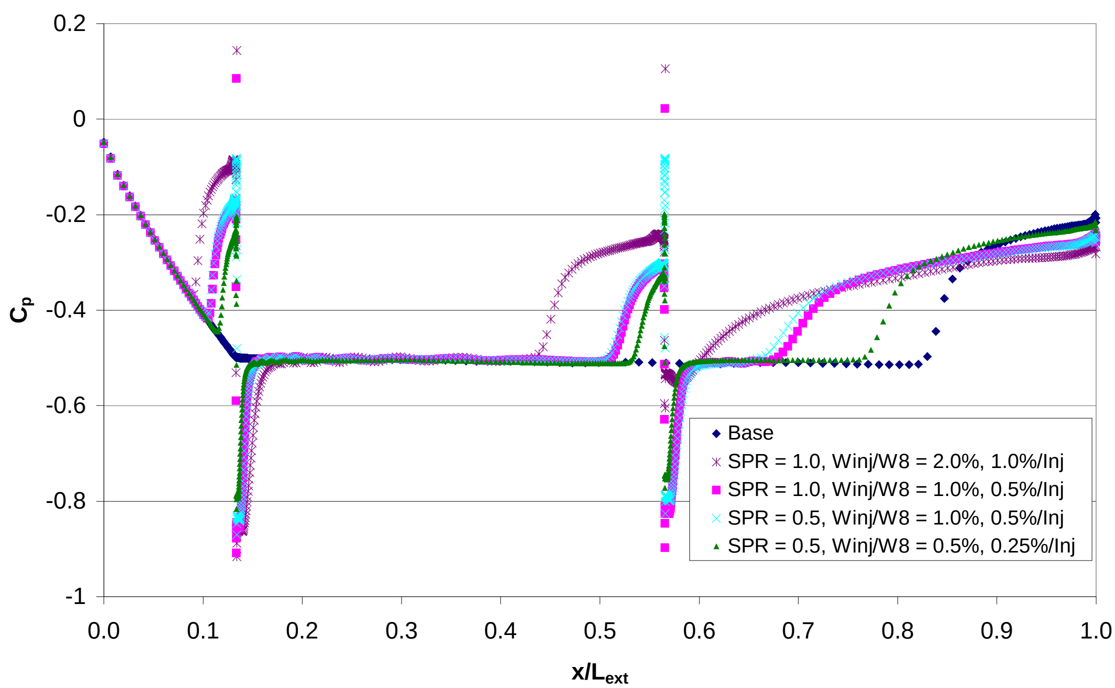

Figure 11: External Flap Pressure Distribution with Two Injectors

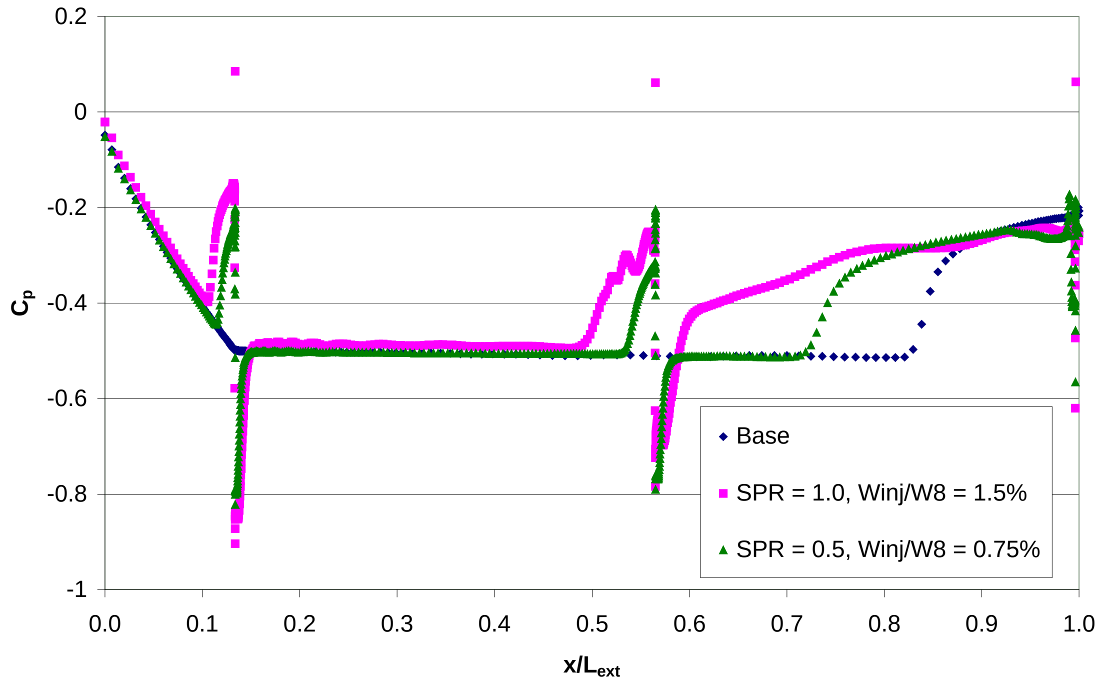

Figure 12: External Flap Pressure Distribution with Three Injectors

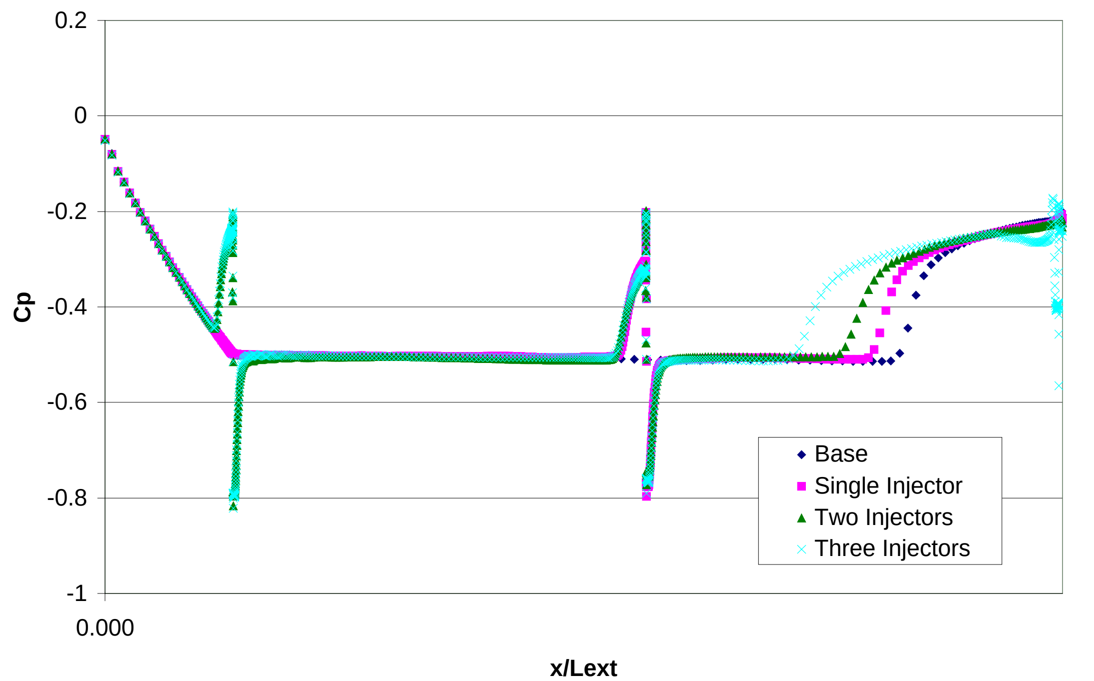

Figure 13: Comparison of Injector Configurations at SPR = 0.5% and Winj/W8 = 0.25% per Injector