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A Feasibility Study of Using Langley 0.3-m Transonic Cryogenic Tunnel Sidewall Boundary-Layer Removal System for Heavy Gas Testing

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Summary

This report presents the results of a preliminary study for using the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) sidewall boundary-layer system with heavy gas, sulfur hexaflouride (SF_6) as the test medium. It is shown that the drive motor speed/power of the existing system and the additional heat load on the tunnel heat exchanger are the major problems limiting the boundary-layer removal system performance. Overcoming these problems can provide the capability to remove about 1.5% of the test section mass flow at Mach number M=0.8 and about 5% at M=0.25. Previous studies have shown that these boundary-layer mass flow removal rates can reduce the boundary-layer thickness by a factor of two at the model station. Also, the effect of upstream boundary-layer removal on the airfoil test data is not likely to be significant under high lifting conditions. Near design conditions, corrections to the test Mach number may be necessary to account for sidewall boundary layer effects.

Introduction

The boundary-layer development on the sidewalls of a two-dimensional wind tunnel affects airfoil test data by introducing three-dimensional disturbances from the junction flow field[1]. This effect has long been recognized and many modern airfoil testing tunnels use some kind of boundary-layer control on the sidewalls. The location of the boundary-layer removal station is either upstream of the model or around the model. Considering the importance of limiting the sidewall boundary-layer effects in airfoil tests, the NASA Langley 0.3-m TCT incorporated a boundary-layer removal system early in its design phase. The present 0.3-m TCT (*Circa 1992*) sidewall boundary-layer removal system has undergone considerable development and research work since 1980. The early work was related to both active and passive removal in the 8" x 24" (*circa 1984*) slotted wall test section.[2,3] Later work relates to a more detailed evaluation of the active system with the presently existing adaptive wall test section.[4,5,6] It was demonstrated that the boundary-layer removal system in the active mode is capable of removing a maximum of 10% of test section flow at M=0.3 and about 4% at M=0.8.[5] The system performance was evaluated in the form of the compressor map, and the tunnel-compressor interface characteristic covering most of the 0.3-m TCT operational envelope.

The presently proposed 0.3-m TCT modification for use with heavy gas, sulfur hexaflouride (SF_6), affects the performance of the existing sidewall boundary-layer removal system. The passive mode of operation of venting the sulfur hexaflouride gas to atmosphere directly cannot be used, since this gas must be confined to closed loop cycle of recovery, liquefaction, and vaporization. Hence, it is required to operate the boundary-layer removal system in the active mode with SF_6 gas. The purpose of this brief study is to identify the operational limits and to discuss the expected benefits achievable by boundary-layer removal.

Nomenclature

b	test section width
c	airfoil chord
C_p	specific heat at constant pressure, kJ/kgK (Cp=0.75 for SF_6 in this study)
D	compressor tip diameter, m
h	test section height
J	compressor blade tip advance ratio
$\dot{m}_{bl}$	total sidewall mass flow removed, kg/s
$\dot{m}_t$	test section mass flow, kg/s
M	test section flow Mach number
N	rotational speed of drive motor
P	tunnel total pressure, atm
P_s	tunnel plenum pressure, atm
P_d	reinjection point total pressure in diffuser, atm
P_{sd}	reinjection point static pressure in diffuser, atm
P_{in}	compressor inlet pressure, atm
P_{out}	compressor outlet pressure, atm
r	sidewall-boundary layer compressor pressure ratio
T	tunnel total temperature, K
x	gear ratio between drive motor and compressor
z	top and bottom wall vertical displacement
α	percentile mass flow ratio, 100 $\dot{m}_b/\dot{m}_t$
γ	ratio of specific heats (γ=1.1 for SF_6 in this study)
δ^*	boundary layer displacement thickness
ρ	density, kg/m^3

Apparatus

The 0.3-m TCT is a single stage fan driven closed circuit tunnel capable of operating in the stagnation pressure range of 1.1 to 6 atm and 78 to 329 K temperature in nitrogen gas. It has an adaptive wall test section of 0.33-m x 0.33-m cross section. The top and bottom walls are of flexible stainless steel plates. The test section Mach number ranges up to transonic speeds for wall adaptation work. However, Mach numbers as high as 1.5 have been obtained with fixed nozzle shaping of adaptive walls.

The operational limits of the tunnel with SF_6 gas test will be different. The maximum pressure will be about same. However, the stagnation temperature will be near ambient conditions of 310 to 320 K. An analysis of the new tunnel operational limits as modeling and control study is presented in reference 8. Figure 1 shows the estimated performance of the tunnel with modifications now proposed and in progress. It can be seen that the maximum achievable test section Mach number with SF_6 gas is likely to be 0.8 at a Reynolds number of 27 million on a 0.18-m chord model.

Active Sidewall-Boundary Layer Removal System Performance with SF_6 Gas

Figure 2a shows a schematic of the boundary-layer removal system presently existing at 0.3-m TCT for the nitrogen gas operation. It consists of a pair of perforated plates flush on the tunnel sidewalls upstream of the model. The suction region is approximately 0.15-m wide by 0.325-m high. The boundary-layer mass flow removed through the perforated plates is carried by separate ducts with individual digital valves (DV1 and DV2) for monitoring the flow. The digital valves consist of 14 numbers of calibrated nozzle expected to choke at very small pressure ratios across the nozzle. The discharge from the digital valves leads to a common duct. The discharged gas has two flow paths. The first path is through valve BL1 which vents the gas to atmosphere and is used for passive operation with nitrogen test gas. The second path leads the flow back to tunnel through a reinjection valve so that the mass equilibrium is maintained. This reinjection is realized through a compressor. The second path goes through an isolation valve to the suction inlet of the compressor. Provision were made for spraying nitrogen to cool the flow into the compressor. However, this design feature did not work and a new strategy of using the system was established as detailed in reference 5.

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The boundary layer compressor is a centrifugal device driven by a variable speed 6 pole, 3-phase 750 kw water cooled AC induction motor. The motor is supplied from a 10-120 Hz variable frequency generator system with constant voltage/frequency ratio. The maximum drive speed is 2140 rpm which is increased to 21000 rpm through a 1:9.8 gear box. The discharge from the compressor outlet has three paths, first leading the flow back to tunnel, second leading to the atmosphere through an isolation valve and third for bypass type surge control valve (SV).

While the concept of active boundary-layer removal system remains essentially same for the SF_6 gas application, the performance limits, pressure loss calibrations, and operational boundaries change. A preliminary study by Atlas Copco has indicated that the compressor can be used with SF_6 gas without modification. However, the compressor speed with SF_6 gas will be lower compared to nitrogen gas. As mentioned earlier, reference 5 provides the most recent on-site performance evaluation of the compressor-ducting system for nitrogen gas boundary-layer removal. Based on these results, the performance envelope of the boundary layer system with SF_6 gas test has been made. The estimated operational boundary of the SF_6 gas version of the 0.3-m TCT is shown in figure 1.[8] This figure shows the limitations on the maximum Mach number-Reynolds number combinations due to heat exchanger cooling capacity limit and the fan over current limit. The operation of the sidewall-boundary layer system naturally affects this envelope due to the thermodynamic interactions between the two systems. A study is now made on this interaction.

Figure 2b shows the compressor-tunnel interface scheme, where as the figure 2c shows the desirable flow control scheme. The flow from the two sidewalls are connected to a high speed radial flow compressor, which creates a pressure ratio such that a mass flow $\dot{m}_{bl}$ is removed from the test section to the down stream diffuser. The pressure ratio required to inject the mass removed from the sidewall back to tunnel circuit can be estimated from the following identity.

$$r = \frac{P_{out}}{P_{in}} = \frac{(1+\frac{\gamma-1}{2}M^2)^{\frac{\gamma+1}{2(\gamma-1)}}}{(1+0.27\frac{\gamma-1}{2}M^2)^{\frac{\gamma+1}{2(\gamma-1)}}} \frac{1}{\left\{1-0.257\, M^2\, \alpha^2(1+\frac{\gamma-1}{2}M^2)\right\}}$$

where $\alpha = 100\,\dfrac{\dot{m}_{bl}}{\dot{m}_t}$

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The denominator expression in brackets corresponds to the line losses in the suction line due to mass flow $\dot{m}_{bl}$. The constant 0.257 estimate is based on the results of reference 5. This loss expression tends to 1 when α the mass flow ratio is zero. The denominator multiplier 0.27 is a function of the area ratio between the test section and the reinjection point of the tunnel. The line loss expression is specific to the existing ducting and valve system with the digital valves full open and has been obtained from experiments detailed in reference 5. The line loss factor is liable to change with any modifications to the existing ducting system. For the SF_6 gas where $\gamma=1.1$, the value of α can be determined for various cases of pressure ratios and tunnel test section Mach number. A plot of mass flow ratio vs M is shown in figure 3, which provides the estimated performance limits for the SF_6 gas sidewall-boundary layer system. This provisional estimate assumes that there are no problems in obtaining the desired surge free pressure ratios (from 1 to 2.4) and mass flows. Continuing on the same premise, the mass flow $\dot{m}_{bl}$ has been estimated for the case of tunnel pressure of 6 atm at 320 K and is shown in figure 4. The mass flows range up to 8 kg/s.

However, the existing Atlas Copco compressor has performance limitations. Utilizing the performance test data from reference 5, the approximate pressure ratio limitation has been determined as a function of drive speed. Though the compressor is a radial flow device, an equivalent compressor tip velocity ratio J is used as the basis to predict compressor performance. This ratio is taken to be invariant between SF_6 gas and nitrogen gas for proper operation.

$$J = \frac{u}{xND} \propto \left\{\frac{\dot{m}_{bl}}{\rho\,N}\right\}_{nitrogen} = \left\{\frac{\dot{m}_{bl}}{\rho\,N}\right\}_{SF_6}$$

Since the ratio of densities between SF_6 and nitrogen is 5.1, the drive speed ratio required for a given mass flows $\dot{m}_{bl}$ is $\frac{1}{5.1}$. Figure 5 shows an estimated plot of pressure ratio and drive speed. The compressor speed is 9.8 times higher than the drive speed. The figure 5 shows that the maximum drive speed cannot exceed about 600-650 revolutions per minute to obtain the desired mass flow and pressure ratios. This figure also shows an approximate location of the surge line. For the 0.3-m TCT boundary compressor system, a 750 kw 2400 synchronous rpm 6 pole induction motor drives the compressor. The speed control system is based on a variable frequency generator of range 10 to 120 Hz, whose lowest stable speed is about 240 to 300 rpm. The power capability of motor is 20 kw/100 rpm. These two limitations constrain the use of the existing system for SF_6 gas application.

The power consumed by the compressor can be estimated using the adiabatic expression:

$$\text{Power} = \dot{m}_{bl}\, C_p\, \Delta T, \quad r = \left(\frac{T + \Delta T}{T}\right)^{\frac{\gamma}{\gamma - 1}}, \quad \Delta T = T\left(r^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

$$\text{Power} = \dot{m}_{bl}\, C_p\, T\left(r^{\frac{\gamma - 1}{\gamma}} - 1\right)$$

This expression has been used to obtain the power required to drive the compressor and is shown in figure 6. The power estimates are based on a tunnel pressure of 6 atm. The power linear scales down with lower pressures. This power results in heating of the tunnel resident gas and hence is an added burden on the tunnel heat exchanger. It further shrinks the tunnel performance boundary shown in figure 1.

Boundary-layer removal effectiveness on airfoil test data:

From the above performance estimates of the boundary layer removal system in the active mode, it is expected that a maximum removal rate of 5% is possible at low Mach numbers. The maximum removal rate reduces to about 1.5% at higher Mach numbers. These removal rates compare favorably with the removal rates used in the earlier airfoil tests with nitrogen.

The main purpose of the boundary layer removal is to reduce the adverse effects of the sidewall boundary layer thickening/separation on the model test data. In this regard, the experience with nitrogen mode operation will be helpful in determining the extent of gain that can be expected with SF_6 gas testing. Extensive experimental and theoretical evaluations of the sidewall boundary-layer effects have been carried out at the 0.3-m TCT. These studies have added to a better understanding of the flow phenomenon at the airfoil/sidewall junction and the extent of its influence on the airfoil mid-span pressure measurements. A brief review of these studies specific to testing in the 0.3-m TCT is presented in the following sections.

Empty Test Section boundary-layer measurements

One of the factors which determines the severity of the sidewall-boundary layer effects is the empty test section boundary-layer thickness. This has been measured with

nitrogen test gas for both the previous slotted wall test section (*Circa 1984*) and the present adaptive wall (*Circa 1992*) test sections. The boundary-layer measurements were made with a total pressure rake at the model location station with different levels of upstream boundary layer removal. The effect of upstream boundary-layer mass flow removal is to decrease the boundary layer thickness at the model station. The extent of this reduction in boundary-layer achievable is shown in figure 7 for adaptive wall test section. The boundary-layer removal is most effective in reducing the boundary-layer thickness, up to about 1% flow removal. With higher removal rates, the effectiveness decreases, and the change in boundary-layer thickness is not significant. For adaptive wall test section, the value of $\frac{2\delta^*}{b}$ is about 0.013 when there is no removal and reduces to about 0.006 with maximum removal at a free stream Reynolds number of 27 million/foot in the Mach number range 0.3 to 0.8. The Reynolds number effect becomes secondary when the suction is present.

Theoretical flat plate boundary layer calculations show that the sidewall boundary-layer displacement δ^* is about 10% less for SF_6 compared to nitrogen for the same stagnation conditions.[6] Hence, the boundary-layer measurements with nitrogen will likely represent an upper bound. With SF_6 gas operation $\frac{2\delta^*}{b}$ is likely to be slightly lower. Further, it is desirable that the boundary-layer removal rates at upstream station be kept less than about 2% of the test section mass flow. Higher mass flows introduce large perturbation and consequent corrections of uncertain magnitude to free stream calibration.

Airfoil Tests

The effect of upstream boundary-layer removal on airfoil test data has been evaluated in the 0.3-m TCT in both the previous slotted wall and present adaptive wall test sections. The adaptive wall test section being much wider, the sidewall boundary-layer effects tend to be less severe than in the slotted wall test section of 0.2-m width. Contrary to observations in other test facilities which prompted installation of sophisticated boundary-layer removal system, the sidewall boundary-layer removal effects in 0.3-m TCT have not been found to be significant under the conditions tested. This is primarily due to the fact that the perforated plates have a high degree of smoothness and do not introduce rapid thickening of the sidewall boundary-layer due to roughness effects under zero removal conditions. Figures 8 to 11 show the measured sidewall boundary-layer removal effects on airfoil characteristics and wall adaptation

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with a 0.23-m chord supercritical airfoil model in the 0.3-m TCT. No significant boundary-layer removal effects can be seen on the mid-span pressure distribution at a Mach number of 0.765 (Figures 7 and 8). However, the top and bottom wall converged shapes with boundary-layer removal are different from no-removal conditions.

Downstream of the removal region, both the top and bottom walls move inwards. This is because the adaptive walls tend to correct for the reduction in the free stream Mach number downstream of the removal region. The wall adjustment strategy responds to the down stream changes in Mach number and drives the walls to hold the Mach number at the upstream value irrespective of the amount of mass flow removed. Since the walls correct for the Mach number changes, the effect of boundary-layer removal on the wall Mach number distribution is not significant (Figure 10).

Figure 11 shows that for airfoils tested in 0.3-m TCT, the lift and drag data are not greatly influenced by the upstream sidewall boundary-layer removal. Under low and near design lifting conditions, when the sidewall boundary-layer is attached, the effect near the mid span is small. Theoretical methods are now available to correct for the sidewall boundary-layer effects under these conditions. At high angles of attack when there is significant separation, it is likely that the boundary-layer removal at an upstream station will not be fully effective in suppressing the separation. Applying suction around the model/sidewall junction region will be more beneficial. However, this has to be done with caution so as not to upset the free stream conditions by applying too much suction.

Sidewall Boundary Corrections

The sidewall boundary-layer thickness tends to reduce in the region of the airfoil model due to acceleration of the flow. This has the effect of introducing a negative blockage for the free stream flow. From physical reasoning, it may be argued that the junction flow effects tend to decrease with increasing model span (or test section width) for a given model chord. The junction flow effects tend to decay non-linearly away from the wall. Hence, the effect near the model mid-span where the measurements are made depends on the model aspect ratio. This is true irrespective of the flow conditions at the junction; either separated or attached. The dependence of residual corrections on aspect ratio has been demonstrated in reference 7, for attached flow conditions. With a high aspect ratio model, the mid-span measurements remain unaffected by the junction

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flow at the sidewall. Following these considerations, corrections to the test Mach number have been shown to depend on the empty test section boundary-layer thickness and the model aspect ratio. With typical boundary-layer thicknesses expected to prevail with SF_6 gas operation, the corrections to test Mach number will be about -0.008 with no boundary layer suction and reducing to about -0.003 with suction. With shorter models of 0.15-m chord, the corrections will be still lower.

Some observations on operational limits

The performance estimates made in this analysis are of a preliminary nature. The analysis is based on certain simplification and assumptions. Following inferences can be drawn from this analysis.

1. The estimate of the compressor drive speed required for SF_6 gas operation, with existing 9.8 gear ratio, is in the range of 100 to 600 rpm. Existing variable speed drive probably cannot be operated lower than 240 to 300 rpm.

2. The drive system needs nearly 130 kw power at $M=0.8$ and $P=5$ atm which is near the high end of pressure-Mach number envelope. The power capability of the drive motor is limited to 20 kw/100 rpm. This limitation is likely to result in an overload of the drive motor if more than 0.2N kw is drawn at any operating point.

3. The compressor induced heat adds to the tunnel flow induced heat and imposes a new burden on the presently proposed 550 kw tunnel heat exchanger. If the boundary-layer system is used, it will further limit the Reynolds number-Mach number envelope of the SF_6 gas version of the tunnel.

4. If the drive speed, drive power, and the heat exchanger problems are overcome, a mass flow removal of 1.5% of test section flow appears to be feasible at $M=0.8$ and a 5% removal at $M=0.25$.

Recommendations

This study shows that the sidewall boundary-layer effects tend to be small for the 0.3-m TCT and cause no significant changes in the test data either with or without boundary-

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layer removal. This is largely due to the fact that the boundary-layer removal media (perforated plates) is effective in not causing any adverse boundary-layer growth due to surface roughness. Considering this fact, it appears that it may not be advisable to undertake any major upgrade of the system, but limit changes to minor upgrades. However, to make effective use of the existing capability of the boundary-layer removal system on a need basis for selected tests, the following recommendations are made.

a) Measure the performance of the system with SF_6 gas and experimentally determine the boundary layer effectiveness. To perform this test, the speed/power constraints on the drive system must be overcome. This study will be similar to the detailed performance evaluation tests with nitrogen.[5]

b) Determine the empty test section boundary-layer thickness with a rake measurement to determine the extent of sidewall boundary-layer corrections necessary for airfoil data.

c) Following the studies in (a) above, arrive at proper calibrations or empirical factor to calculate the boundary-layer removal rates under various test conditions.

d) Minor modifications to boundary-layer removal ducting so that the suction can be applied around the model for high lift testing. The suction required for high lift testing will be much smaller than compared to the upstream removal rates.

e) Improvements to flow rate measurement system using orifice plates as discussed in reference 5 in lieu of item (c) if found necessary after detailed testing.

Acknowledgements

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8. Balakrishna, S, and Kilgore, W. A.: Modeling & Control Study of the NASA 0.3-Meter Transonic Cryogenic Tunnel for Use with Sulfur Hexaflouride, NASA CR 189737, December, 1992.
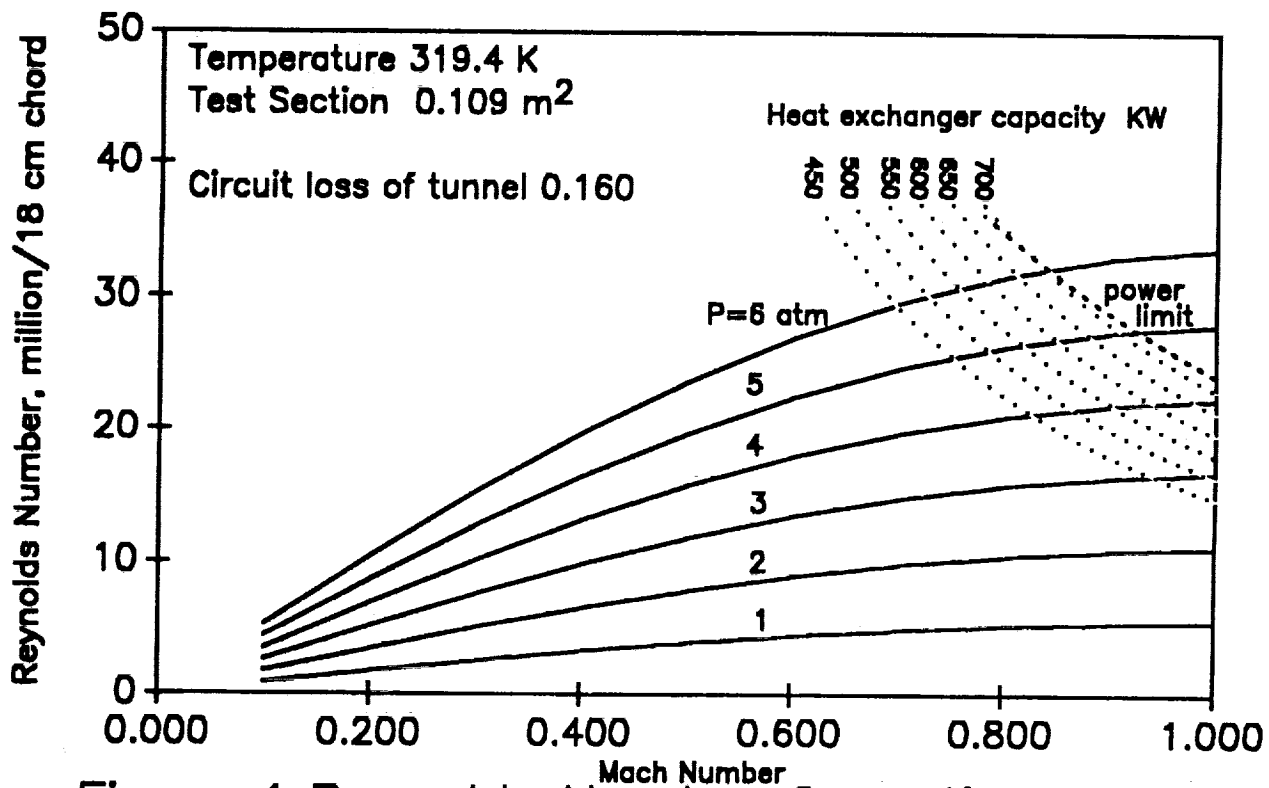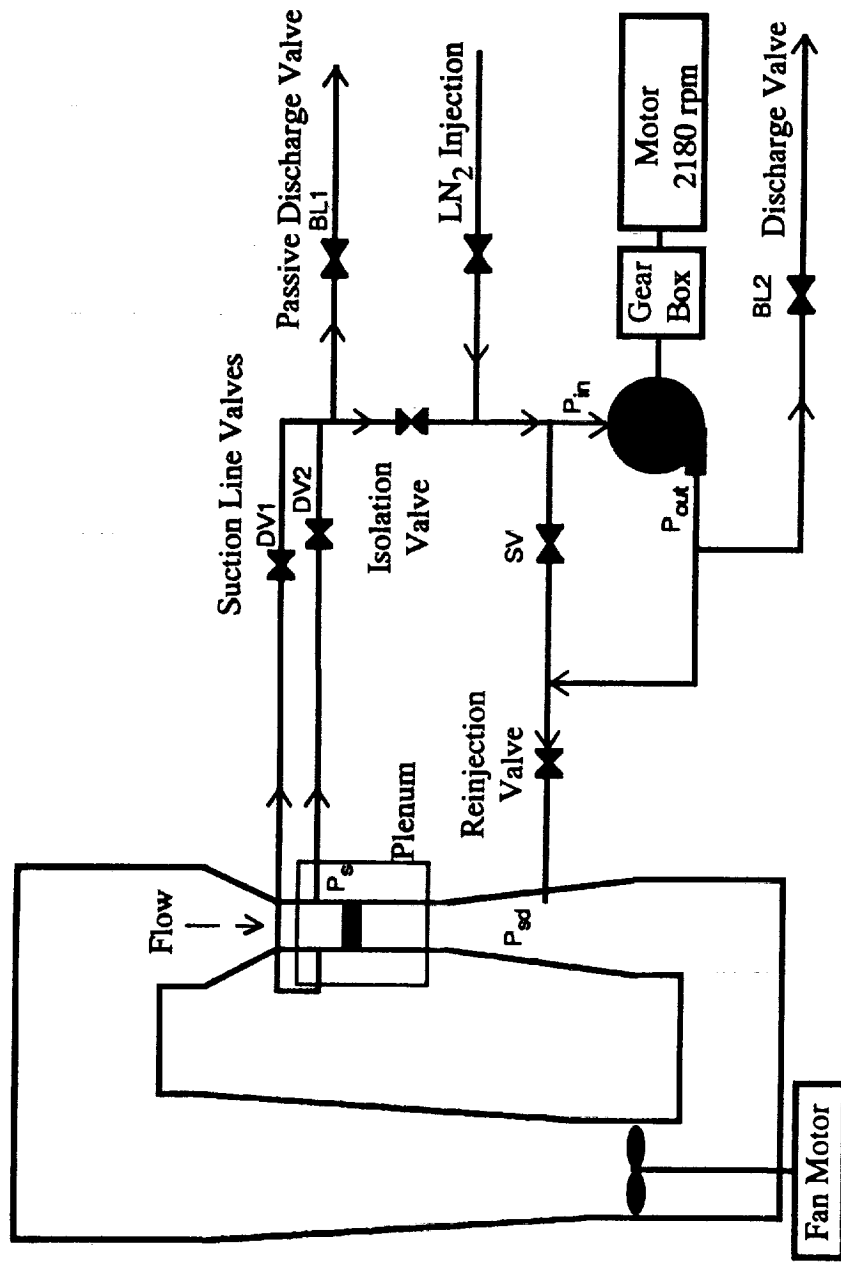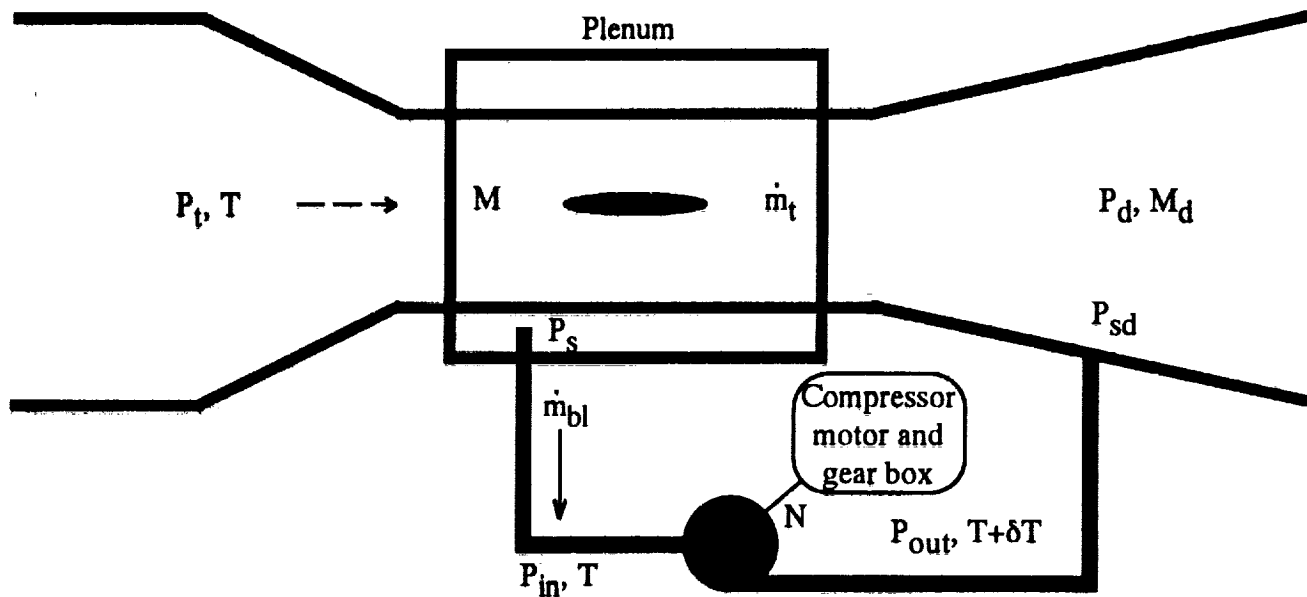
Figure 1:Reynolds Number Operating Envelope

Figure 2A. Existing 0.3-m TCT boundary-layer control schematic for SF6.

Tunnel static pressure ratio, P_{sd}/P_s
Compressor pressure ratio, P_{out}/P_{in}

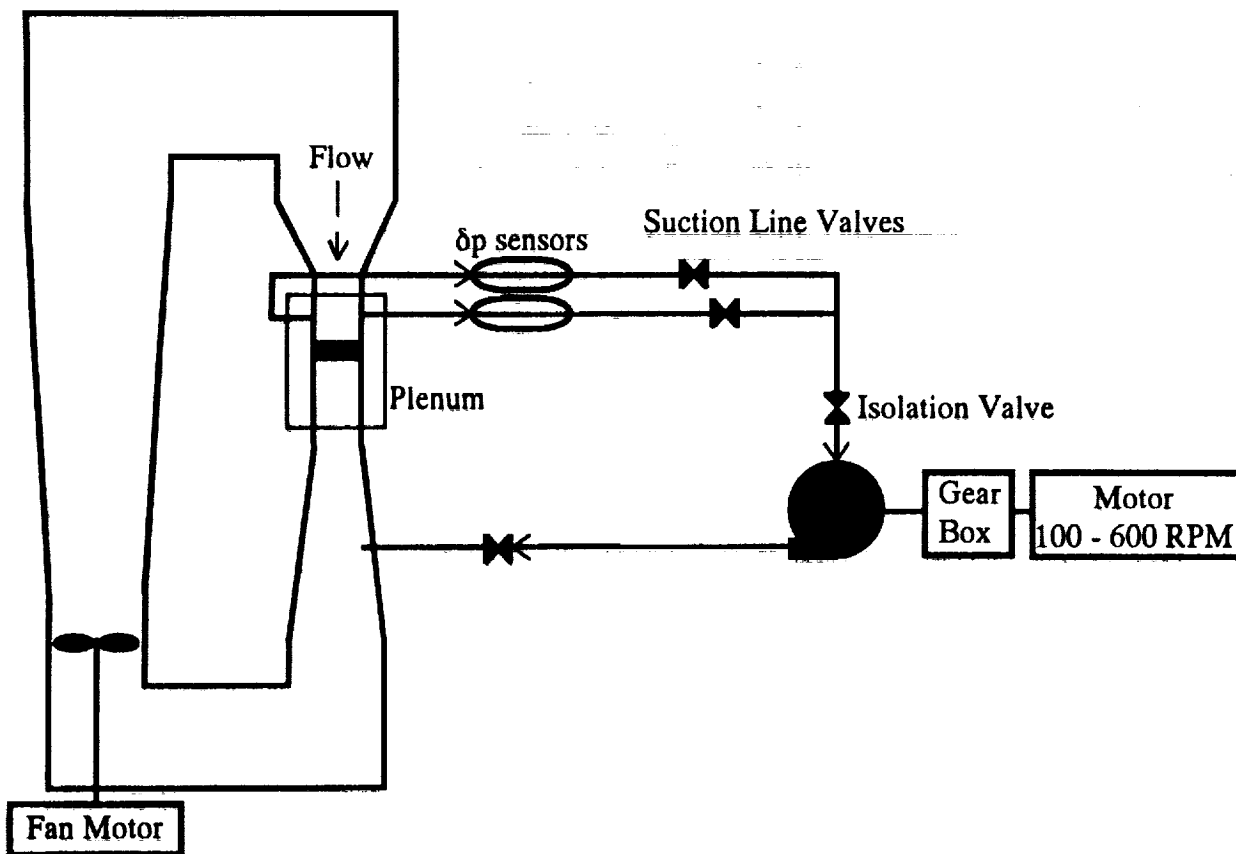**Figure 2B.** Tunnel circuit and boundary-layer control compressor interface schematic.

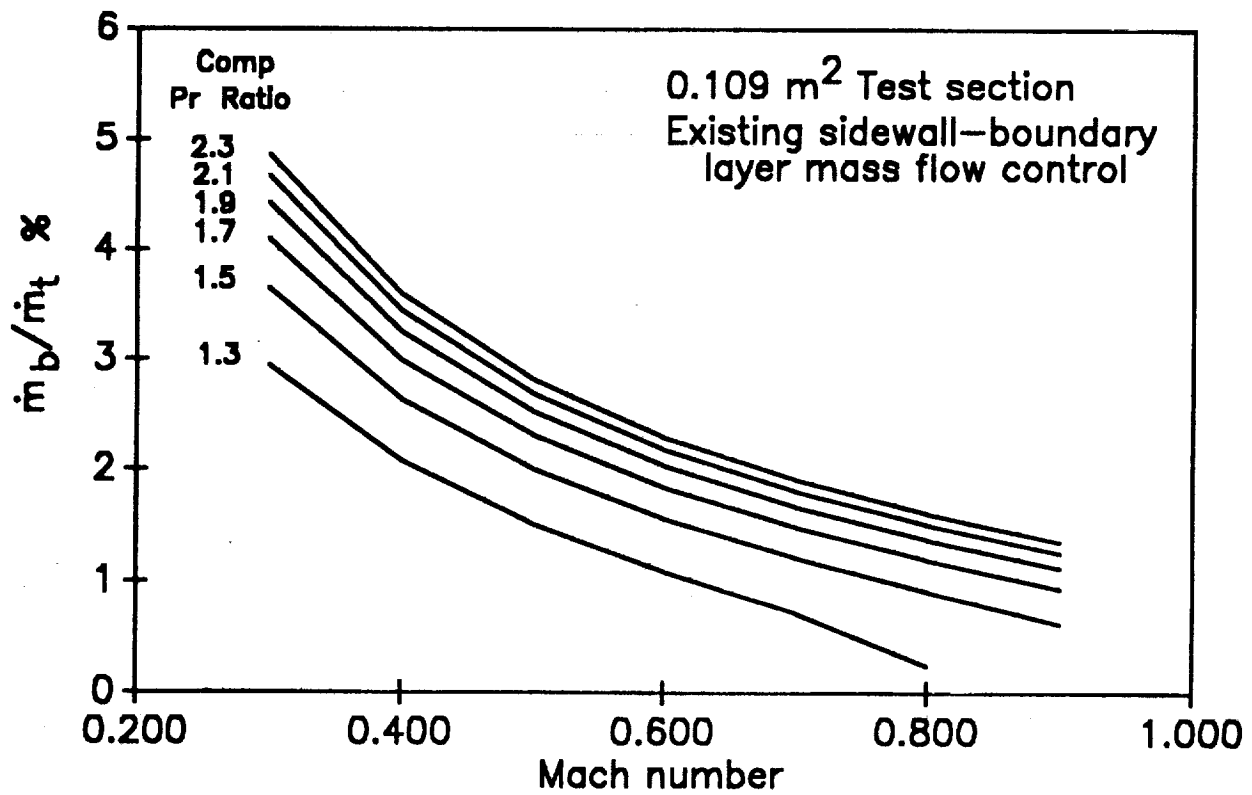**Figure 2C.** Proposed 0.3-m TCT boundary-layer control schematic for SF6.

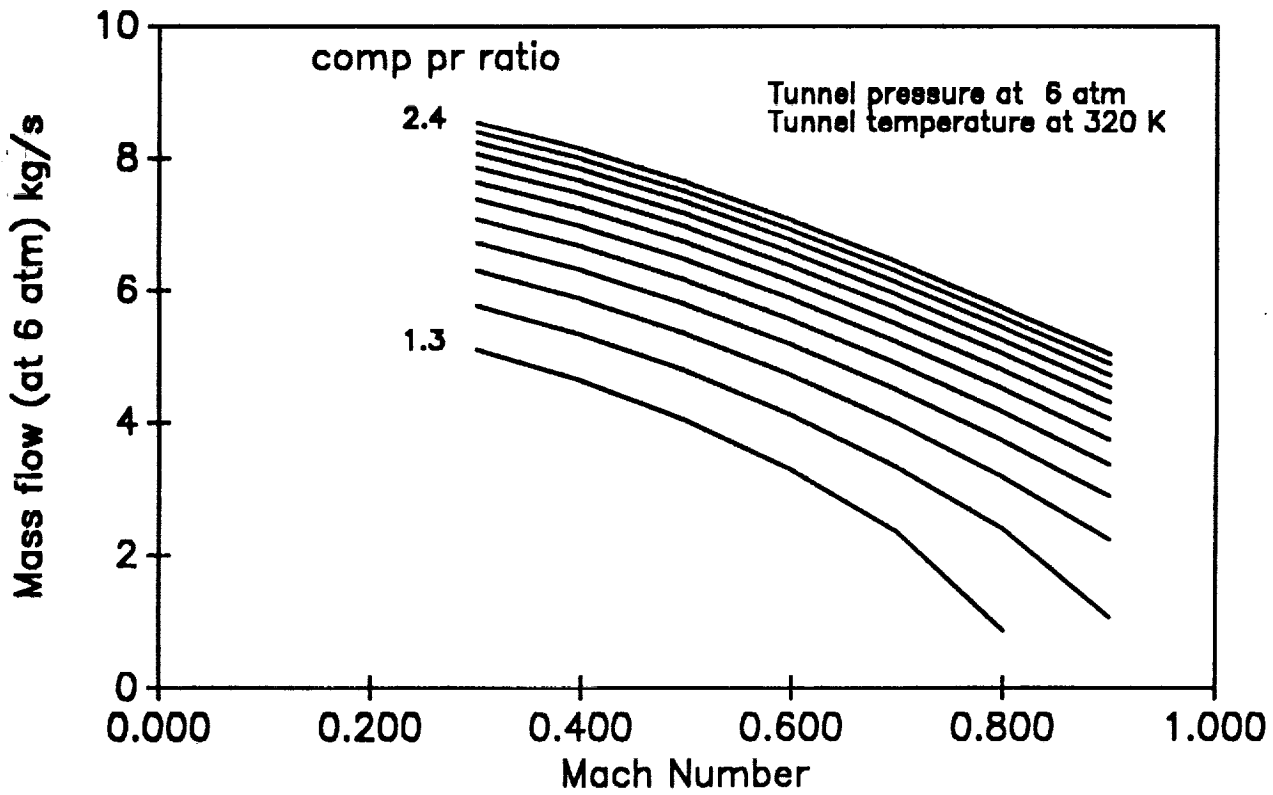Figure 3:Estimated performance Limits for the Heavygas
Sidewall—Boundary Layer system

Figure 4: Estimated mass flow for the heavygas
Sidewall—Boundary layer system
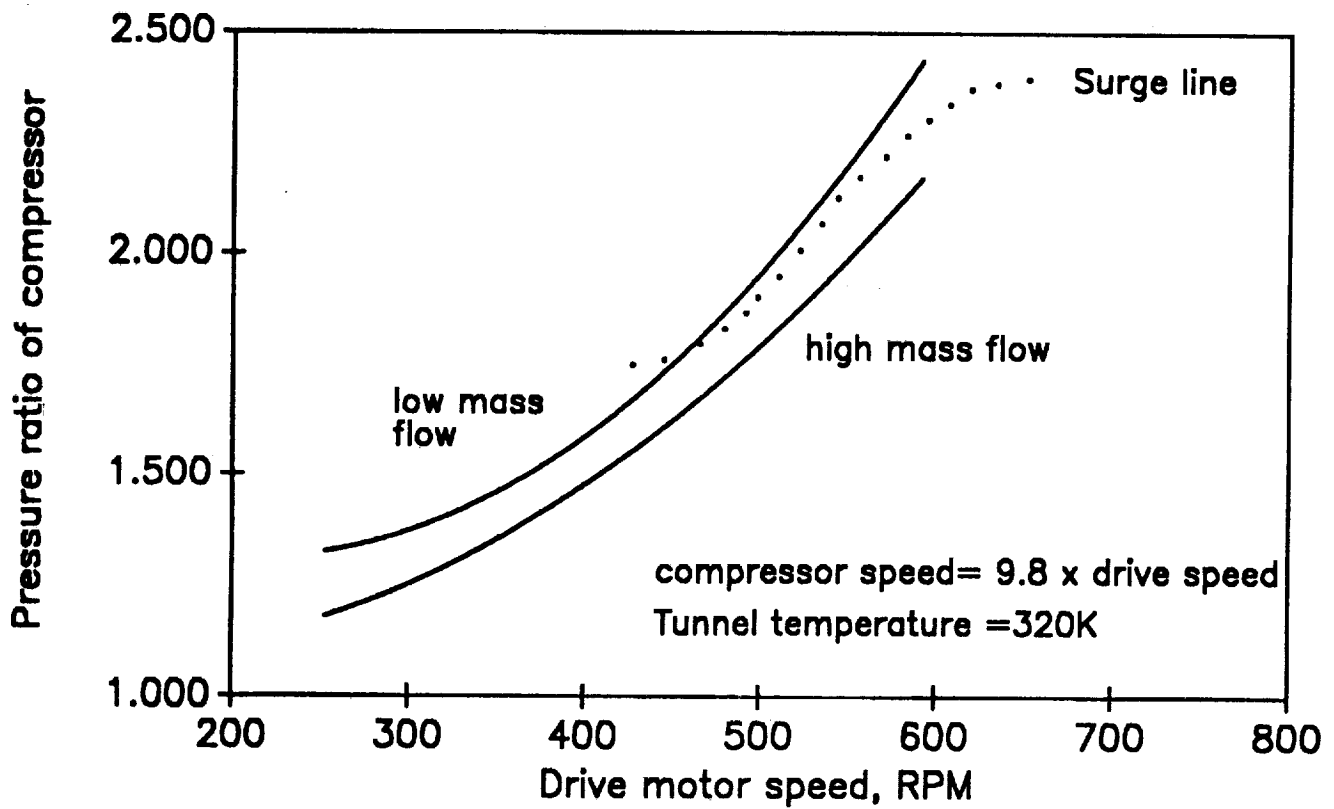
Figure 5 Estimated drive speed—pressure ratio for heavy gas
Sidewall—Boundary layer system
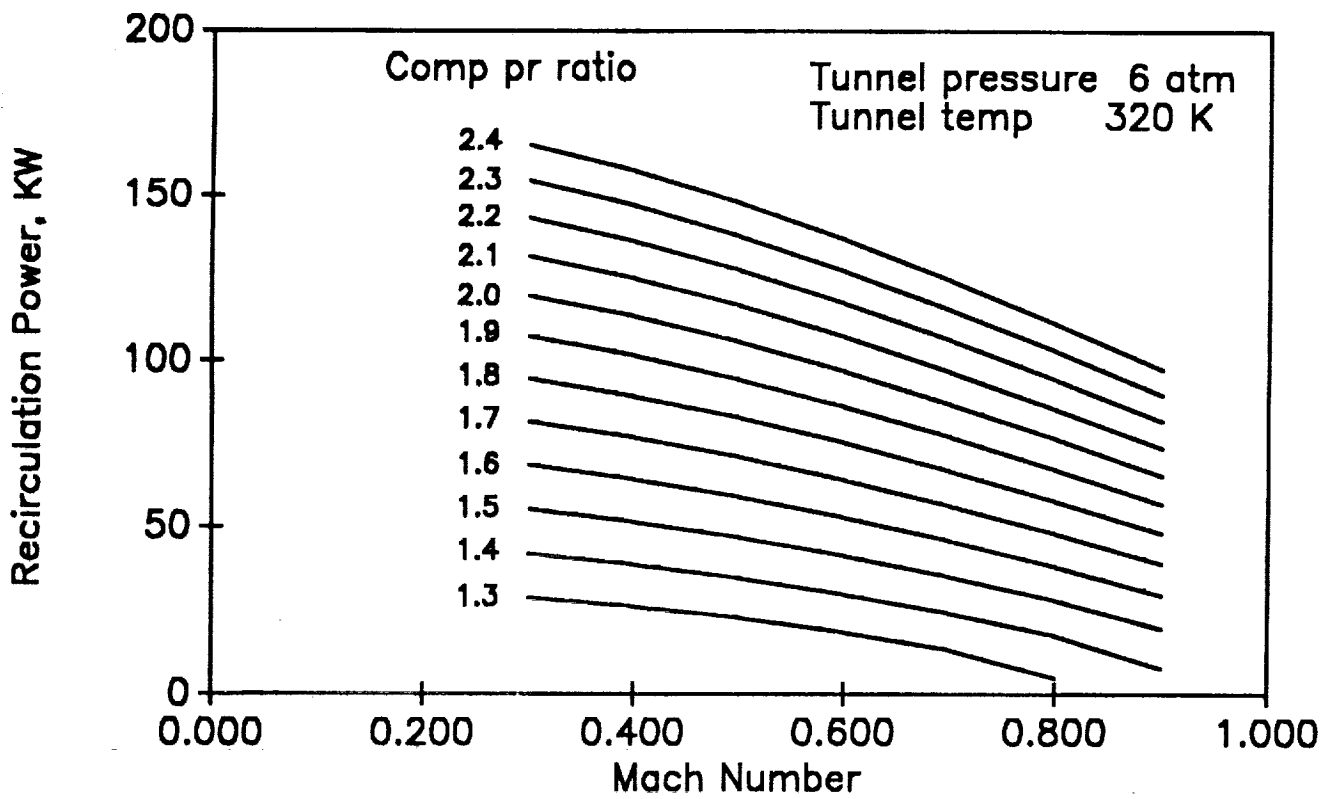
Figure 6: Estimate of Power required for heavy gas
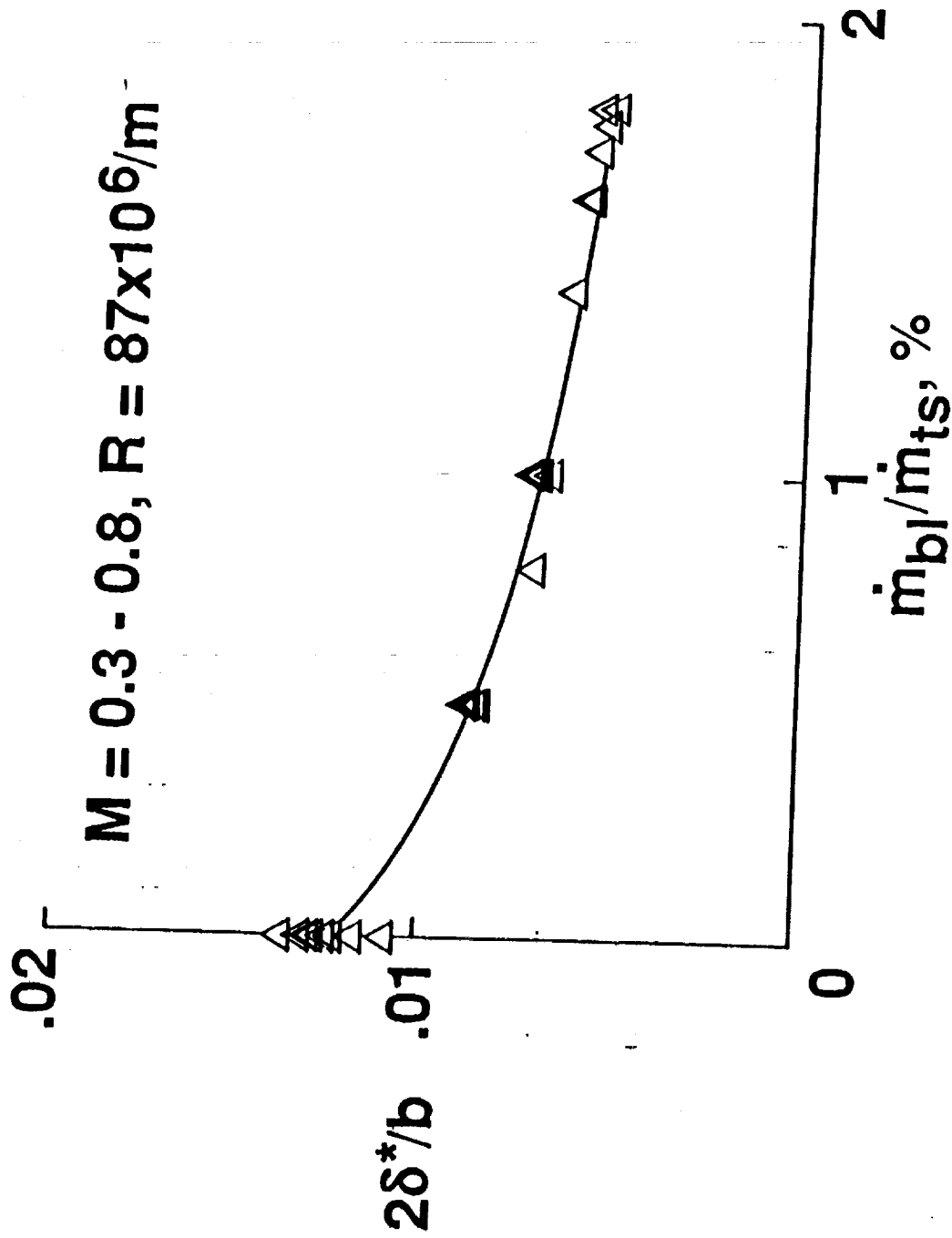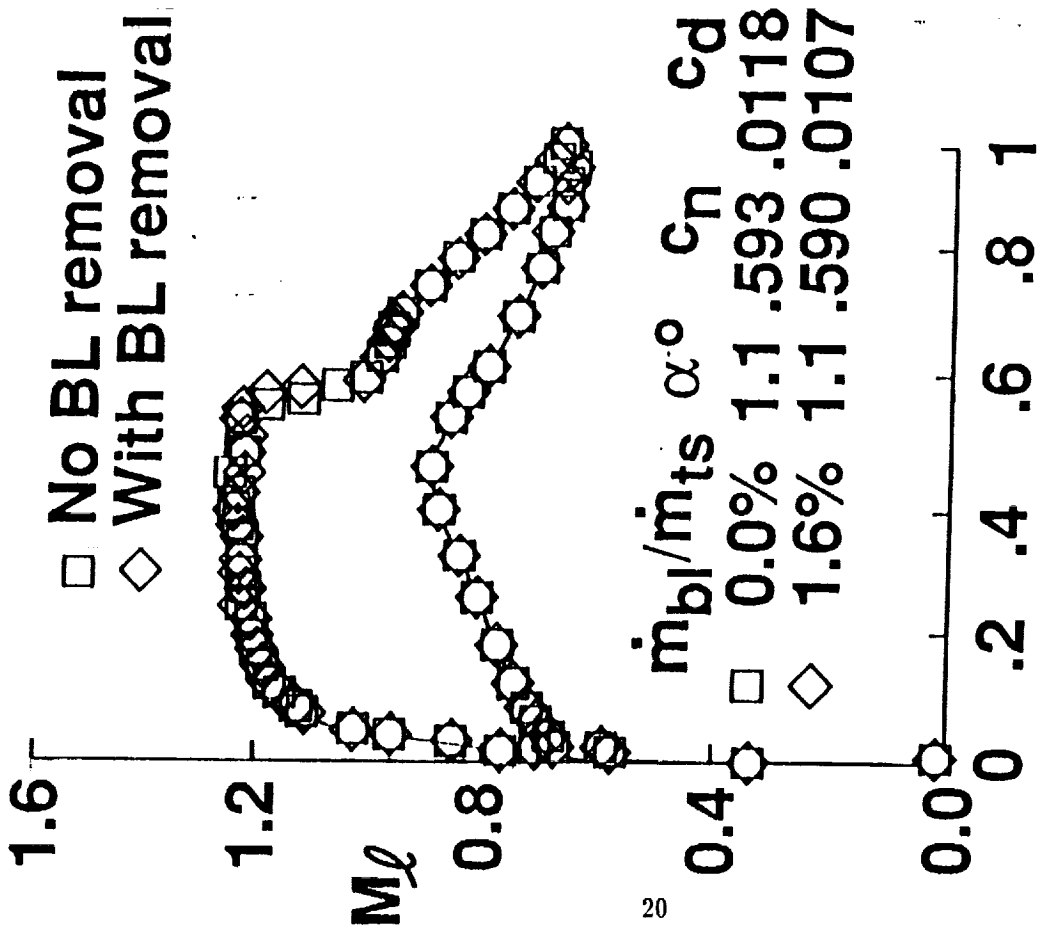sidewall—boundary layer suction system
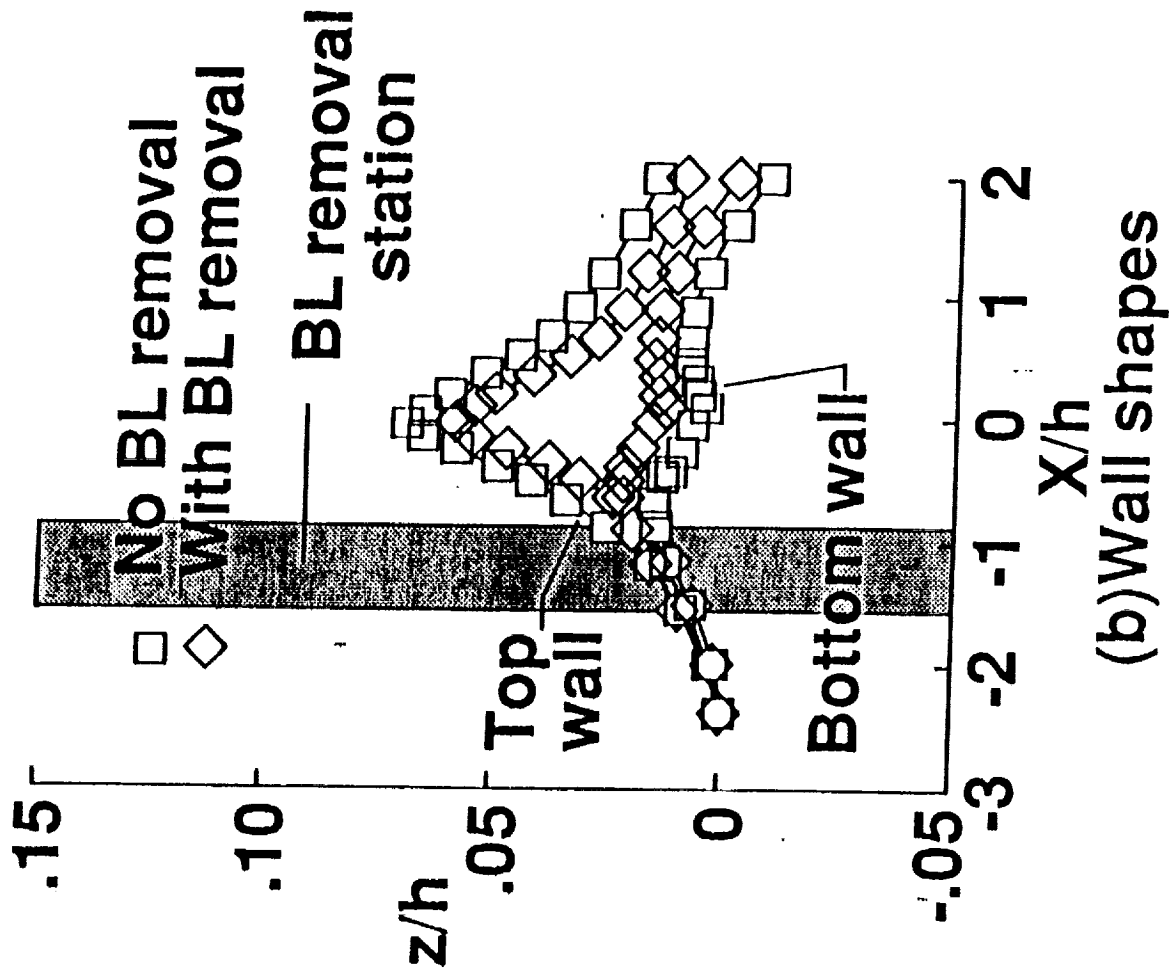
Fig 7. Displacement thickness variation at model station with upstream boundary-layer removal (Empty test section).

M = 0.3 - 0.8, R = 87x10⁶/m⁻

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□ No BL removal
◇ With BL removal

BL removal
station

Top wall

Bottom wall

z/h

.15

.10

.05

0

-.05

-3 -2 -1 0 1 2

X/h

(b) Wall shapes

□ No BL removal
◇ With BL removal

	$\dot{m}_{bl}/\dot{m}_{ts}$	α°	c_n	c_d
□	0.0%	1.1	.593	.0118
◇	1.6%	1.1	.590	.0107

M_ℓ

1.6

1.2

0.8

0.4

0.0
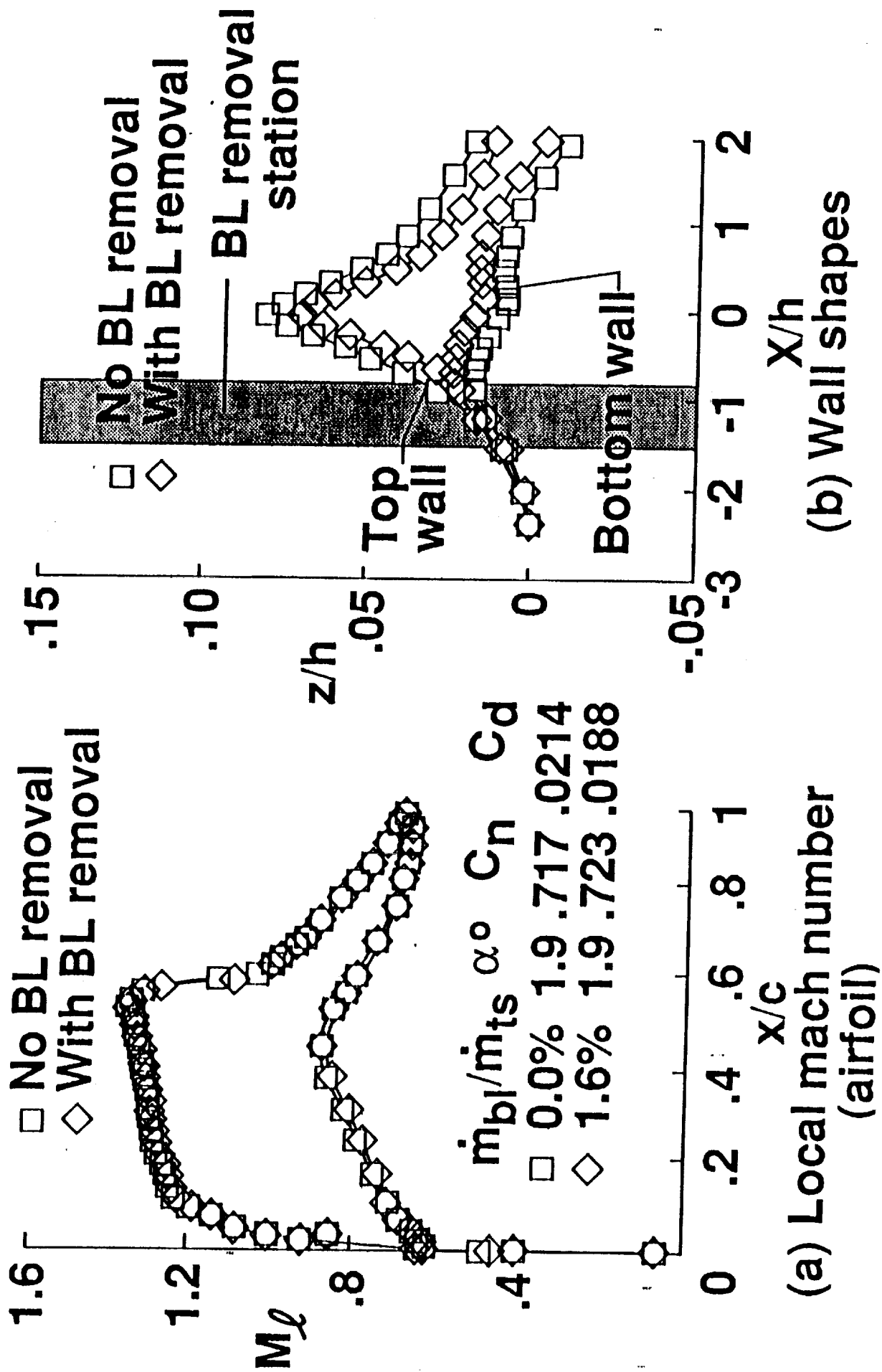
0 .2 .4 .6 .8 1

x/c

(a) Local mach number (airfoil)

Fig. 8. Effect of upstream boundary-layer removal on airfoil local Mach number and top and bottom wall shapes ($M = 0.765$, $R_c = 20 \times 10^6$, $\alpha = 1.1^\circ$)
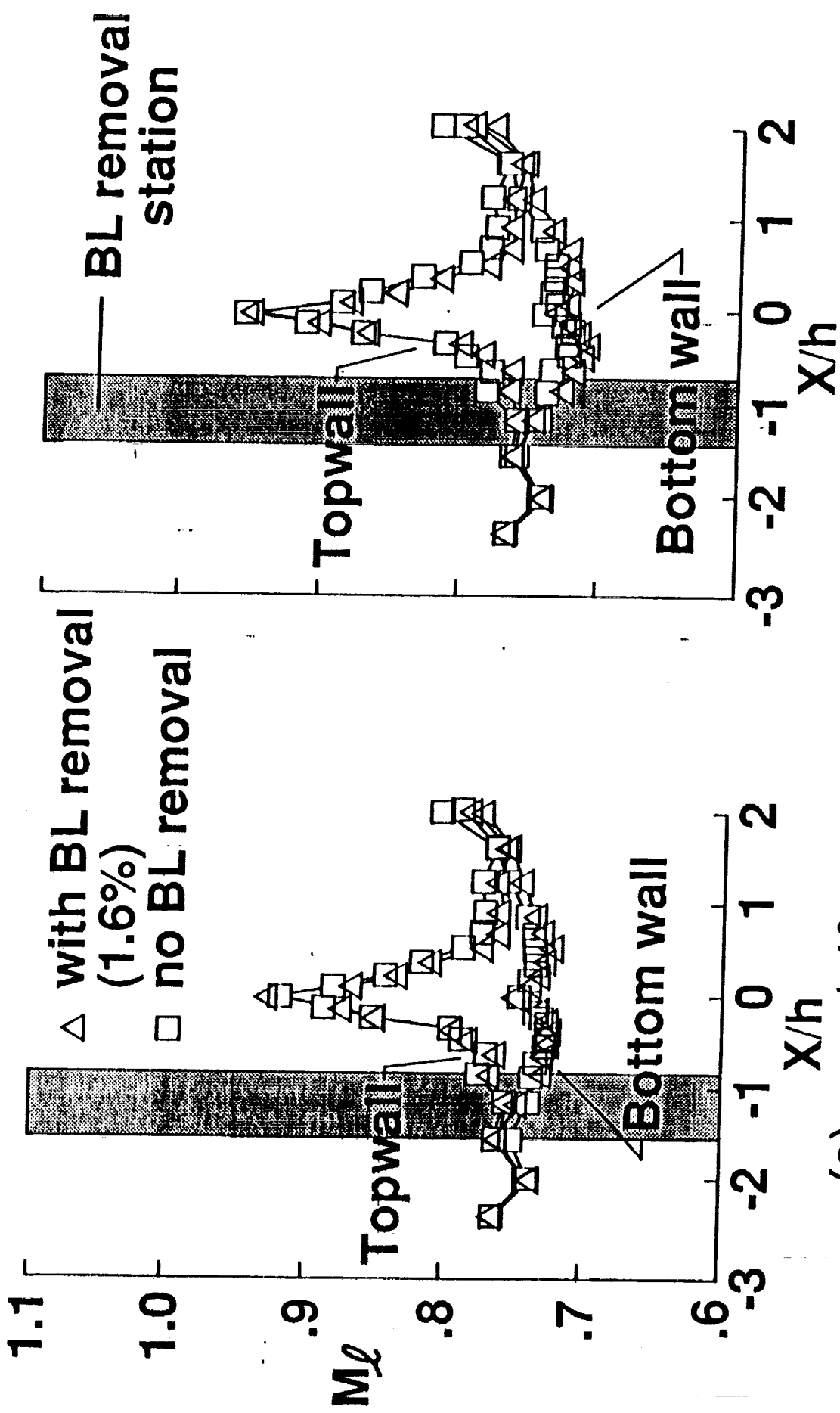
Fig. 9. Effect of upstream boundary-layer removal on airfoil local Mach number and top and bottom wall shapes ($M_\infty = 0.765$, $R_c = 20 \times 10^6$, $\alpha = 1.9°$)

Fig. 10. Effect of boundary-layer removal on wall Mach number distribution $(M_\infty = 0.765, R_c = 20 \times 10^6)$.
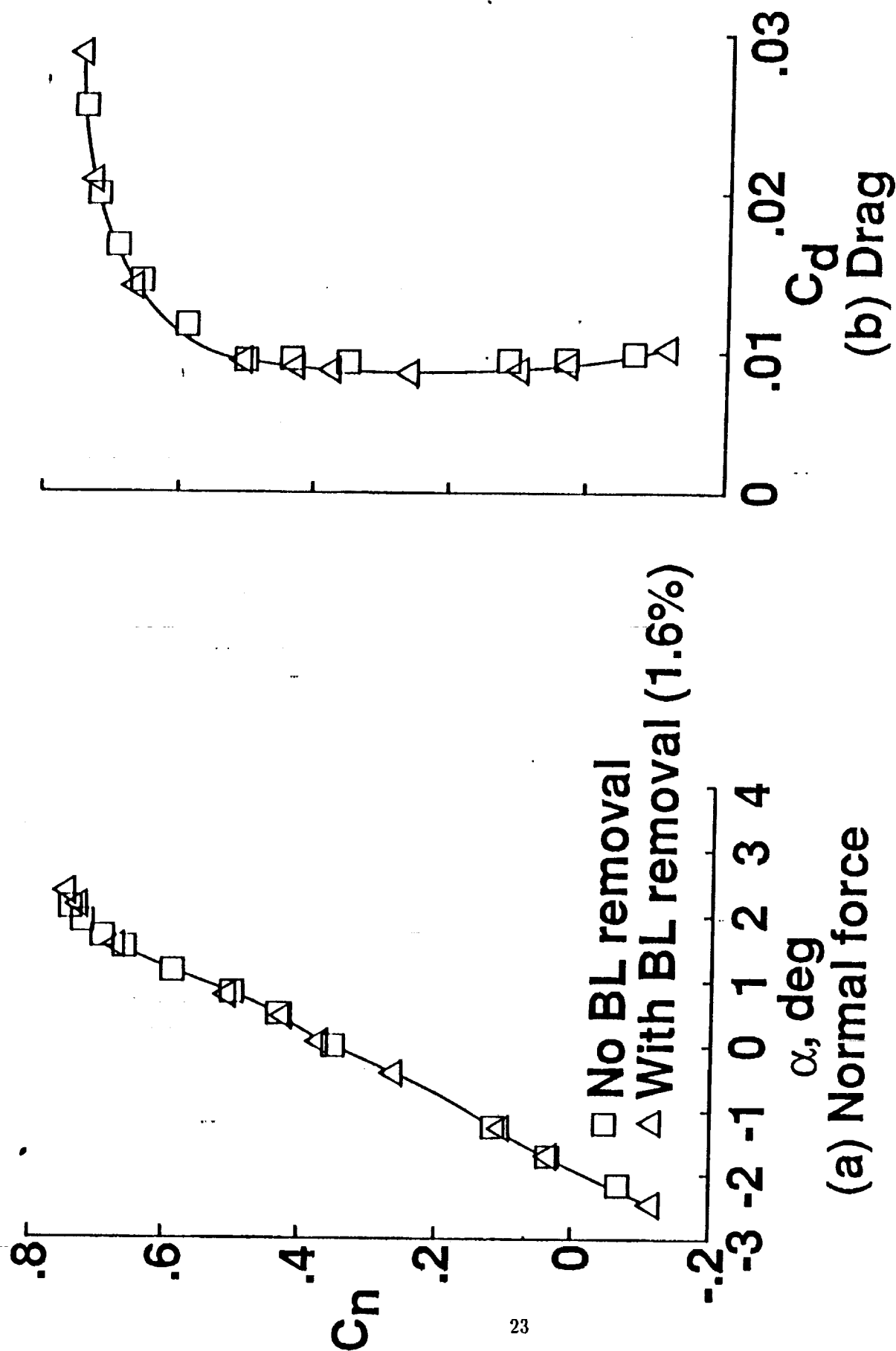
Fig. 11. Comparison of airfoil normal force and drag coefficients with and without sidewall boundary-layer removal ($M=0.765$, $R_c=20 \times 10^6$).

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REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words)

This report presents the results of a preliminary study for using the 0.3-m Transonic Cryogenic Tunnel sidewall boundary-layer removal system with heavy gas, sulfur hexafluoride as the test medium. It is shown that the drive motor speed/power of the existing system and the additional heat load on the tunnel heat exchanger are the major problems limiting the boundary-layer removal system performance. Overcoming these problems can provide the capability to remove about 1.5% of the test section mass flow at Mach number M=0.8 and about 5% at M=0.25. Previous studies have shown that these boundary-layer mass flow removal rates can reduce the boundary-layer thickness by a factor of two at the model station. Also, the effect of upstream boundary-layer removal on the airfoil test data is not likely to be significant under high lifting conditions. Near design conditions, corrections to the test Mach number may be necessary to account for sidewall boundary-layer effects.

14. SUBJECT TERMS
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