



Overview of Circulation Control Research (Emphasizing NASA CFD and Experiments)

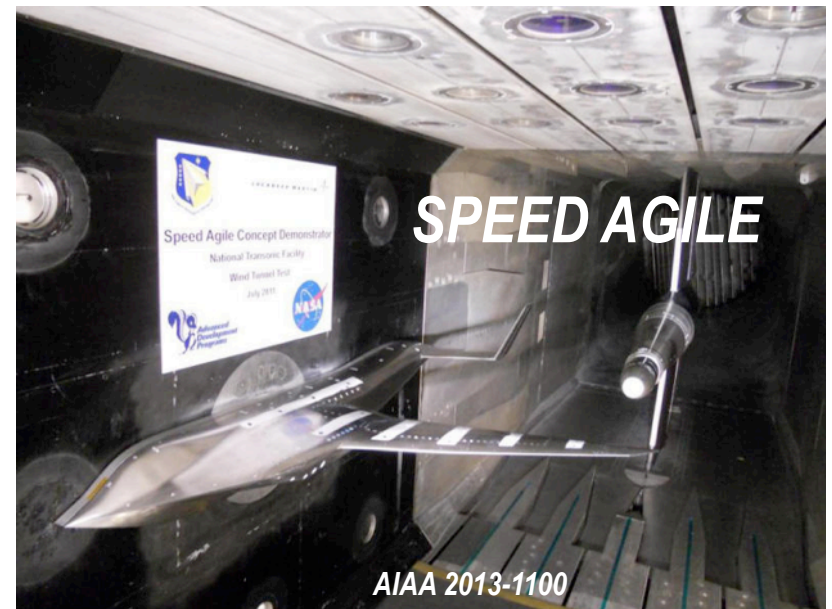
**Gregory S. Jones, Ph.D.
Configuration Aerodynamics Branch
NASA Langley Research Center**





OUTLINE

- BACKGROUND
- 2-D EXPERIMENTS
- 3-D EXPERIMENTS
- CONCLUDING REMARKS





SOLVING AVIATION'S CHALLENGES THROUGH NASA INNOVATION

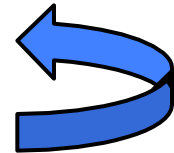




AERONAUTICS RESEARCH MISSION DIRECTORATE (ARMED)



- ***Advanced Air Vehicles Program (AAVP)***
Advanced Air Transport Technology (AATT)



- ***Airspace Operations and Safety Program (AOSP)***



- ***Integrated Aviation Systems Program (IASP)***



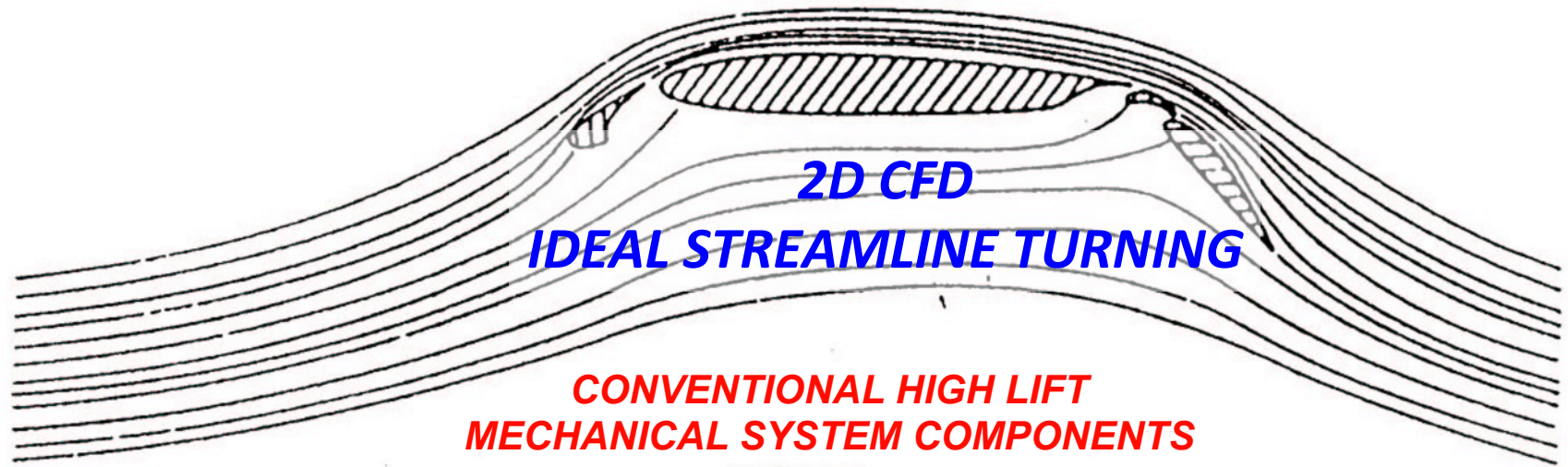
- ***Transformative Aeronautics Concepts Program (TACP)***

WHAT RESEARCH DO I CONTRIBUTE TO THE ADVANCED AIR TRANSPORT TECHNOLOGY?

- *Subject Matter Expert* in Flow Physics associated with Powered Lift and Next Generation Low Drag Cruise Wings
 - Active Flow Control
 - Circulation Control and Simplified High Lift Systems (Coanda)
- Integrated Active Flow Control Systems into Advanced Aircraft and Propulsion Systems
- Dual Use Technologies
 - DOD (AFRL and ONR)
 - CIVIL Aviation



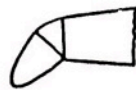
CONVENTIONAL HIGH LIFT SYSTEMS



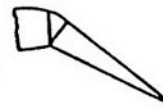
LEADING-EDGE

TRAILING-EDGE

L.E. DROOP



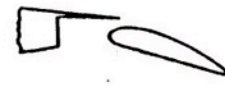
PLAIN
FLAP



L.E. SLAT

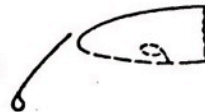


1-SLOT
FLAP



Boeing 767 & 787

FLAT
KRUEGER



2-SLOT
FLAP



Boeing 777

CURVED
KRUEGER



3-SLOT
FLAP



Boeing 747 & 737

INCREASING
COMPLEXITY AND
WEIGHT

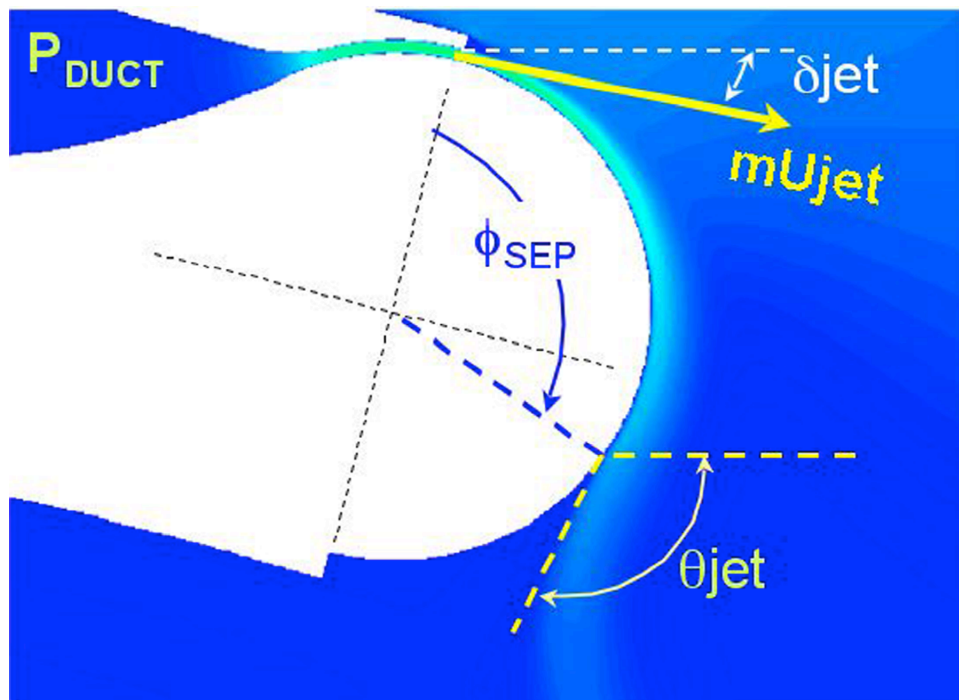
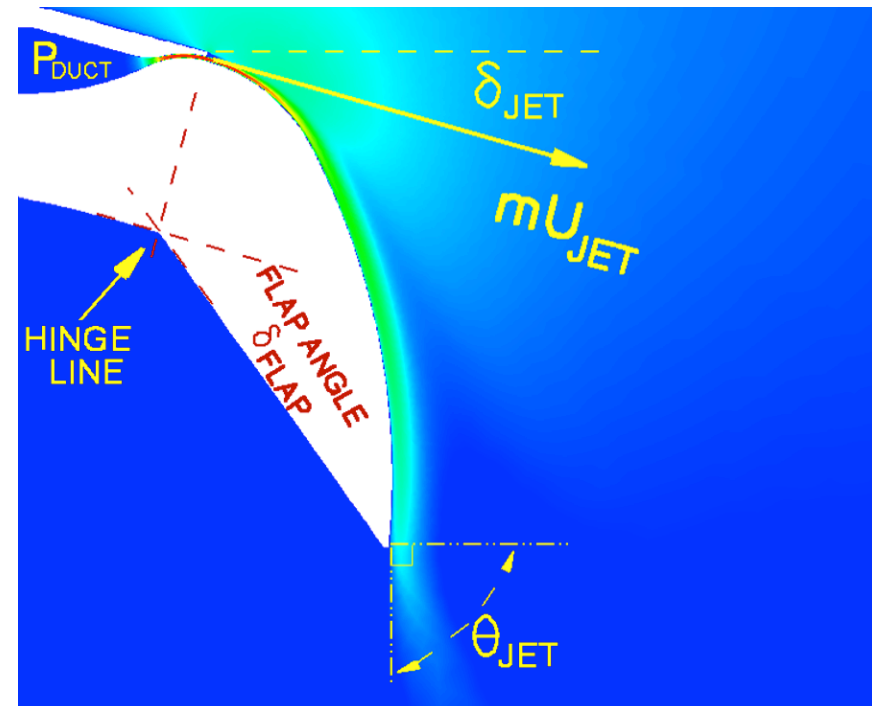


CIRCULATION CONTROL TERMINOLOGY

- Circulation control devices are typically related to actively blown systems (e.g., pneumatic flaps)
- Circulation control surfaces can have almost any curved shape

Circular TE - jet separation is not fixed

Internally Blown Flap - jet separation can be fixed to TE flap





$$C_{\mu} = 0.00$$

CIRCULATION CONTROL

The **Coandă effect** was named after Romanian aerodynamics pioneer **Henri Coandă**, who was the first to recognize the practical application of the phenomenon in aircraft development.



Mach Number: 0.0 0.4 0.8 1.2 1.6 2.0



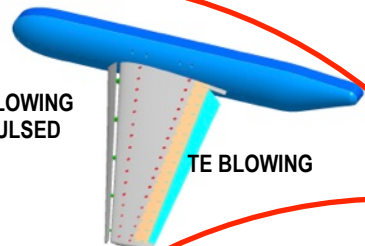
PARTNERSHIPS

NASA LaRC

TE BLOWING
& PULSED

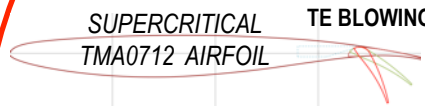
SUPERCritical
GACC AIRFOIL

TE BLOWING



SUPERCritical
TMA0712 AIRFOIL

TE BLOWING



TE BLOWING
& PULSED

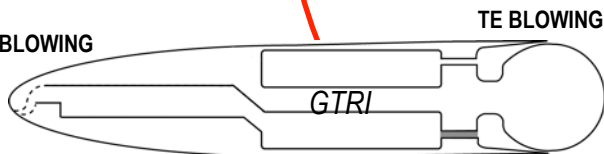
University of Florida



LE BLOWING

TE BLOWING

GTRI

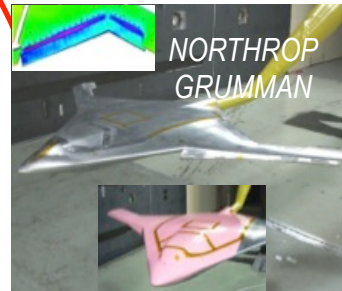


CFD

ONR



NORTHROP
GRUMMAN



LOCKHEED
MARTIN



AFRL



BOEING



CAL POLY



DOD & Industry

University

CHALLENGES OF CIRCULATION CONTROL

Can the technology buy it's way onto a next generation Aircraft

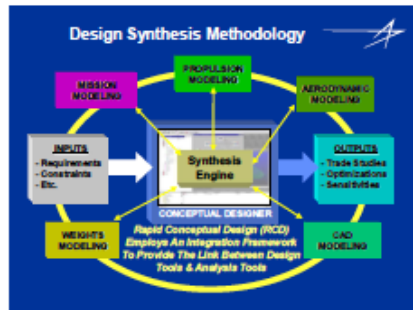
- Is it safe?*
- Does it reduce the weight?*
- Where do you get the air?*
- Can you predict the performance?*
- How does the added performance benefit the air traveling public?*

These questions are typically answered in a system study related to a specific design

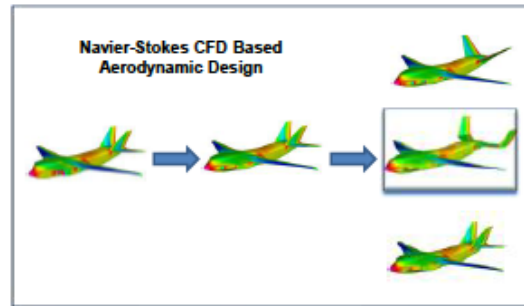


TYPICAL AIRCRAFT DESIGN PROCESS

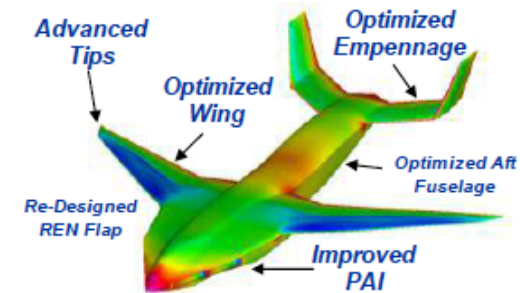
Conceptual Design



Preliminary Design

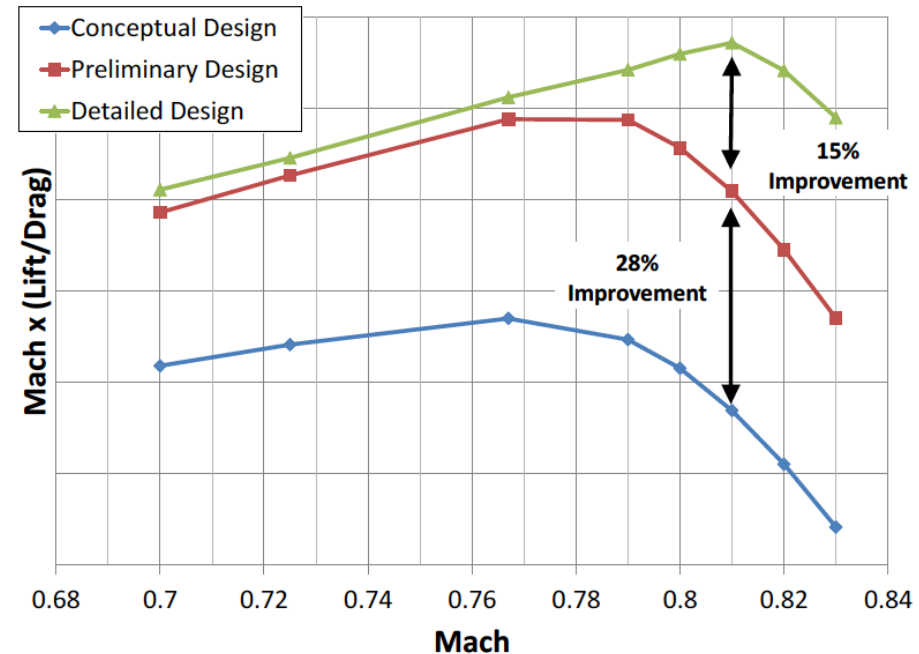


Detailed Design



AFRL/LM

Speed Agile Concept Demonstrator





DESIGNING WITH CFD

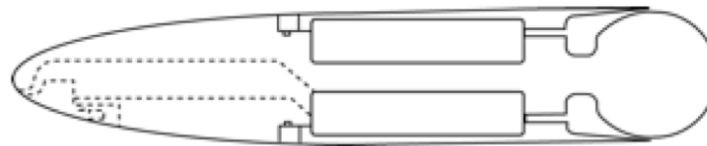
- ***ADVANCES IN CFD HAVE MADE IT POSSIBLE TO DO TRADE STUDIES FOR FULL AIRCRAFT CONFIGURATIONS***
- ***CFD STILL STRUGGLES WITH SEPARATED FLOWS AND BOUNDARY LAYER TRANSITION ON FULL AIRCRAFT CONFIGURATIONS***
 - ***TURBULENCE MODELING IS A KEY ACTIVITY IN CFD DEVELOPMENT***
- ***CFD VALIDATION USING ADVANCED EXPERIMENTAL DATA BASES REMAINS A CRITICAL TOOL IN THE DEVELOPMENT PROCESS OF AIRCRAFT DESIGN***



CFD VALIDATION PROCESS

Benchmark Cases

Fundamental Powered Lift

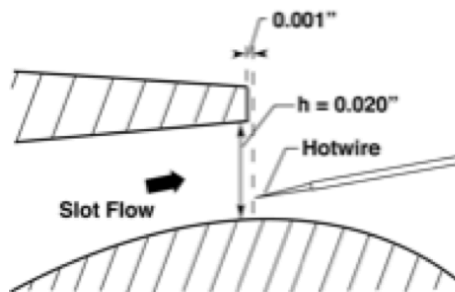


2-D CC Airfoil w/ Upper and Lower Blowing

GTRI/NASA LaRC – MTF/BART

Unit Problems

Fundamental Wall Bounded Jet

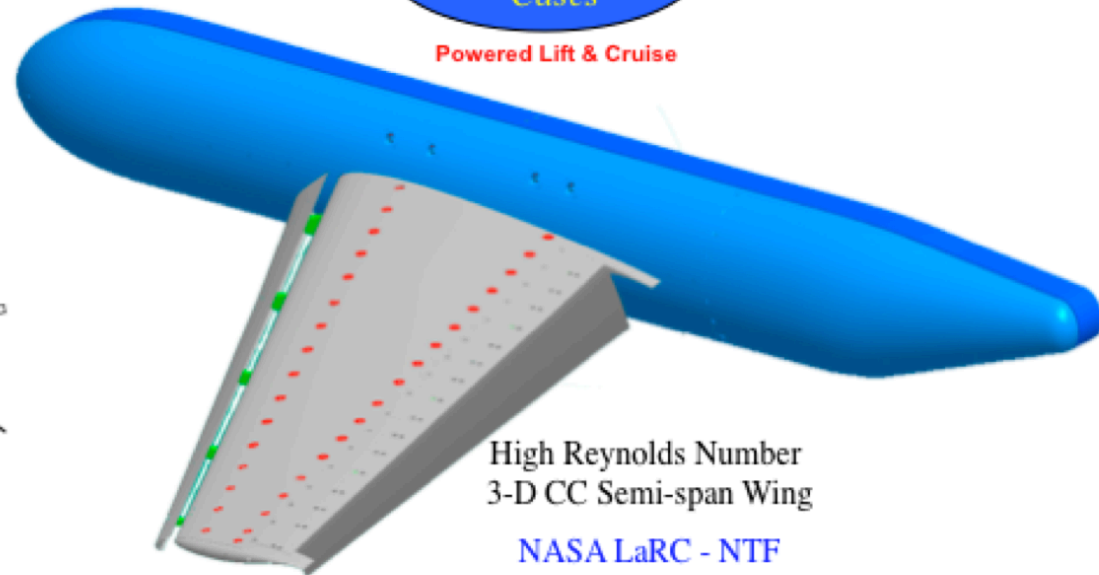


Jet Exit Velocity Profile

NASA LaRC – CC Lab

Subsystem Cases

Powered Lift & Cruise



High Reynolds Number
3-D CC Semi-span Wing

NASA LaRC - NTF

Complete System

Integrated Powered Lift



3-D Hybrid Wing Body w/
USB augmented w/ CC Wing

Cal Poly/NASA ARC - NFAC

Increasing Geometric And Flow Complexity



OBJECTIVES FOR VALIDATION DATA BASE

- Characterize model performance
 - Parametric study of slot height (h) for LE and TE blowing
- Select limited configurations for detailed study
 - Document boundary conditions (emphasizing C_μ variables)
 - Document flow field using multiple measurement techniques including uncertainty analysis

$$C_\mu = \frac{\text{THRUST}}{q_\infty S} = \frac{2hb_{\text{JET}}}{cb} \frac{\rho_{\text{JET}}}{\rho_\infty} \frac{U_{\text{JET}}^2}{U_\infty^2} = \frac{\dot{m}U_{\text{JET}}}{q_\infty S}$$

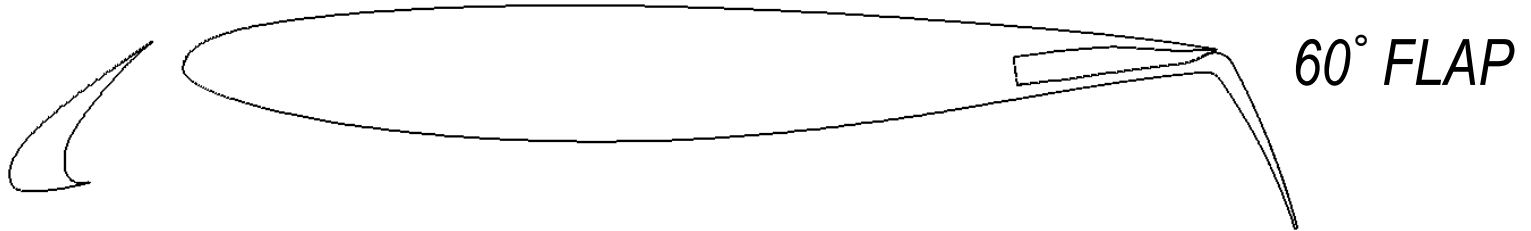
Local measurements
 U_{JET} profile characterizes h
captures variations in
slot height (h) w/ duct pressure
(b = slot width; S = wing area)

Global measurements
assumes mass flow and U_{JET}
uniform along span

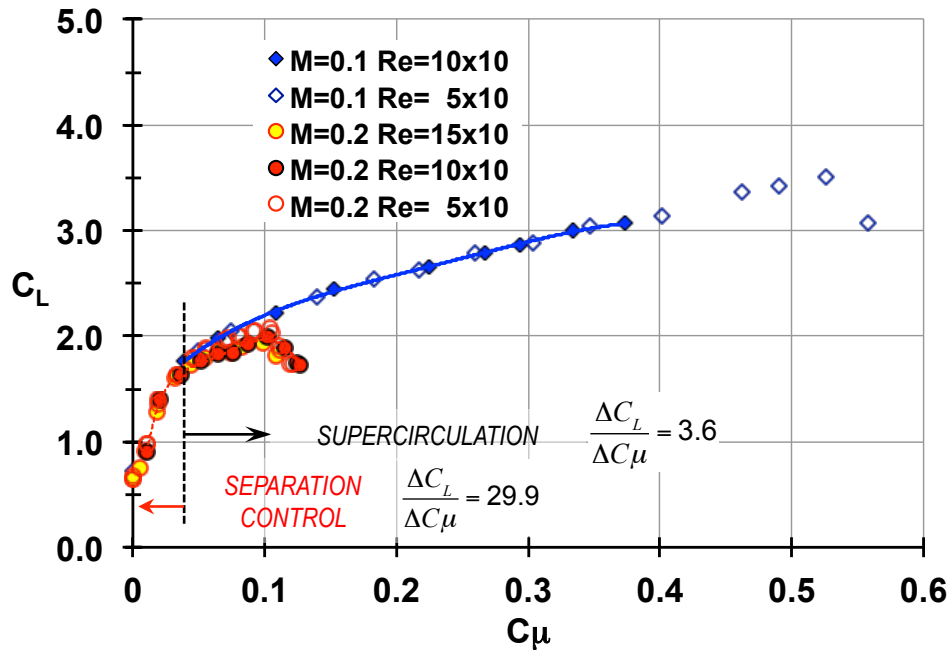
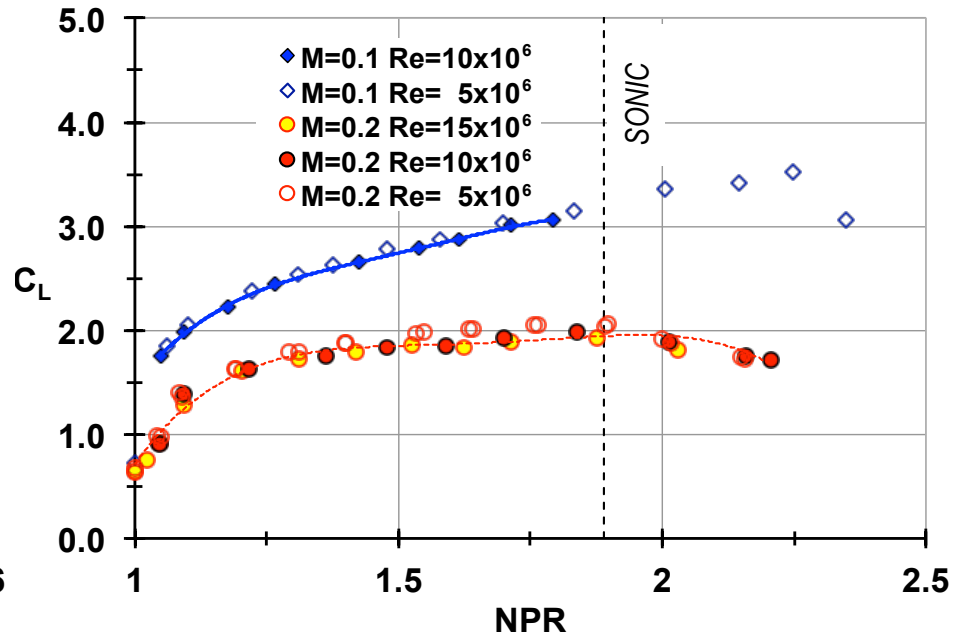


LIFT PERFORMANCE WITH BLOWING

$\alpha = 0.0^\circ$



60° FLAP

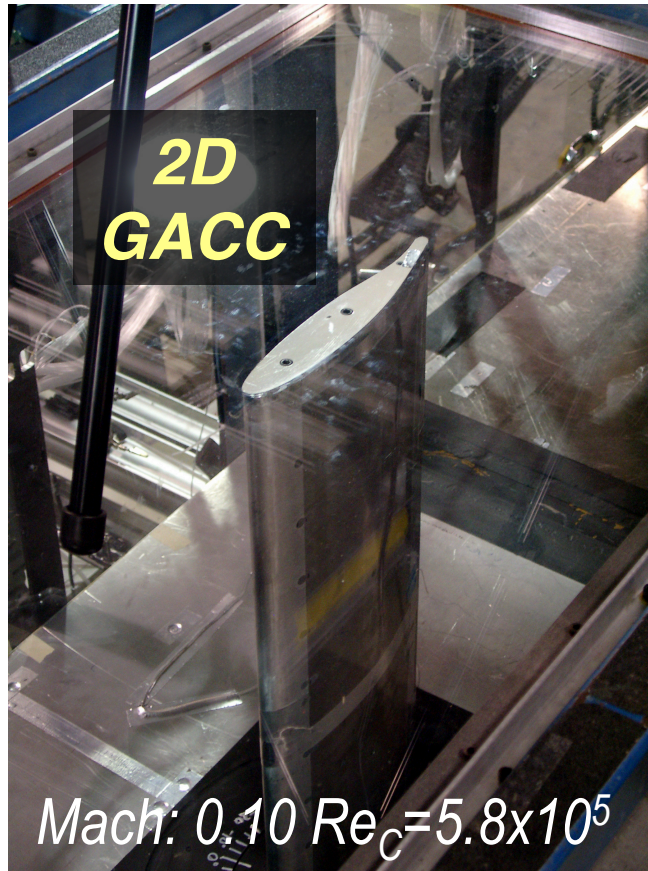
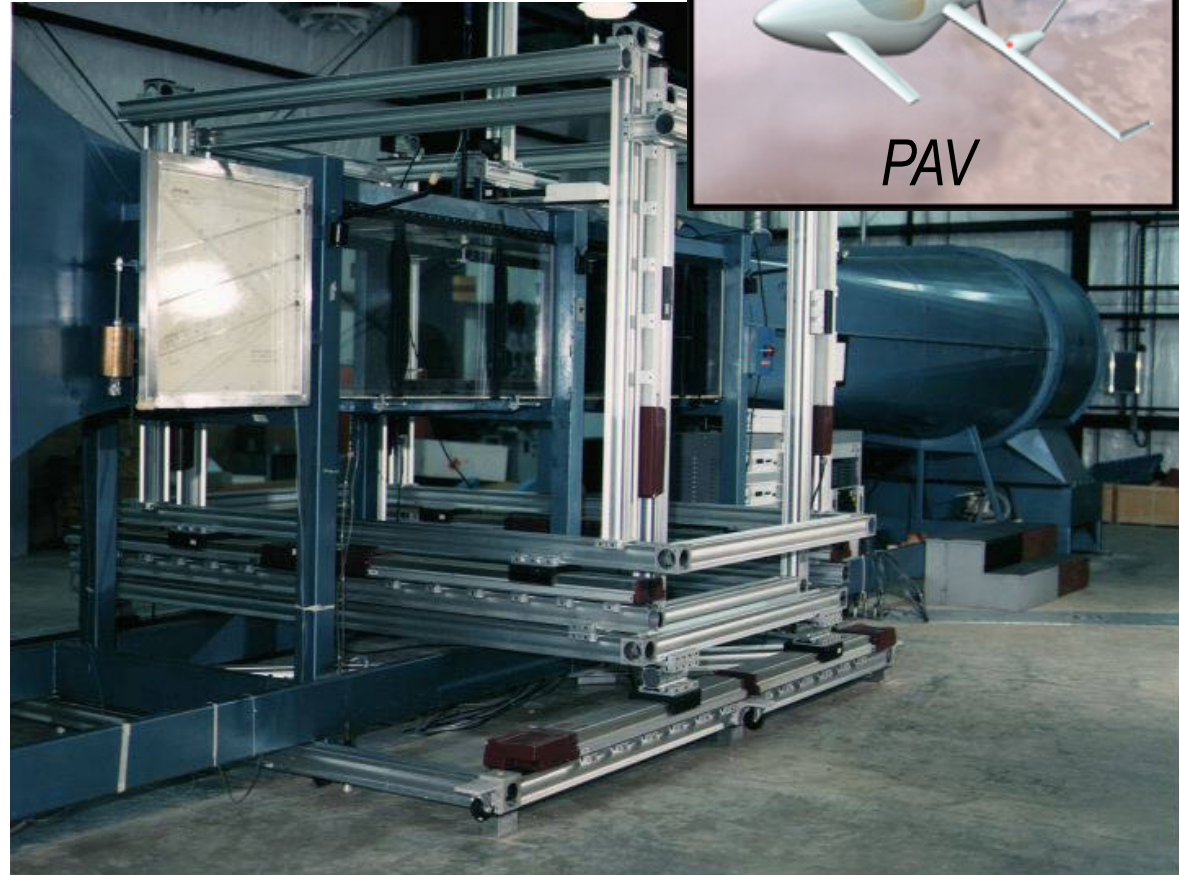




SHIFT GEARS TO 2D



2-D TESTING IN THE BASIC AERODYNAMIC RESEARCH TUNNEL

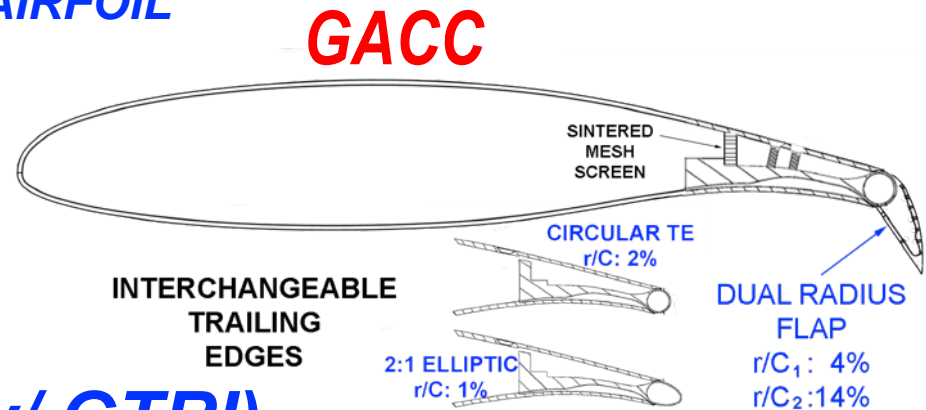




NASA 2-D CFD VALIDATION TEST BEDS

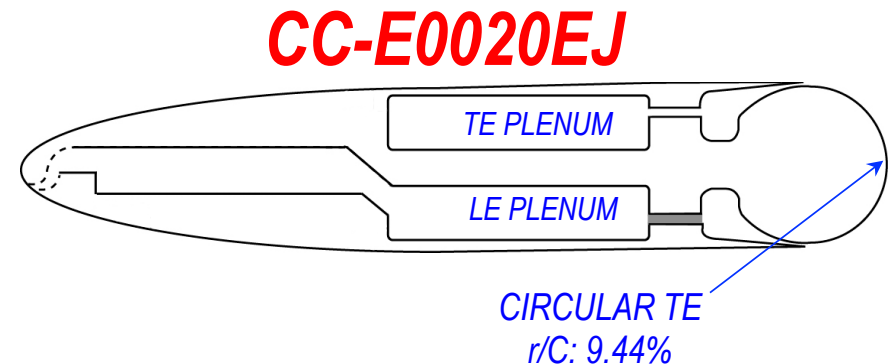
•2D-GACC

- 17% THICK SUPERCRITICAL AIRFOIL
- TE BLOWING
- VARIABLE FLAP SHAPE



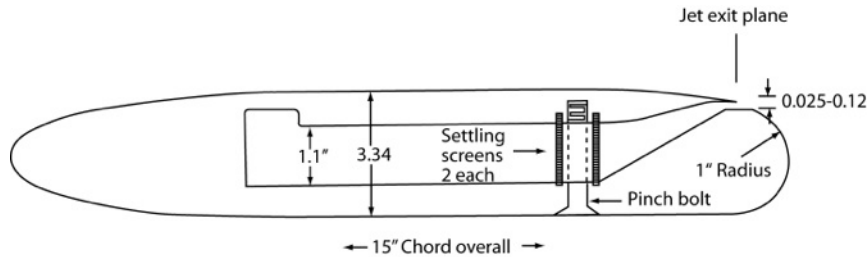
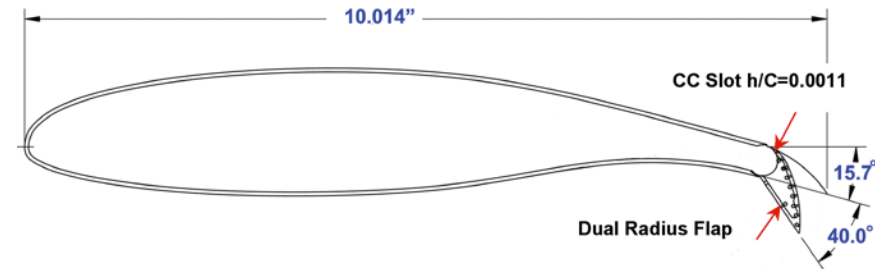
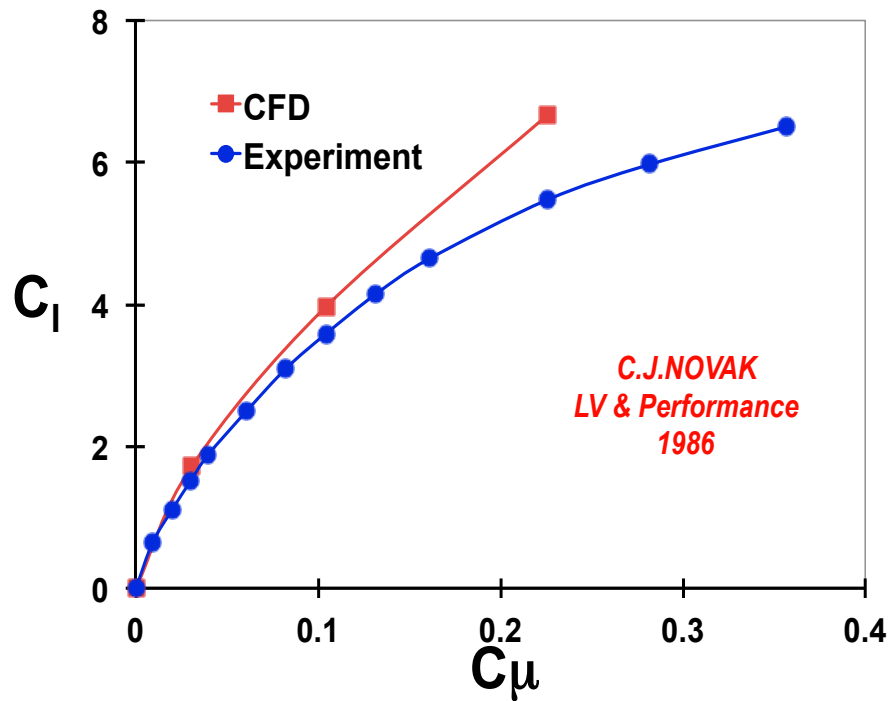
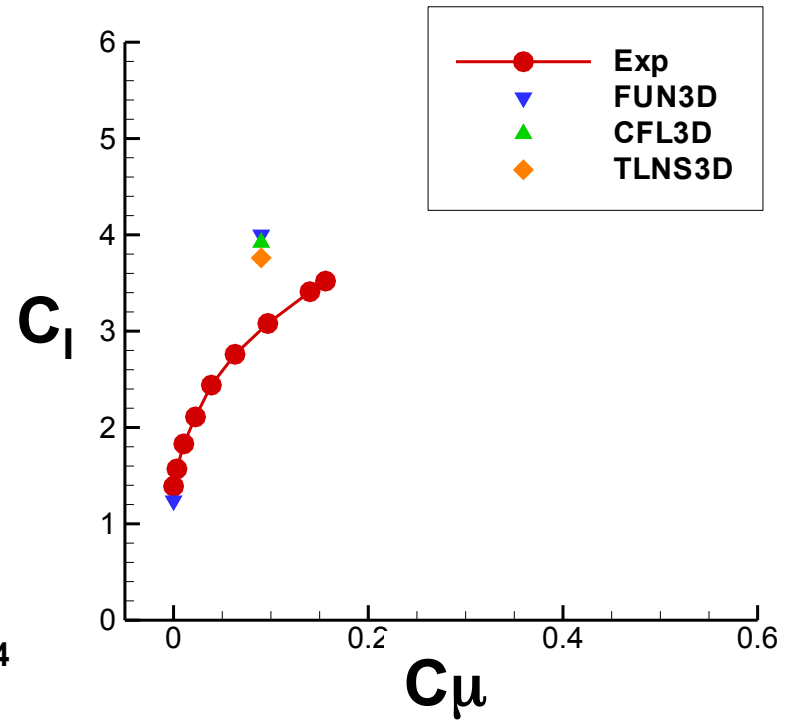
•2D-NRA (Cooperative w/ GTRI)

- 20% THICK ELLIPTIC AIRFOIL
- LE & TE BLOWING





CAN WE PREDICT 2-D CC PERFORMANCE





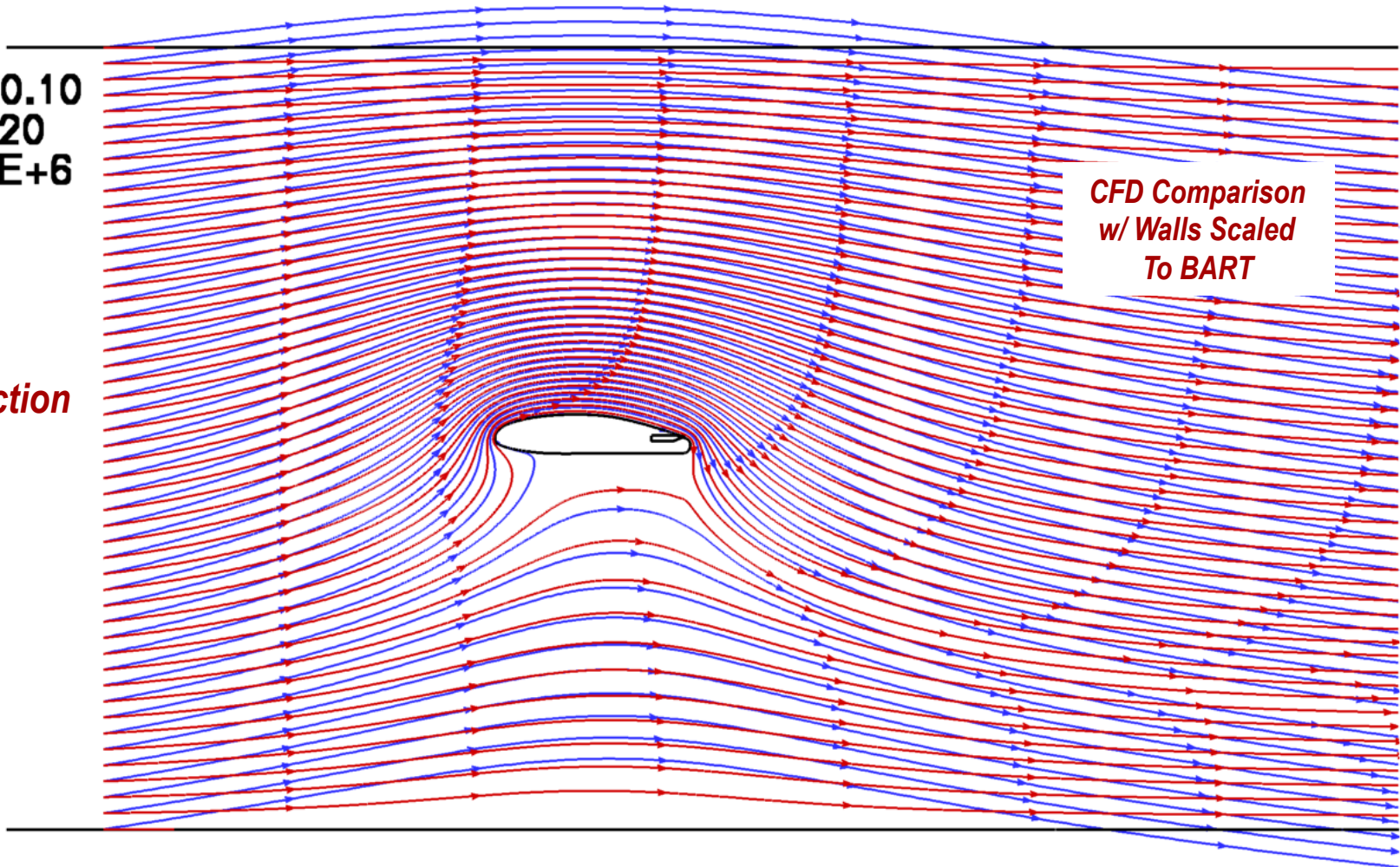
CFD VALIDATION : 2-D WALL EFFECTS

Comparison of streamlines with and without tunnel walls

$\text{Rho}_{\text{ugrd}} = 0.10$
 $\text{Mach} = 0.120$
 $\text{Re} = 4.275\text{E}+6$

CFD Comparison
w/ Walls Scaled
To BART

Alpha Correction
Needed

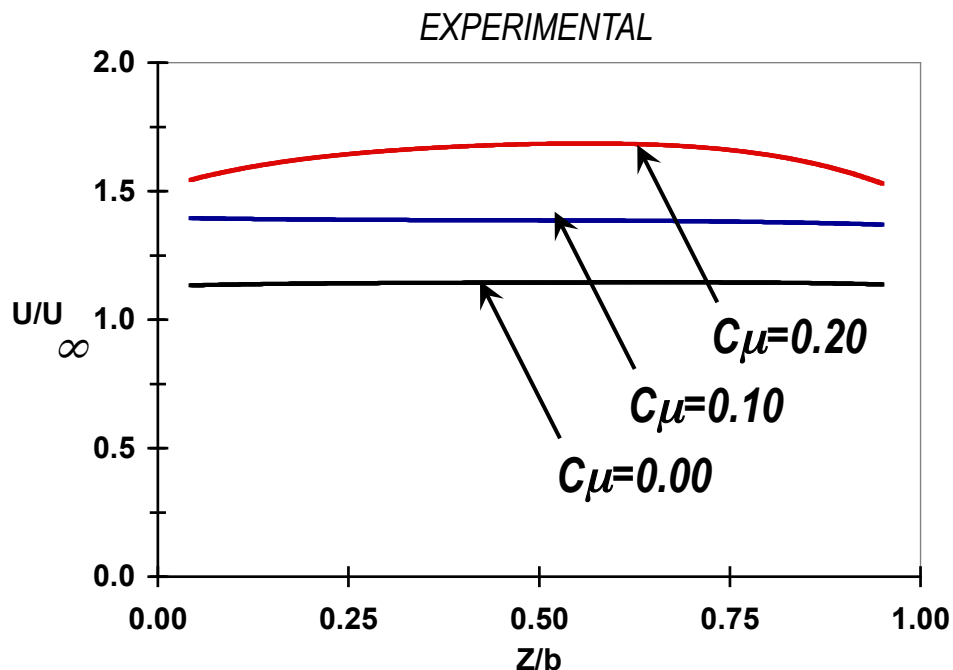


CFD - OVERFLOW

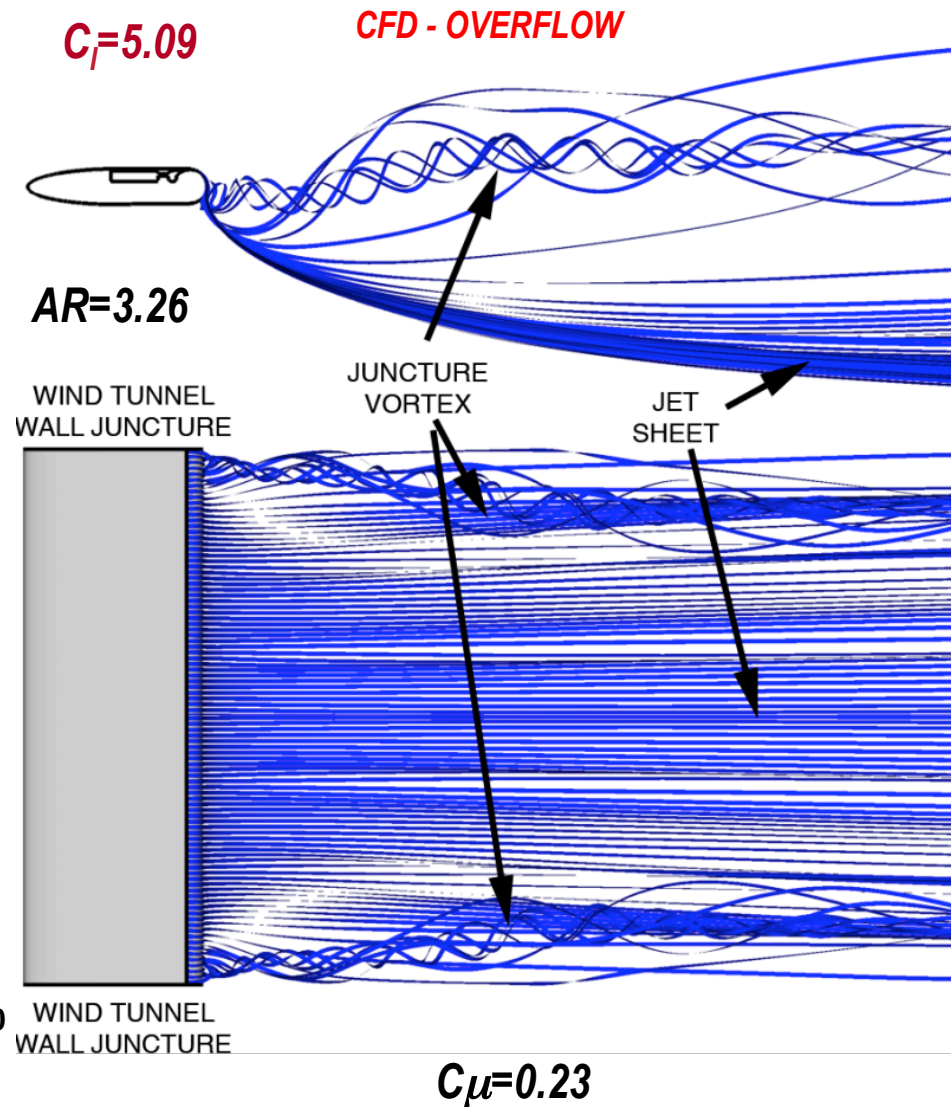


3-D JUNCTURE EFFECTS

Juncture flow influence on two-dimensionality increases with blowing



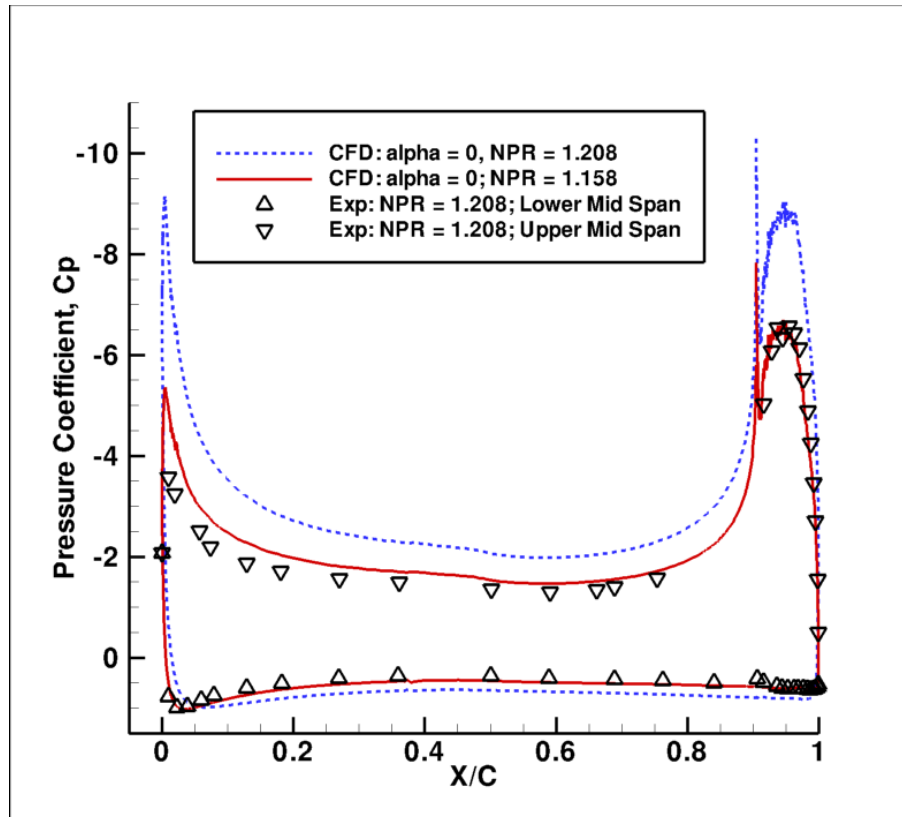
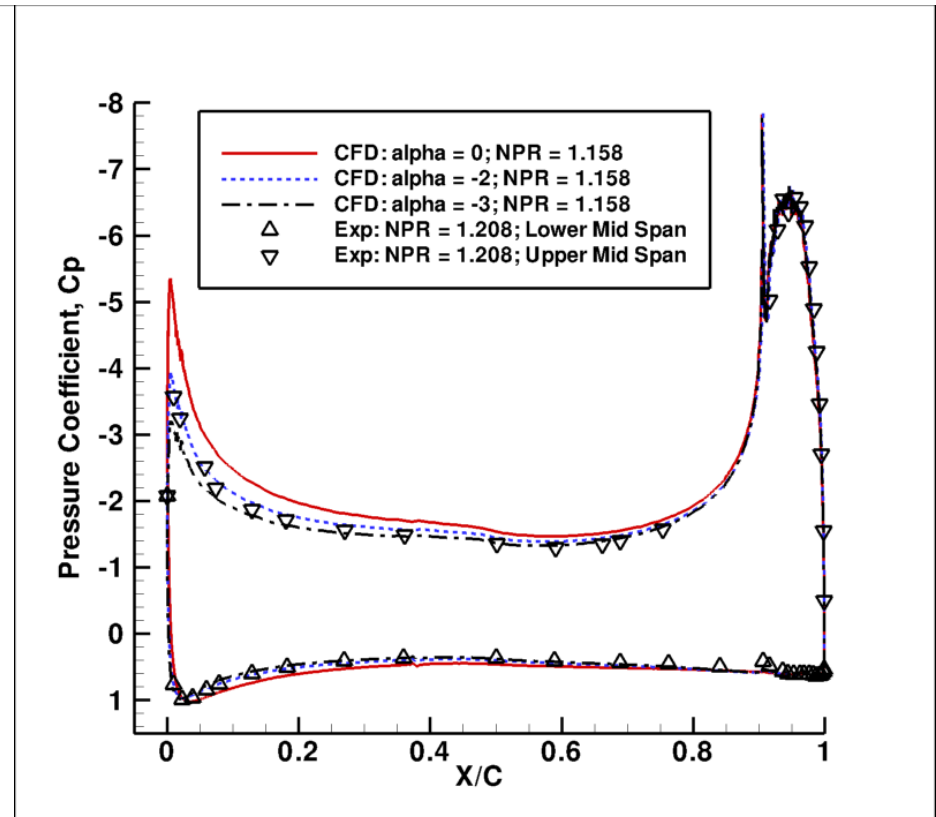
Pitot Static Probe Location
 $x/c = 0.5$ $y/b = 0.5$ $y = 1.0''$





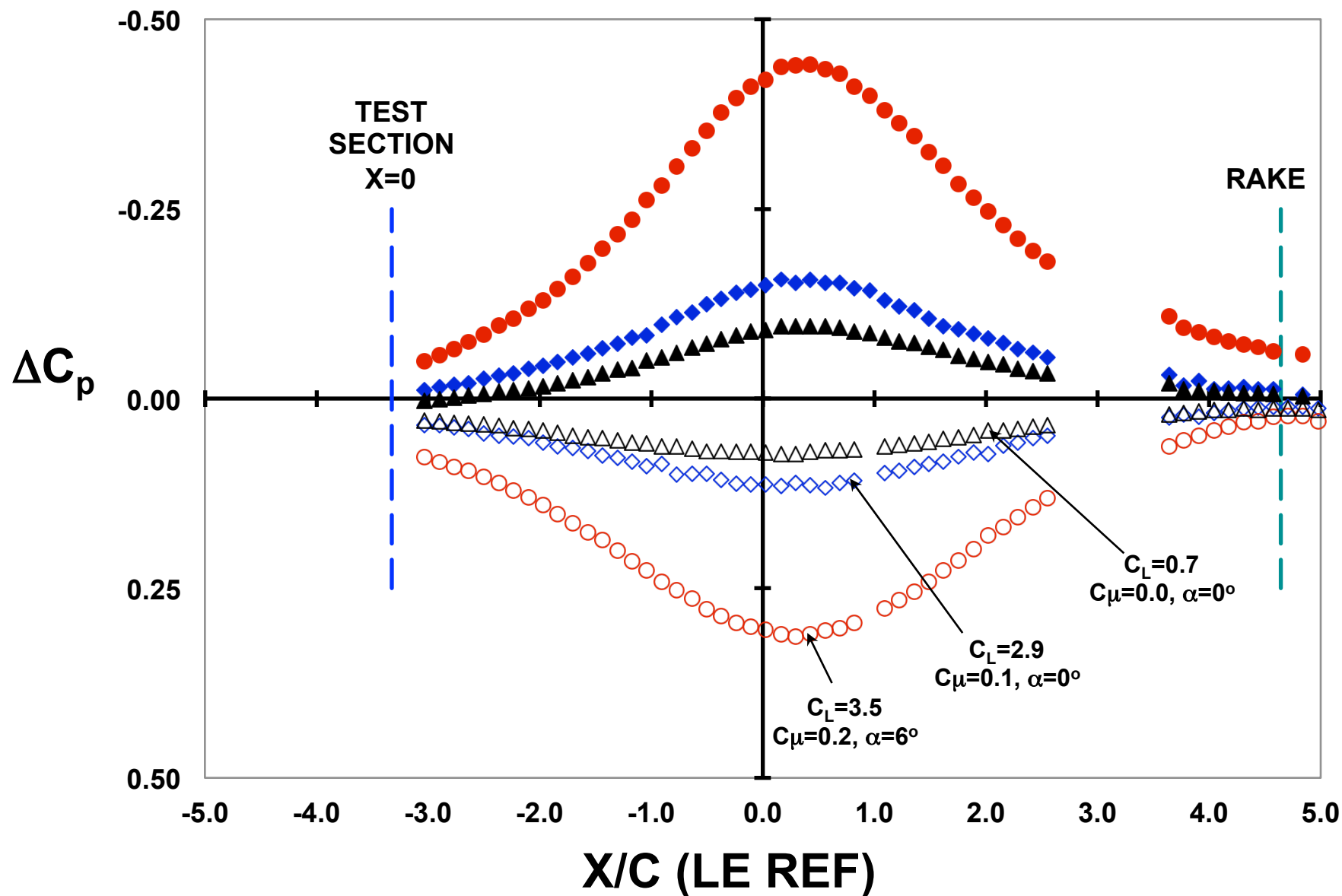
ESTIMATED WALL CORRECTIONS

- Wall corrections for 2D CFD estimated using CFD approach
 - NPR adjusted in CFD to match suction peak at trailing edge
 - Angle-of-attack adjusted to match suction peak at airfoil leading edge
- Estimated AOA correction is -2.0 deg for $C_{\mu}=0.11$ case





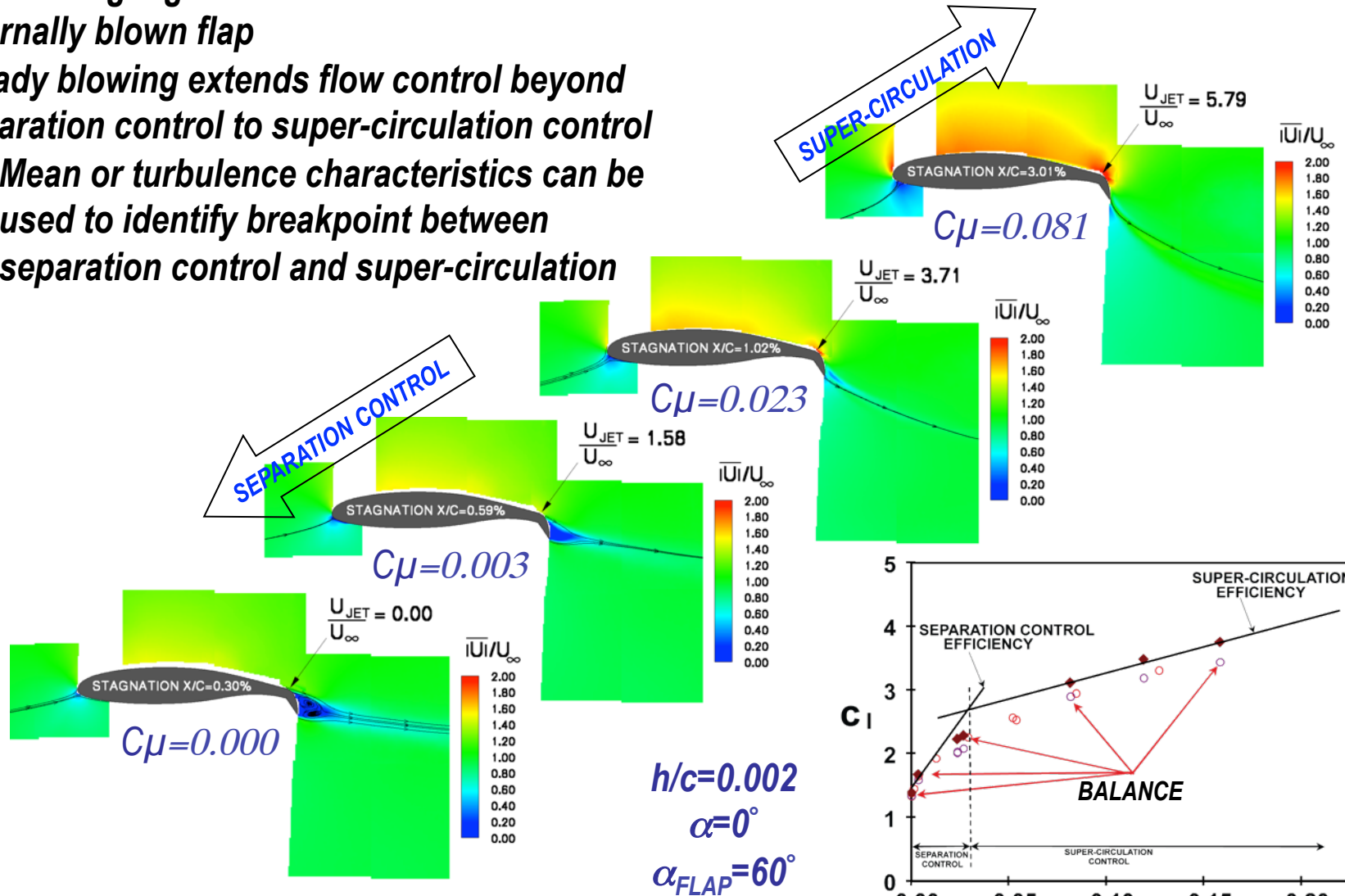
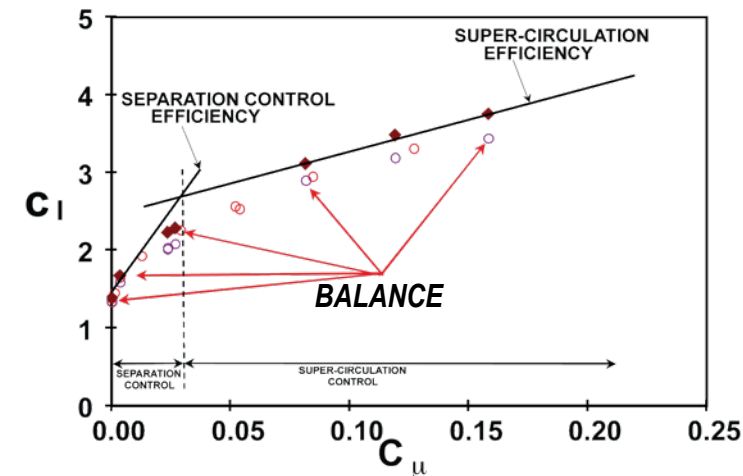
GACC WALL SIGNATURE





EXAMPLE OF PIV MEAN VELOCITY FOR INTERNALLY BLOWN FLAP

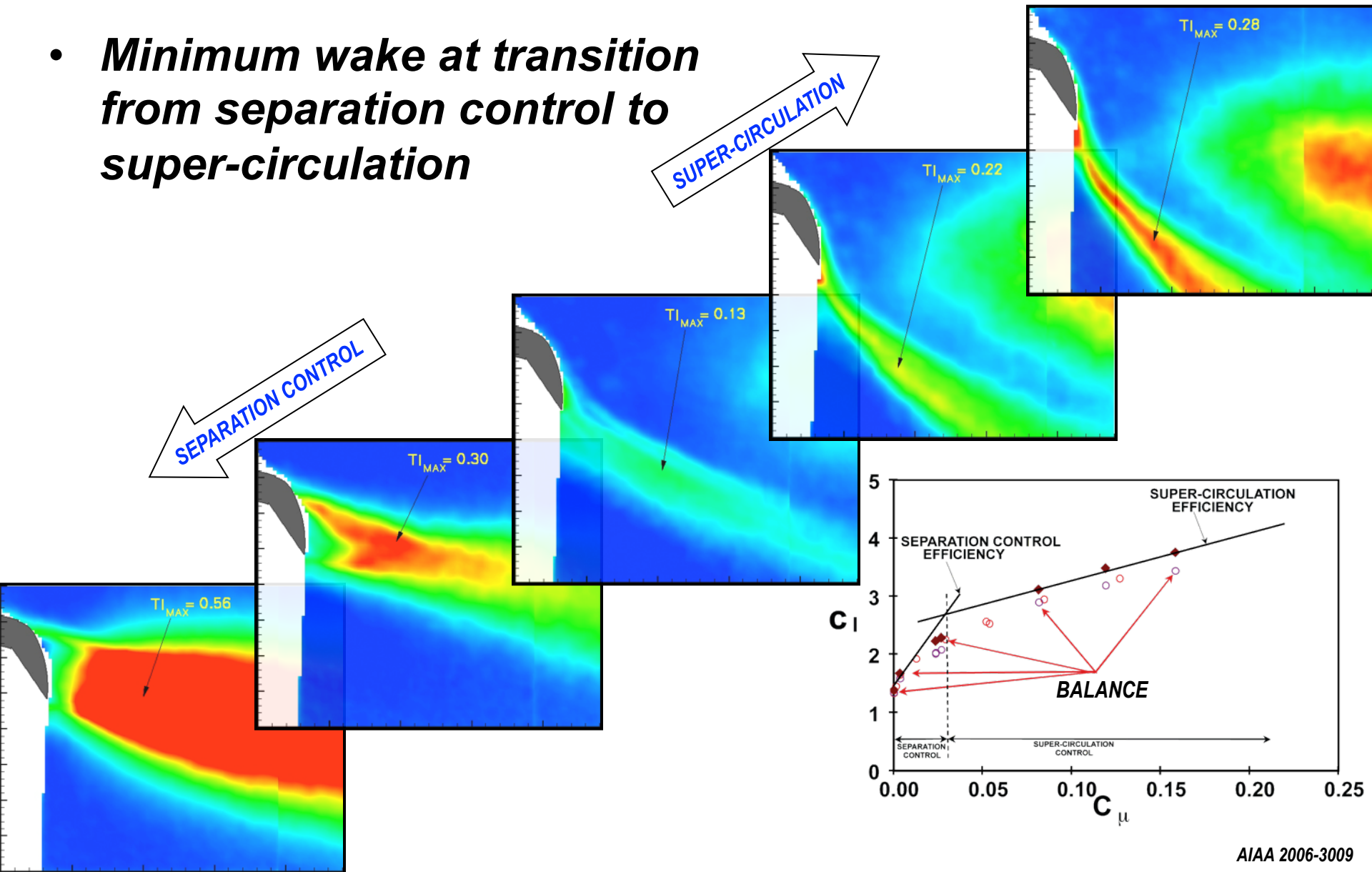
- PIV data highlight streamline characteristics for a internally blown flap
- Steady blowing extends flow control beyond separation control to super-circulation control
 - Mean or turbulence characteristics can be used to identify breakpoint between separation control and super-circulation





WAKE TURBULENCE IS A FUNCTION OF C_{μ}

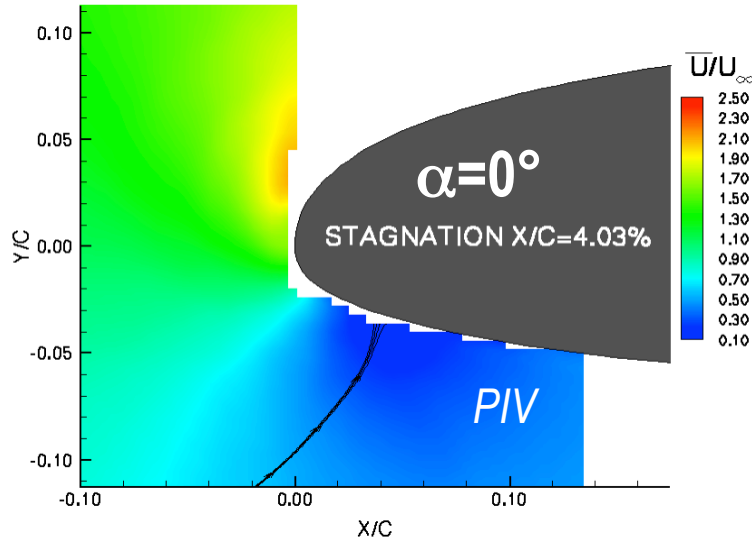
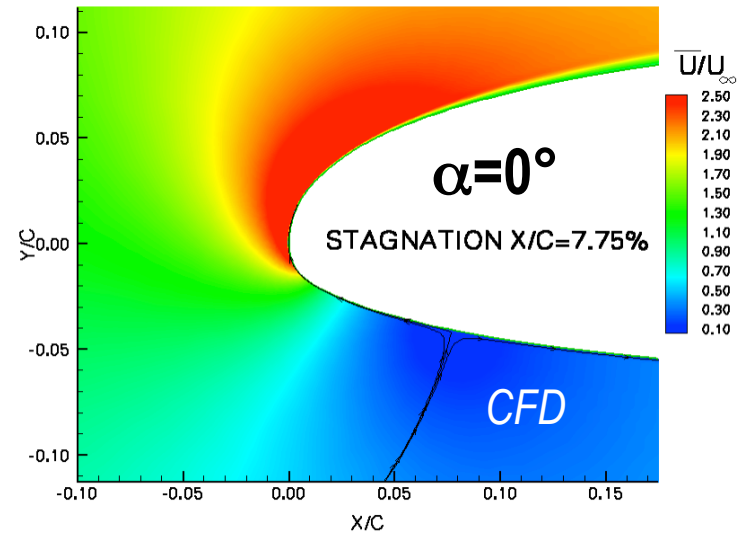
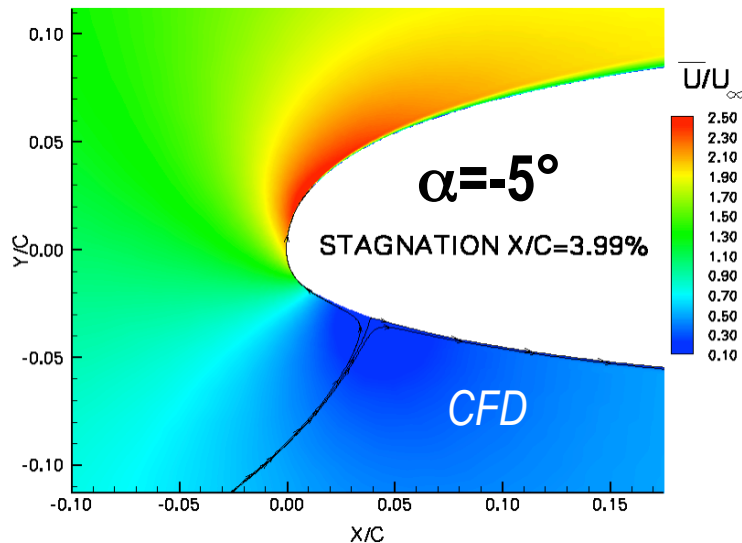
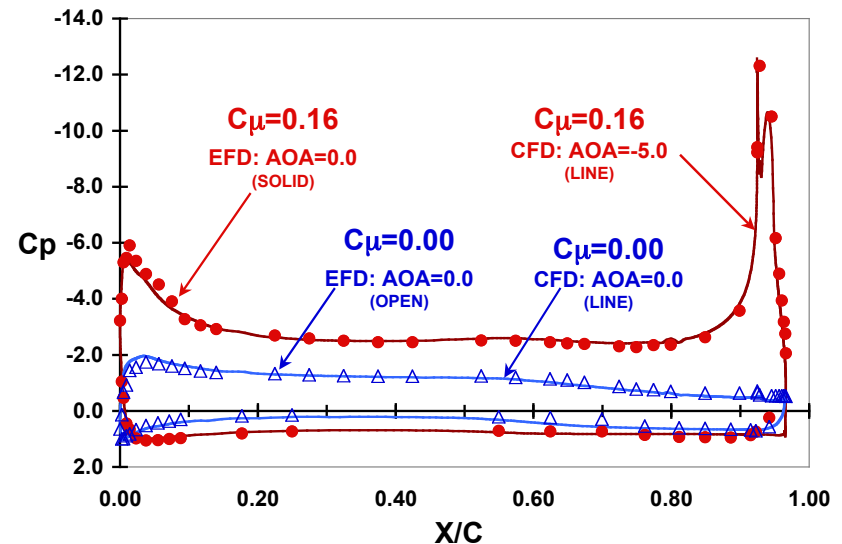
- *Minimum wake at transition from separation control to super-circulation*





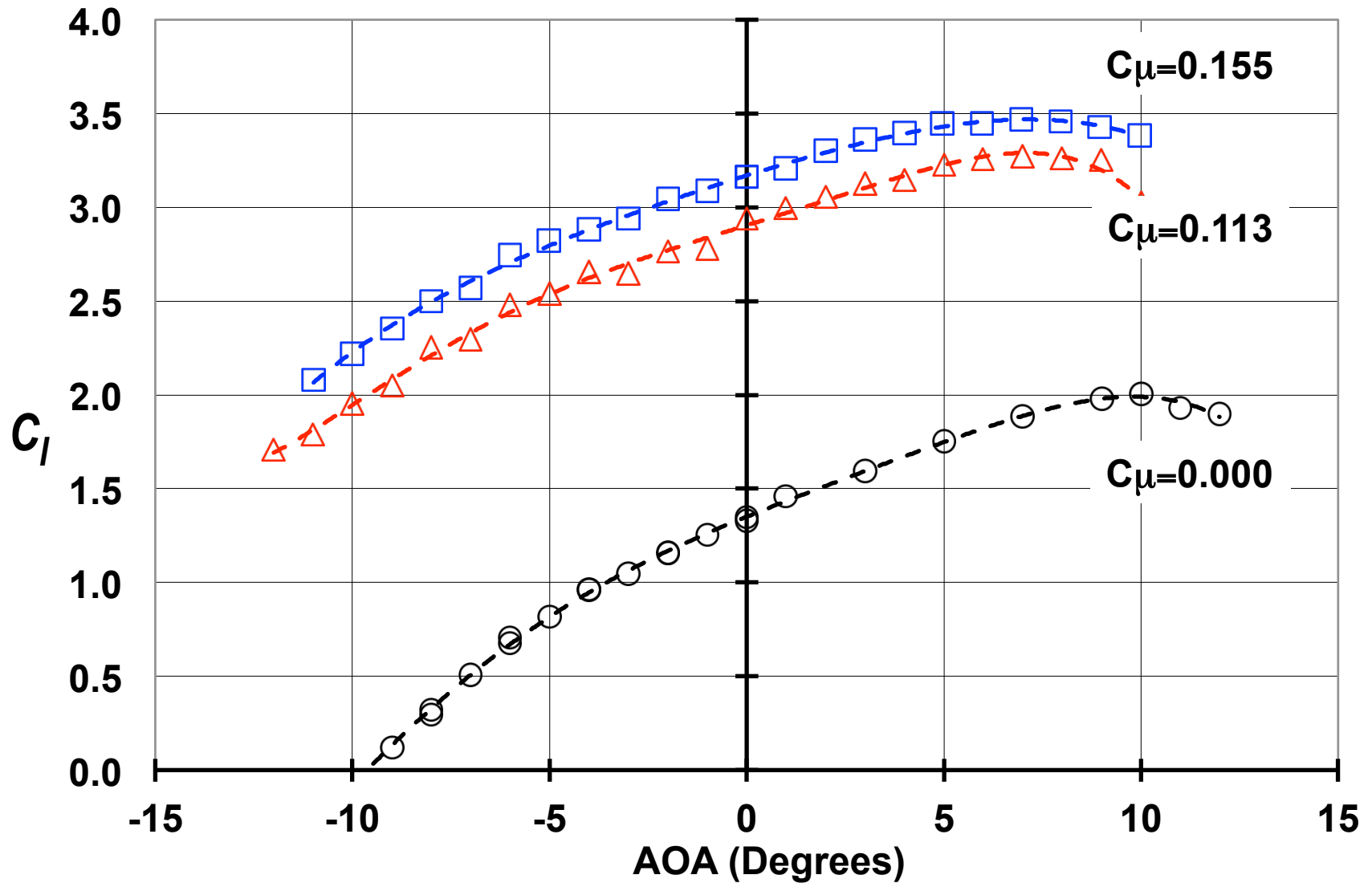
INFLUENCE OF TUNNEL WALLS

GACC Stagnation





GACC LIFT PERFORMANCE





SHIFT GEARS 3D

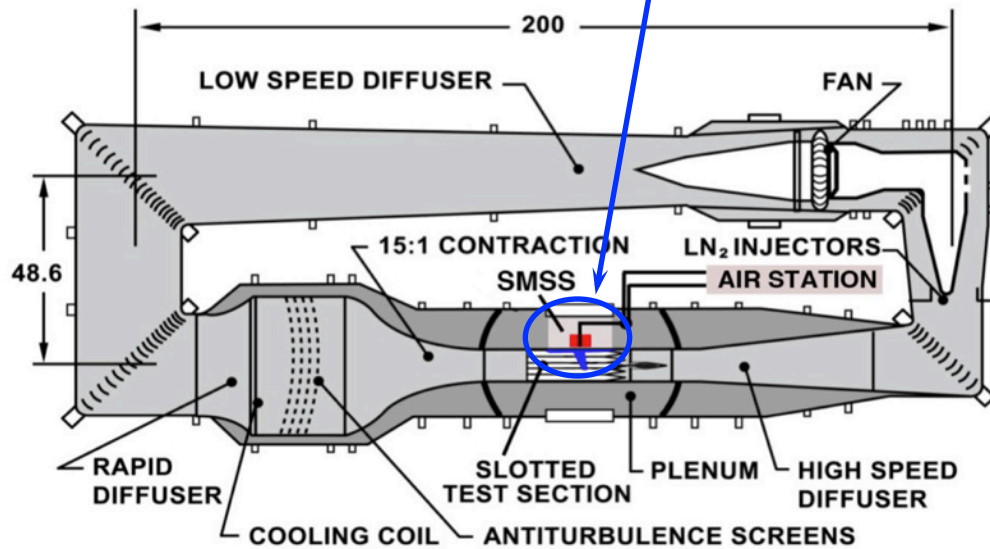
NTF FAST-MAC MODEL USED FOR 3-D DEVELOPMENT OF CC



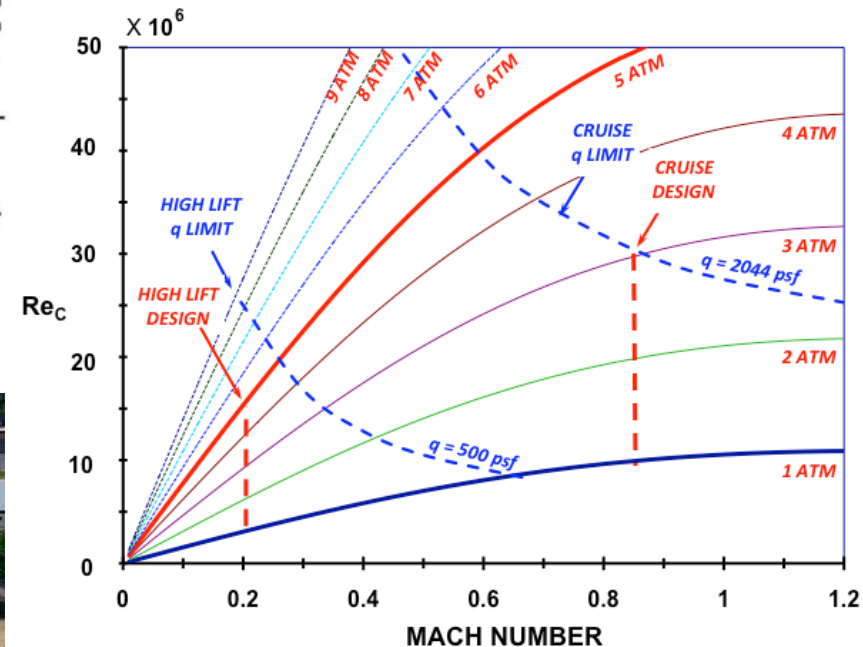


3-D CC TESTING IN THE NATIONAL TRANSONIC FACILITY

NTF SEMI-SPAN CONFIGURATION



FAST-MAC OPERATING ENVELOPE ($T_0 = -50^\circ\text{F}$)





NTF TEST OBJECTIVES

- ***Document the effect of Reynolds number on circulation control aerodynamics***

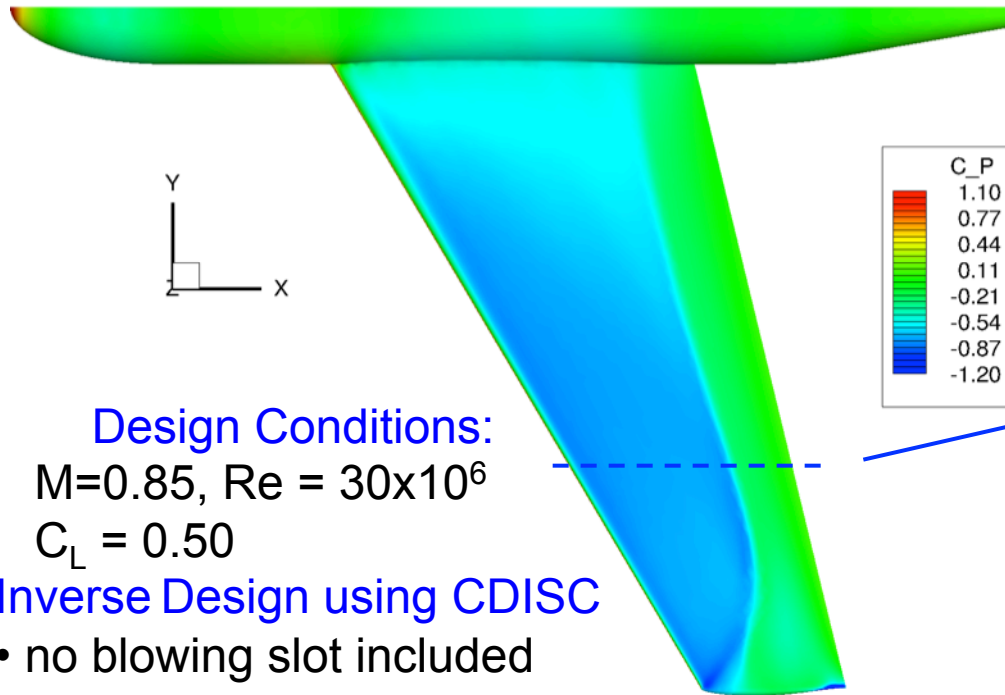
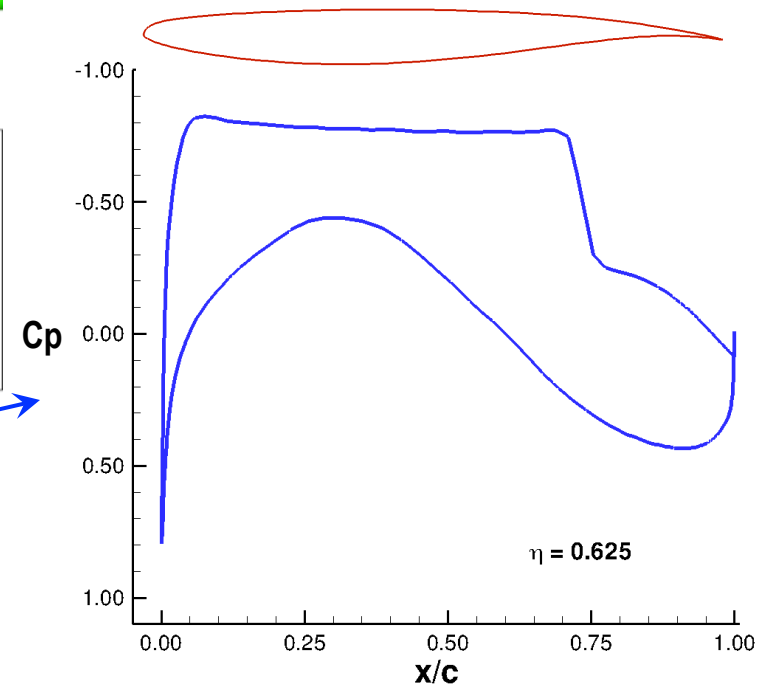
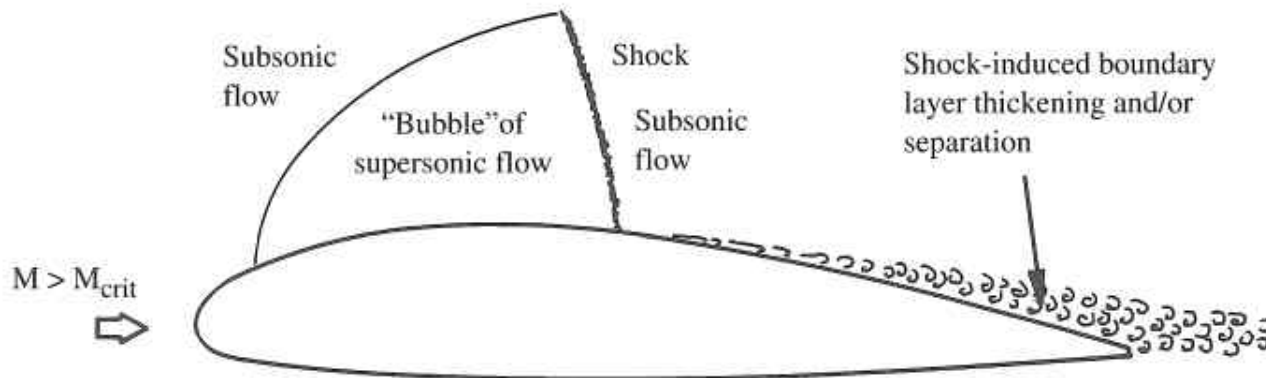
- ***High Lift*** Evaluate different blowing geometries associated with a simplified high-lift system ($0.10 < \text{Mach} < 0.20$)
- ***Cruise*** Explore the drag reduction potential of the blown flap in the stowed cruise position, at transonic speeds ($0.70 < \text{Mach} < 0.88$)

- ***Develop an open dataset for CFD code validation***
- ***To validate, evolve, and refine test techniques, methodology, and procedures relating to circulation control and propulsion testing***



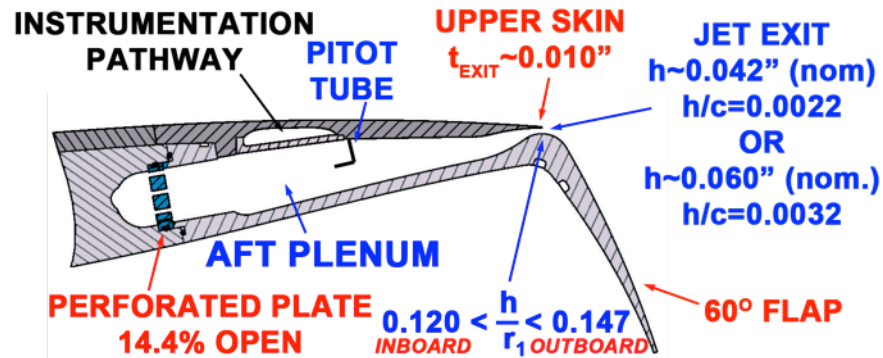
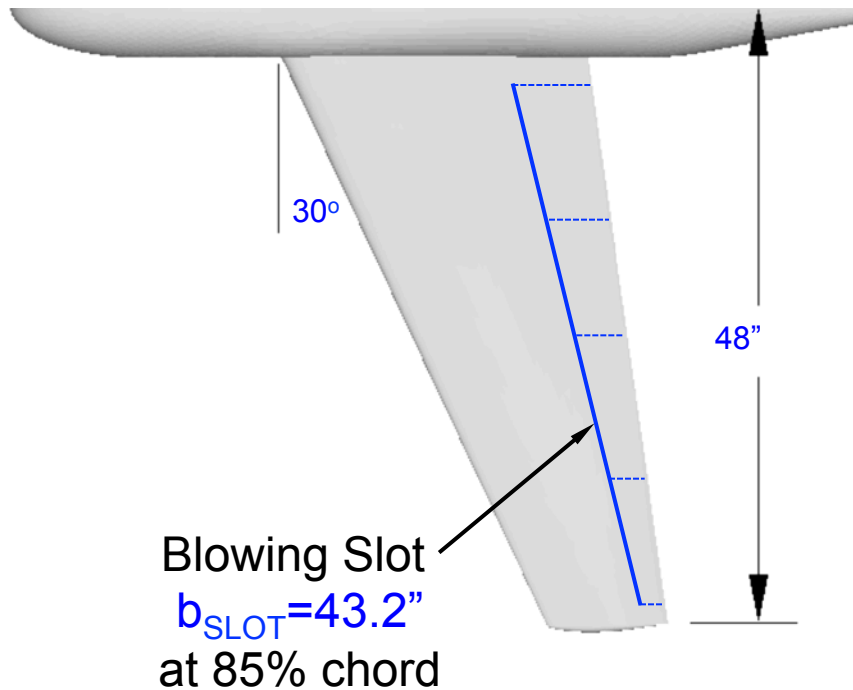
PREDICTED AERODYNAMIC CHARACTERISTICS OF FAST-MAC

WING DESIGN (BASELINE - NO BLOWING) USING CFD





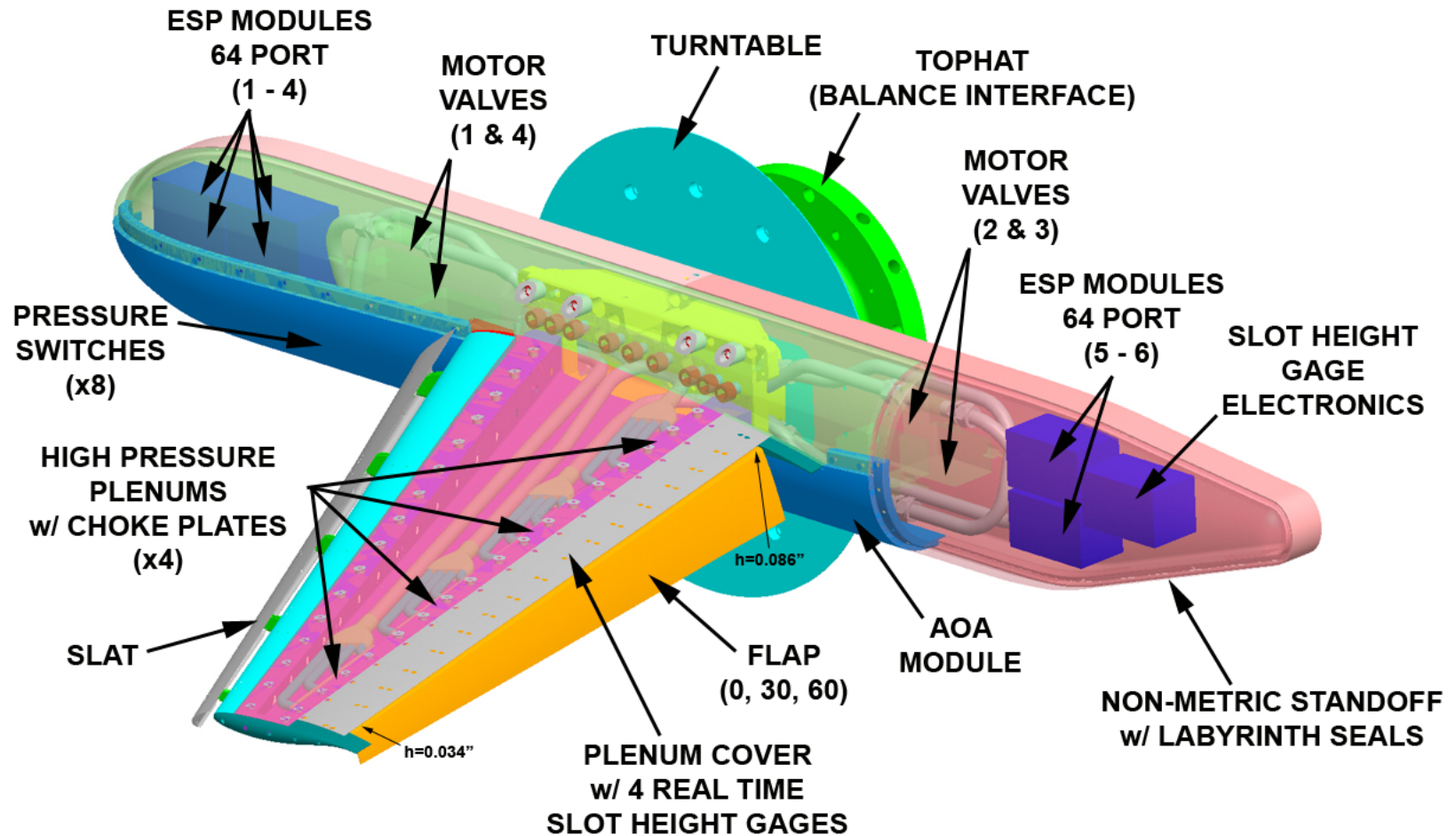
FEATURES OF FAST-MAC MODEL ASSEMBLY



Wing Parameters:
 $AR = 5.0$, $\lambda = 0.40$
 $MAC = 19.4 \text{ in.}$
 $5^\circ \text{ Twist (Root - Tip)}$



INTERNAL FEATURES OF NTF SEMI-SPAN MODEL ASSEMBLY



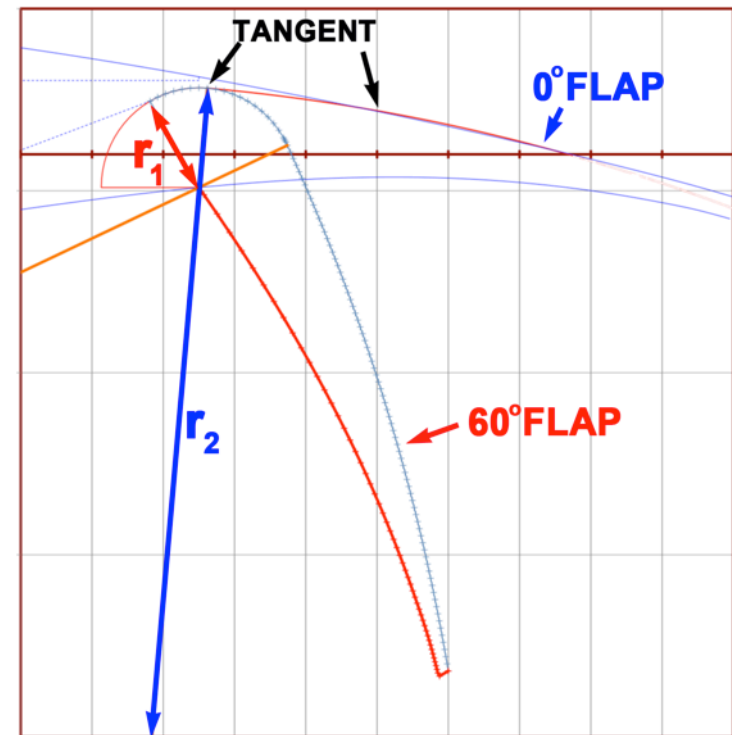


CIRCULATION CONTROL FLAP DESIGN GUIDELINES

12% THICK SUPERCritical WING

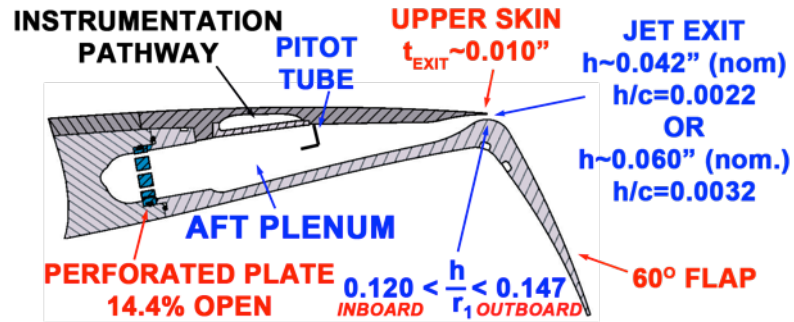
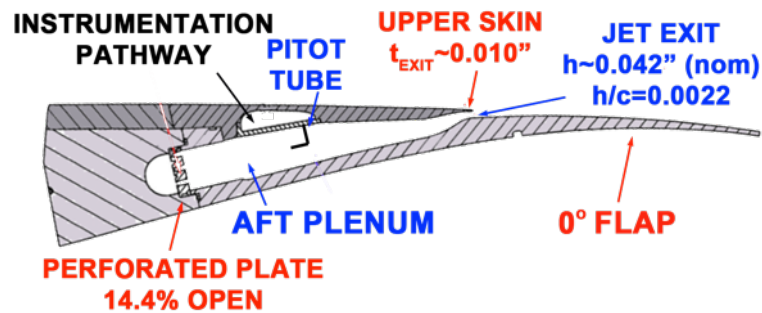


- **Tangential Ejection Angle WRT Upstream Flow**
- **Continuous Curvature - $r_2/r_1=44$ (2nd Derivative)**
- **Merge with a “Streamline” Extension of Upper Surface OML**
- **No Obstructions for at Least 10 Slot Heights Inside**
- **Nozzle Must be Convergent**

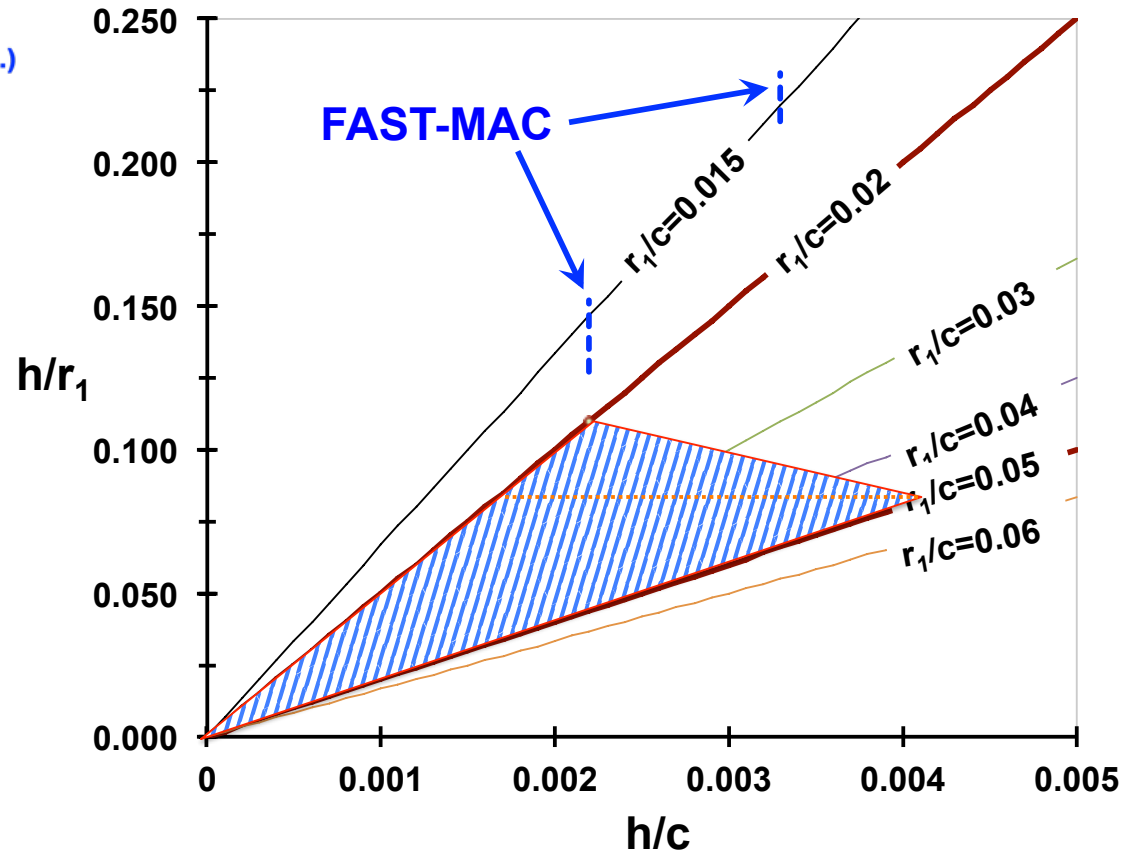




CIRCULATION CONTROL DUAL RADIUS FLAP DESIGN



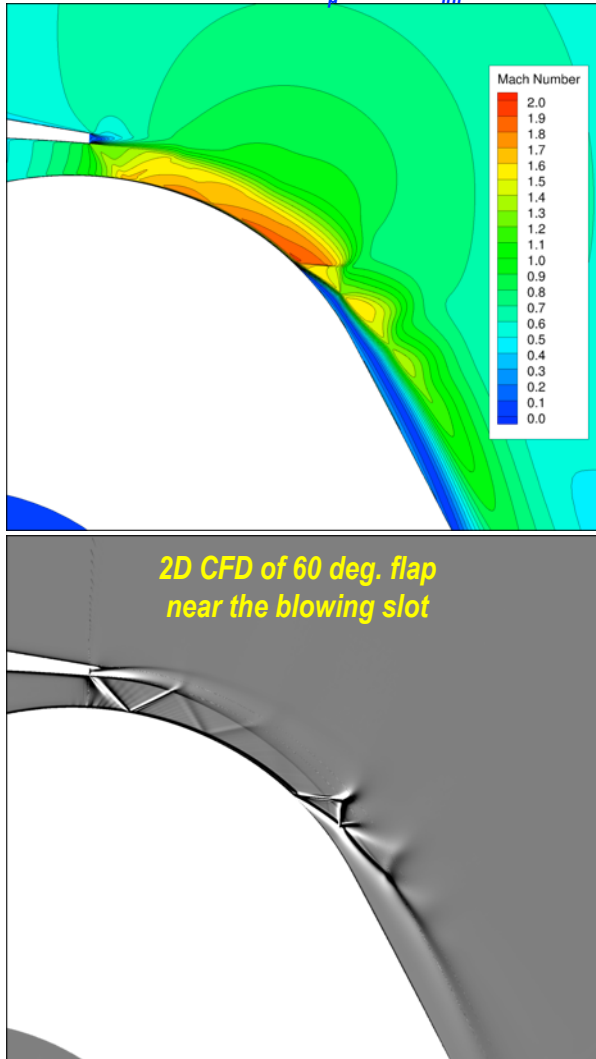
FIRST RADIUS DESIGN GUIDELINES



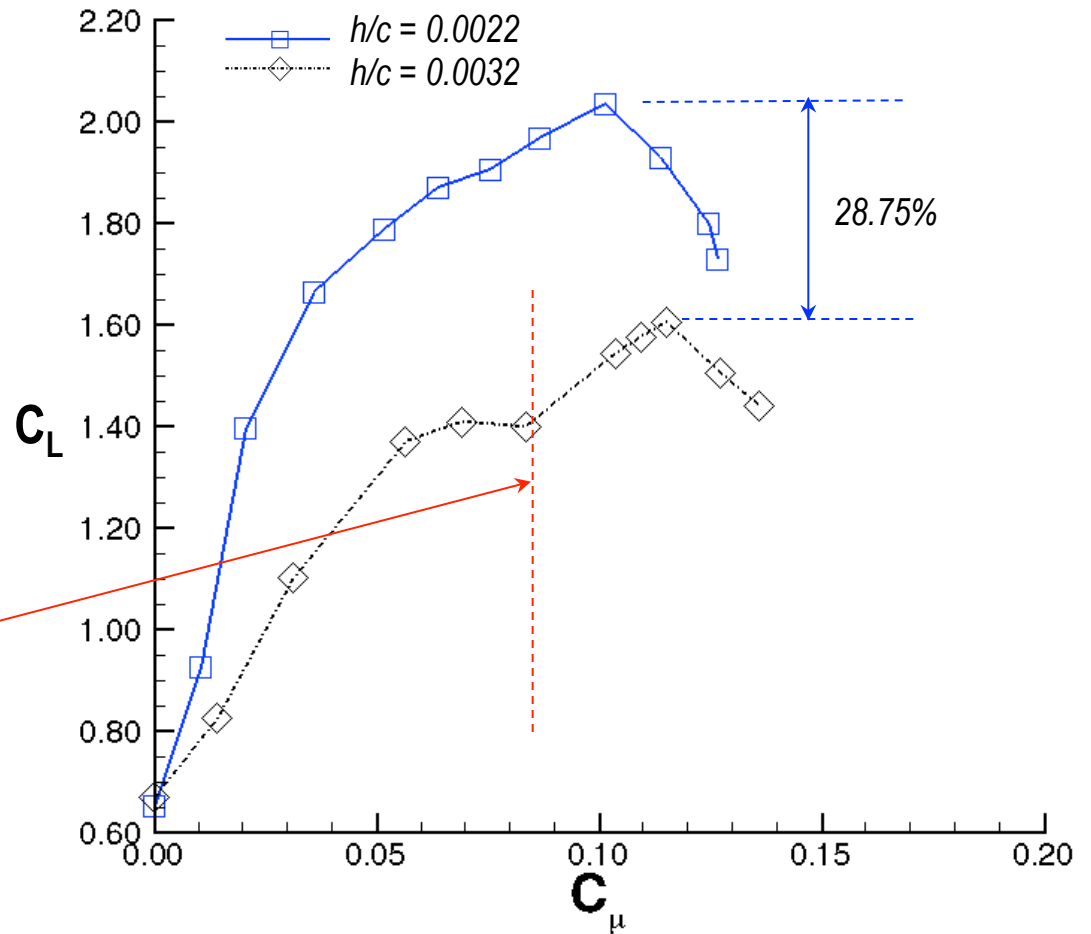


LOW-SPEED SLOT HEIGHT PERFORMANCE

0.033" slot, NPR = 2.0, $C_{\mu}=0.09$, $M_{inf}=0.2$

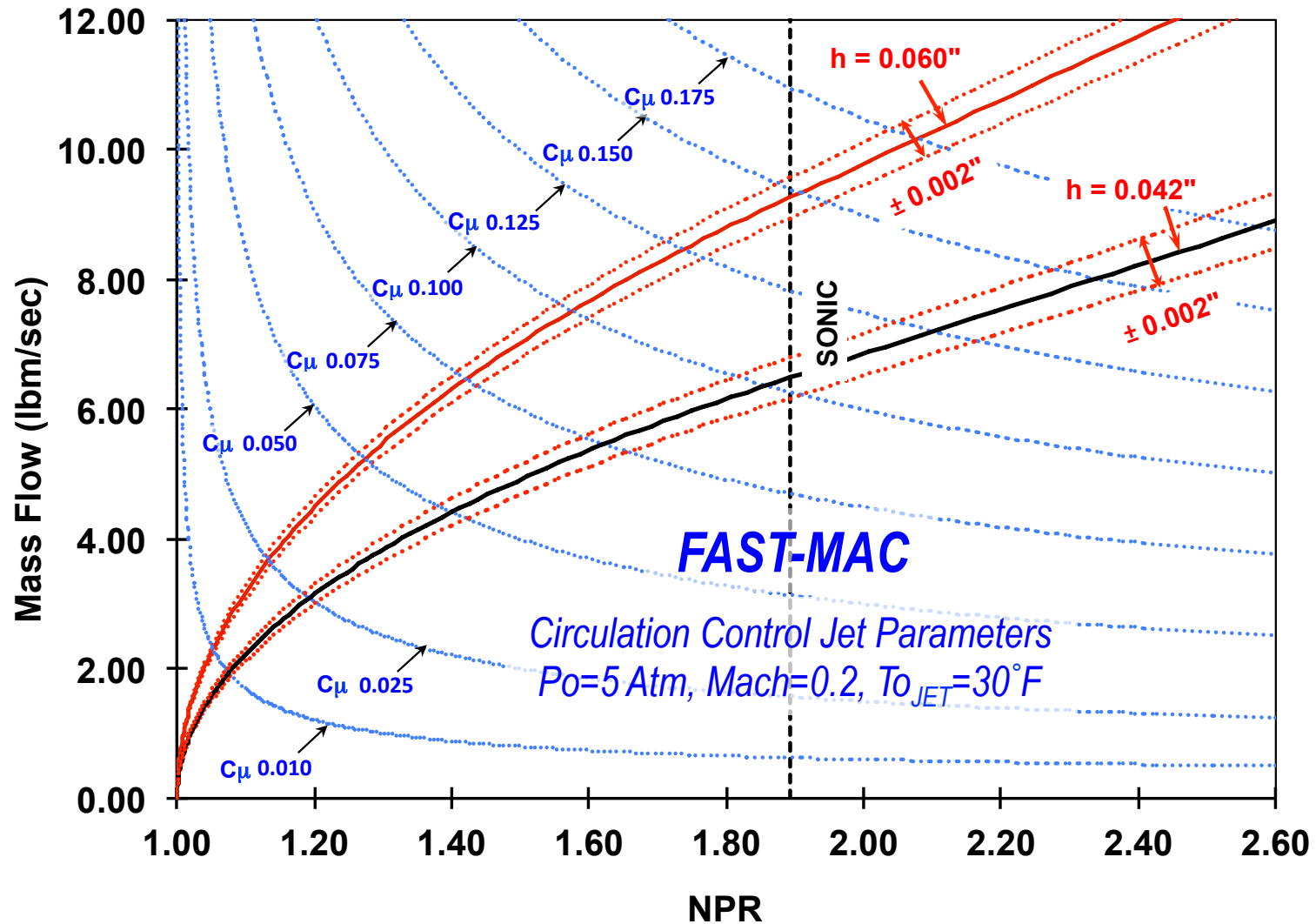


Experimental Lift Performance Improves With Smaller h/c





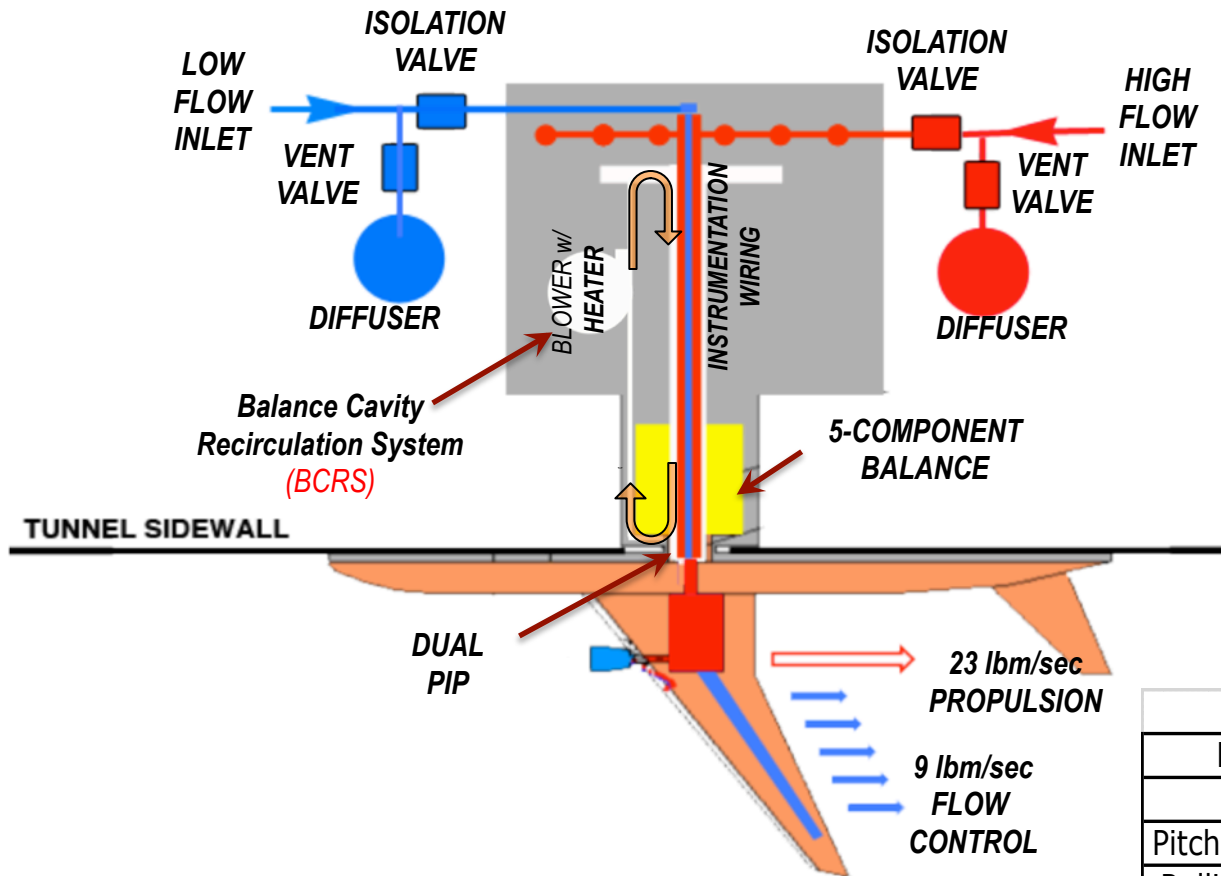
BLOWING REQUIREMENTS FOR TWO DIFFERENT SLOTS HEIGHTS FOR THE FAST-MAC MODEL





SCHEMATIC OF THE NTF DUAL FLOW HIGH PRESSURE AIR DELIVERY SYSTEM FOR SEMI-SPAN MODELS

SIDEWALL MODEL SUPPORT SYSTEM (SMSS)



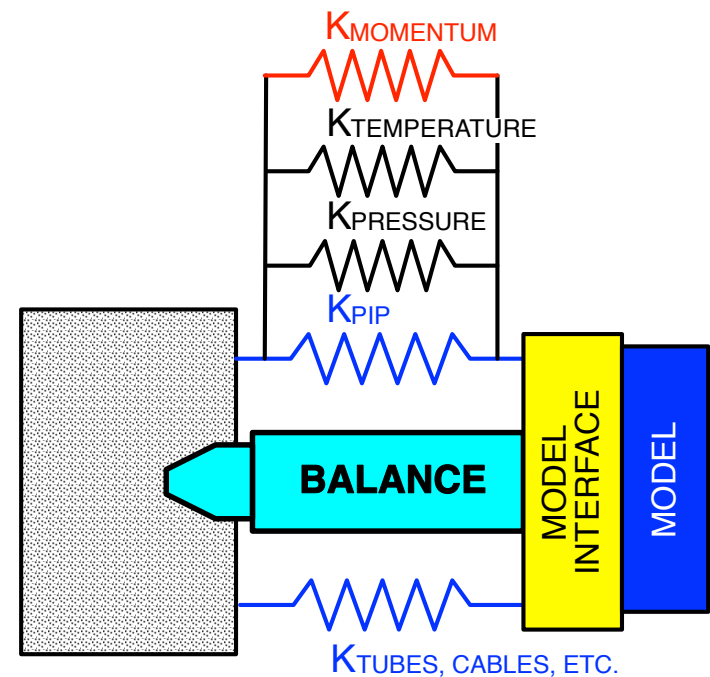
This System Provides Unique Opportunities for Studying Integrated Powered Effects and Flow Control Effects at High Reynolds Conditions

Component	NTF 117S
Normal Force lbs (N)	12,000 (53,379)
Axial Force lbs (N)	1,800 (8,007)
Pitching Moment lbs-in (N-m)	90,000 (10,169)
Rolling Moment lbs-in (N-m)	669,000 (7,558)
Yawing Moment lbs-in (N-m)	100,350 (11,338)

TWO TYPES OF TARES NEED TO BE DETERMINED

JET-OFF TARES

Changes in the spring constant of the balance resulting from the Flow Transfer Device (Bellows/**Pressure Interface Part (PIP)** assembly), Steel tubing, cables, etc. bridging the metric and nonmetric portions of the model



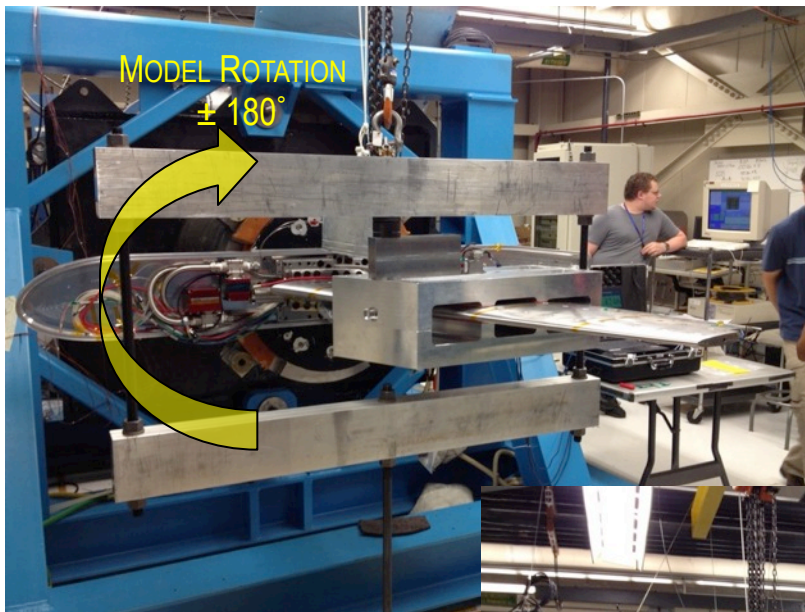
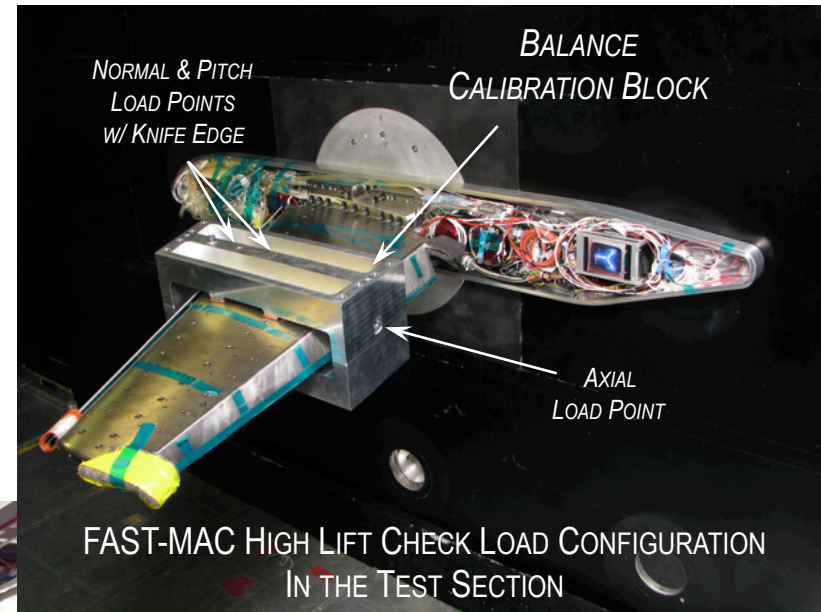
JET-ON TARES

Changes in the spring constant of the bellows resulting from **pressurization of the PIP**, local pressure differences from one end of the PIP to the other, and misalignment of the momentum transfer vector



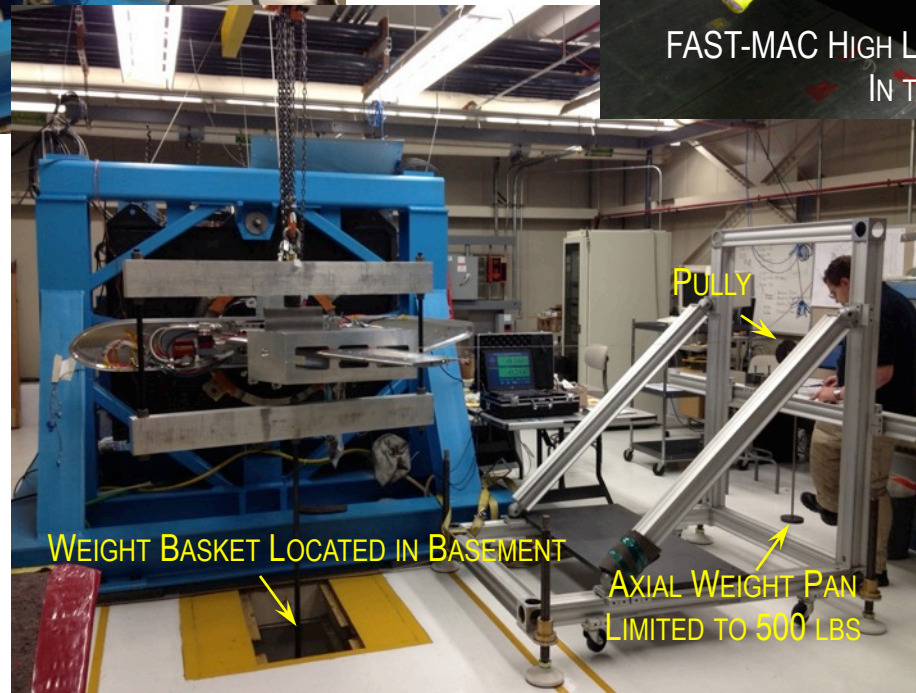
MODEL PREPARATION AREA

FAST-MAC MODEL LOADINGS



MODEL PREP AREA LOAD LIMITS

$$F_{\text{NORMAL}} = 12000 \text{ LBS}$$
$$F_{\text{AXIAL}} = 1800 \text{ LBS}$$



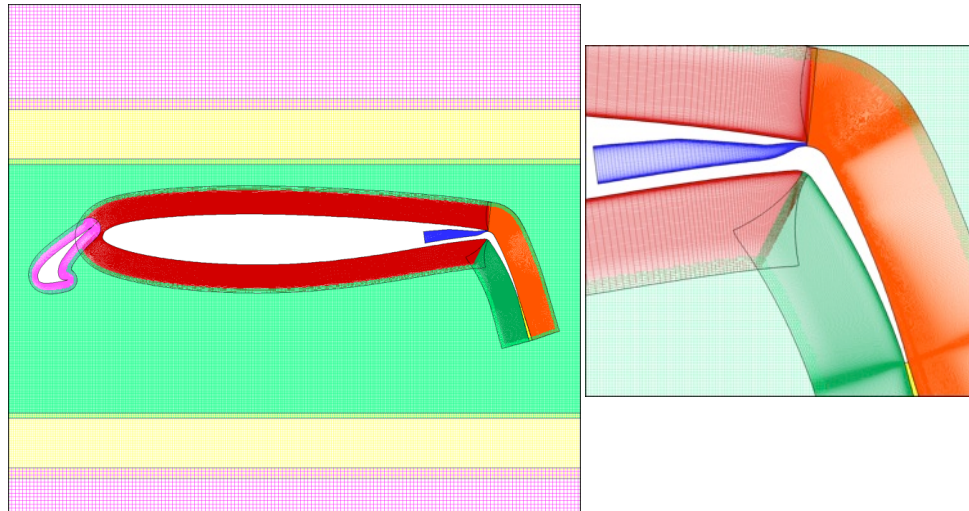
TEST SECTION LOAD LIMITS

$$F_{\text{NORMAL}} = 1000 \text{ LBS}$$
$$F_{\text{AXIAL}} = 500 \text{ LBS}$$



USING CFD AS A GUIDE TO UNDERSTANDING THE PHYSICS

2D OVERFLOW



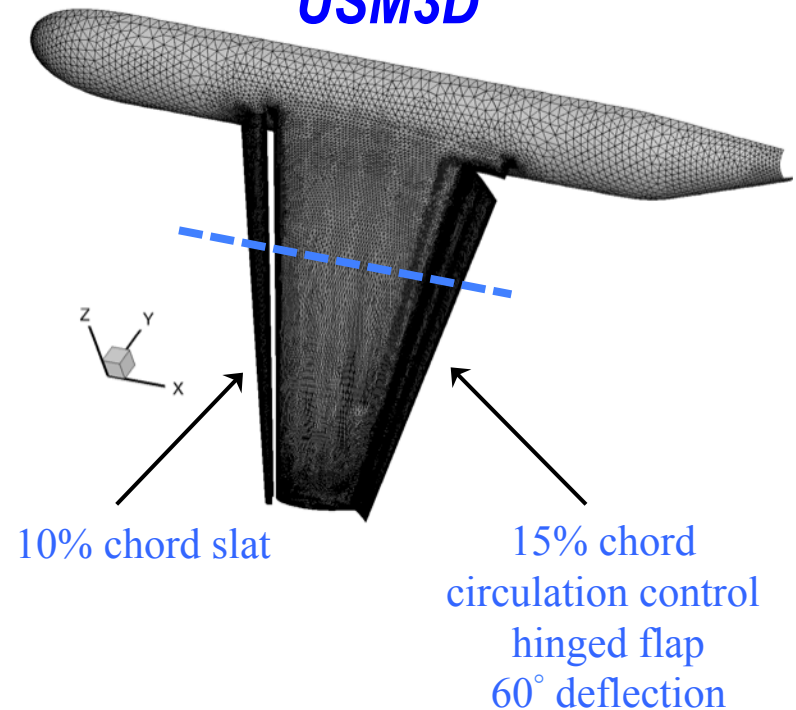
RANS flow solver

S-A Turbulence model

Rotational/Curvature correction

(1.07 million grid points)

USM3D



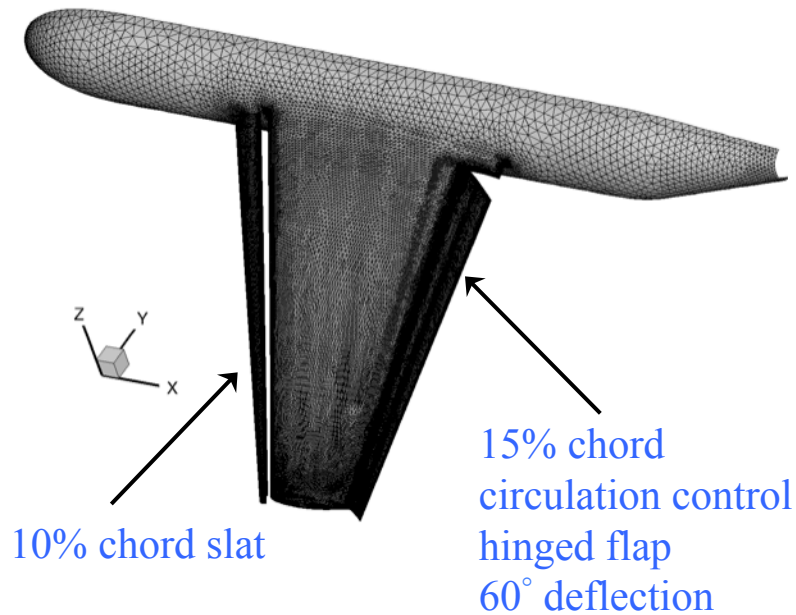
Full-Viscous Simulation

S-A Turbulence Model

(35 million cells)

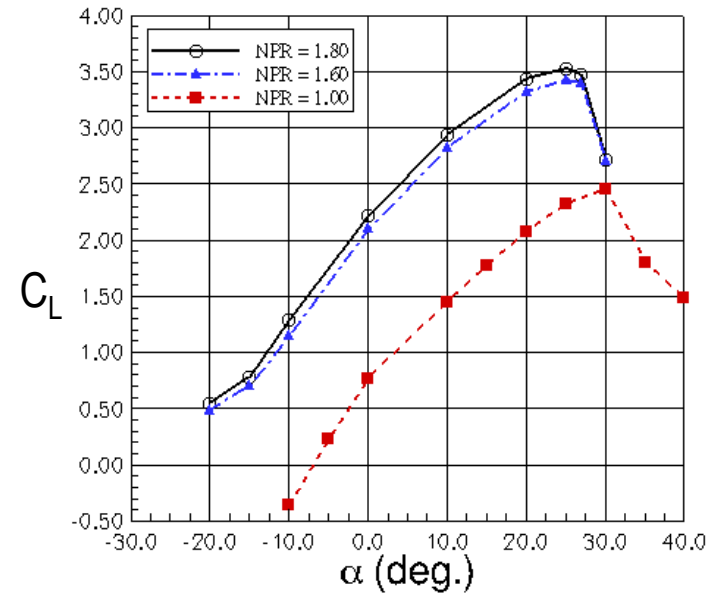


AERODYNAMIC CHARACTERISTICS OF SEMI-SPAN HIGH-LIFT DESIGN WITH BLOWING

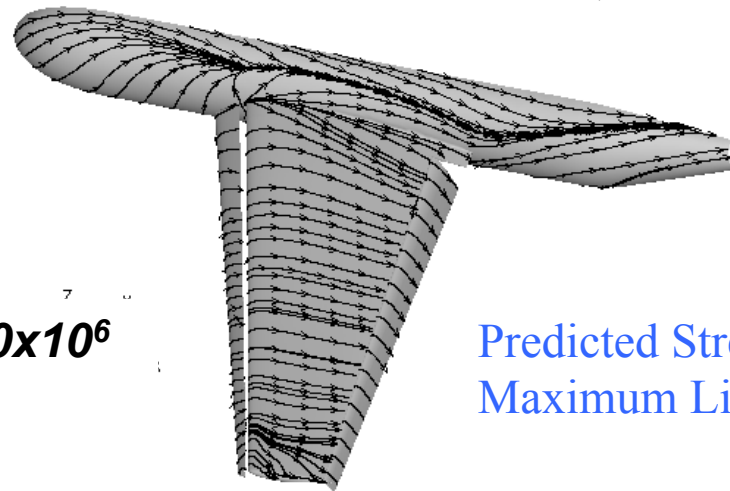


USM3D, full-viscous simulation, S-A turbulence model (35 million cells)

$M=0.20$, $\alpha=25^\circ$, $NPR=1.80$, $Re=20 \times 10^6$

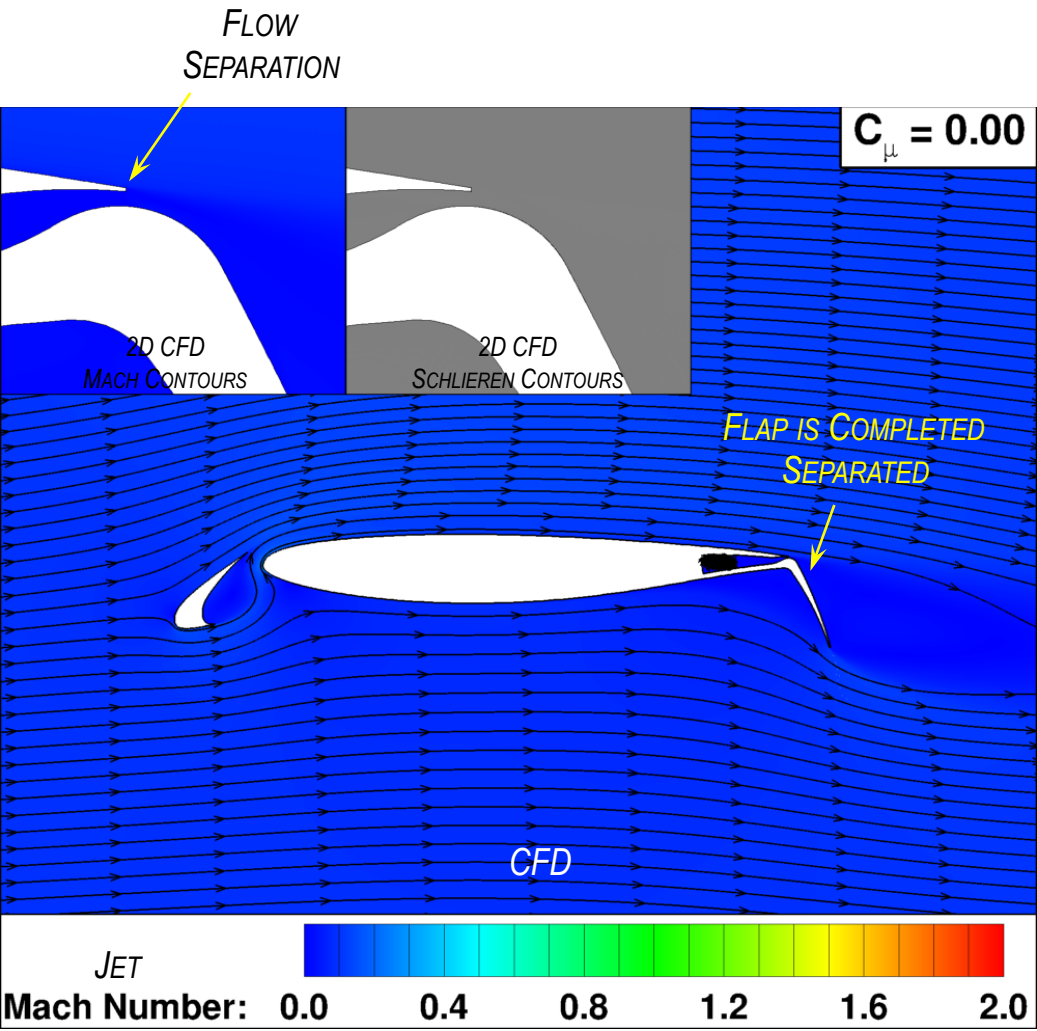
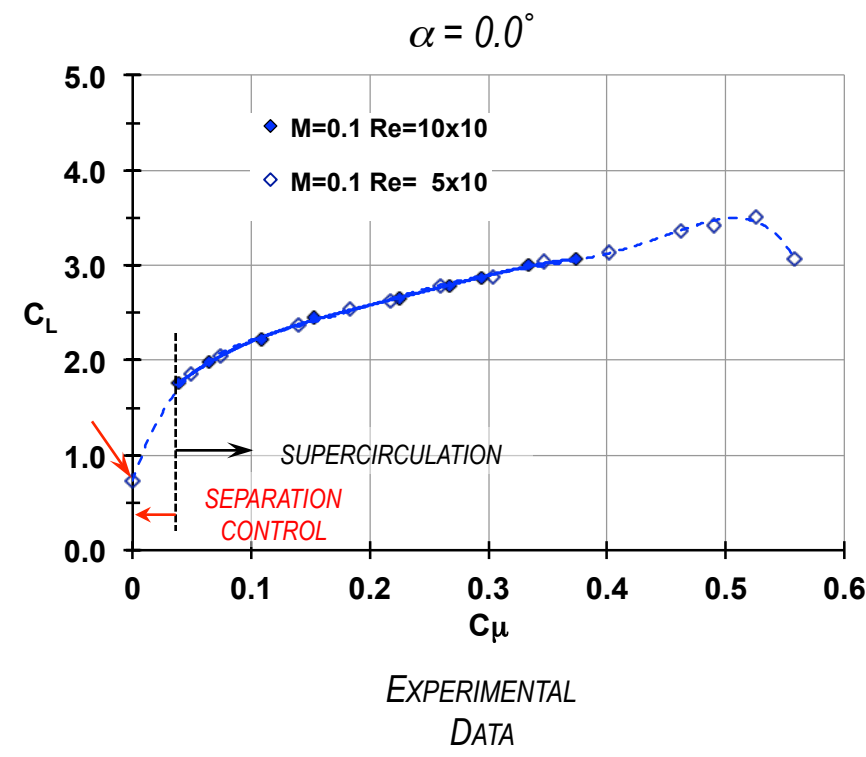


$M=0.20$, $Re=20 \times 10^6$



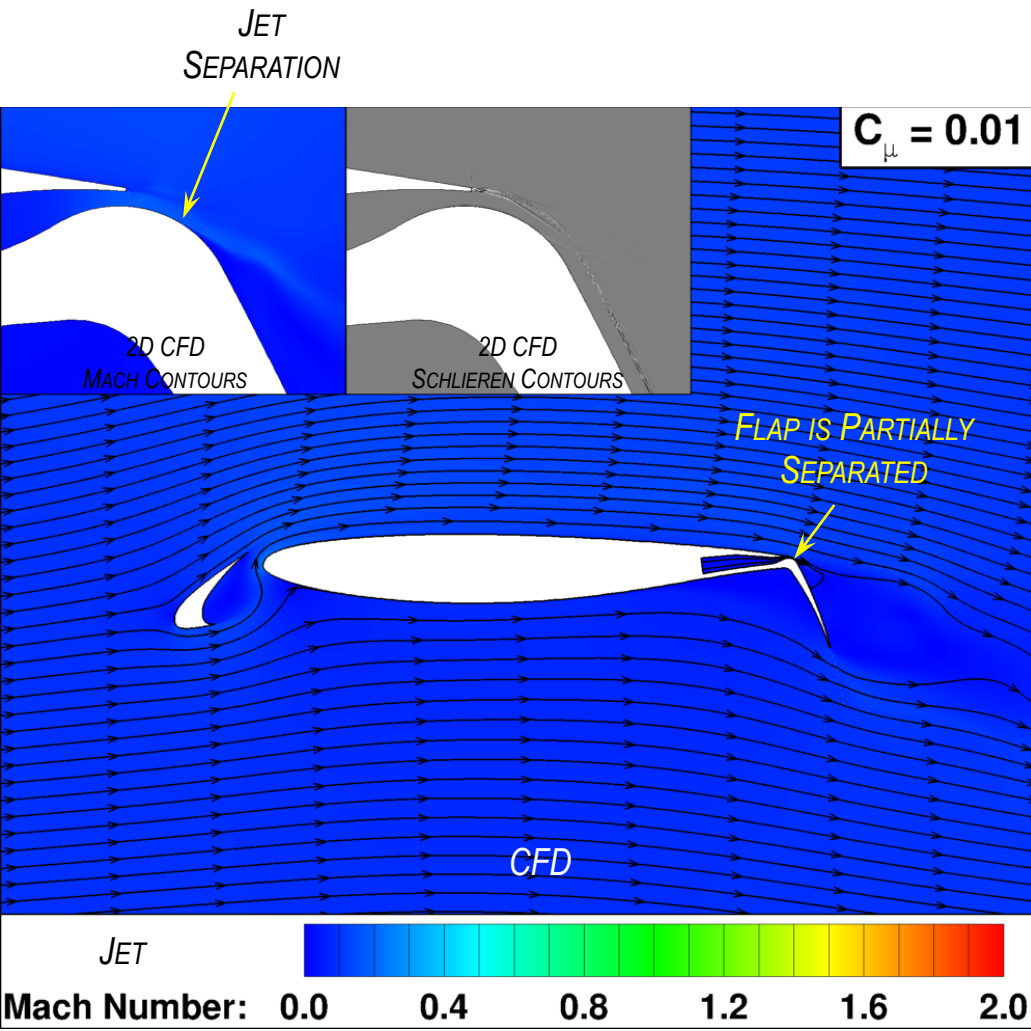
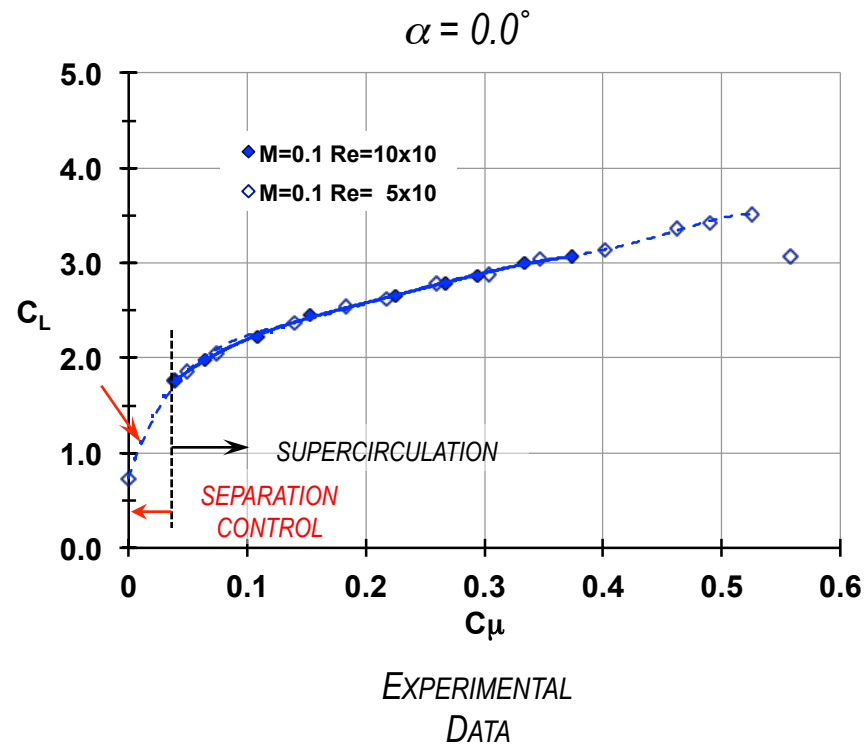


2-D PERFORMANCE WITH BLOWING - MACH = 0.1



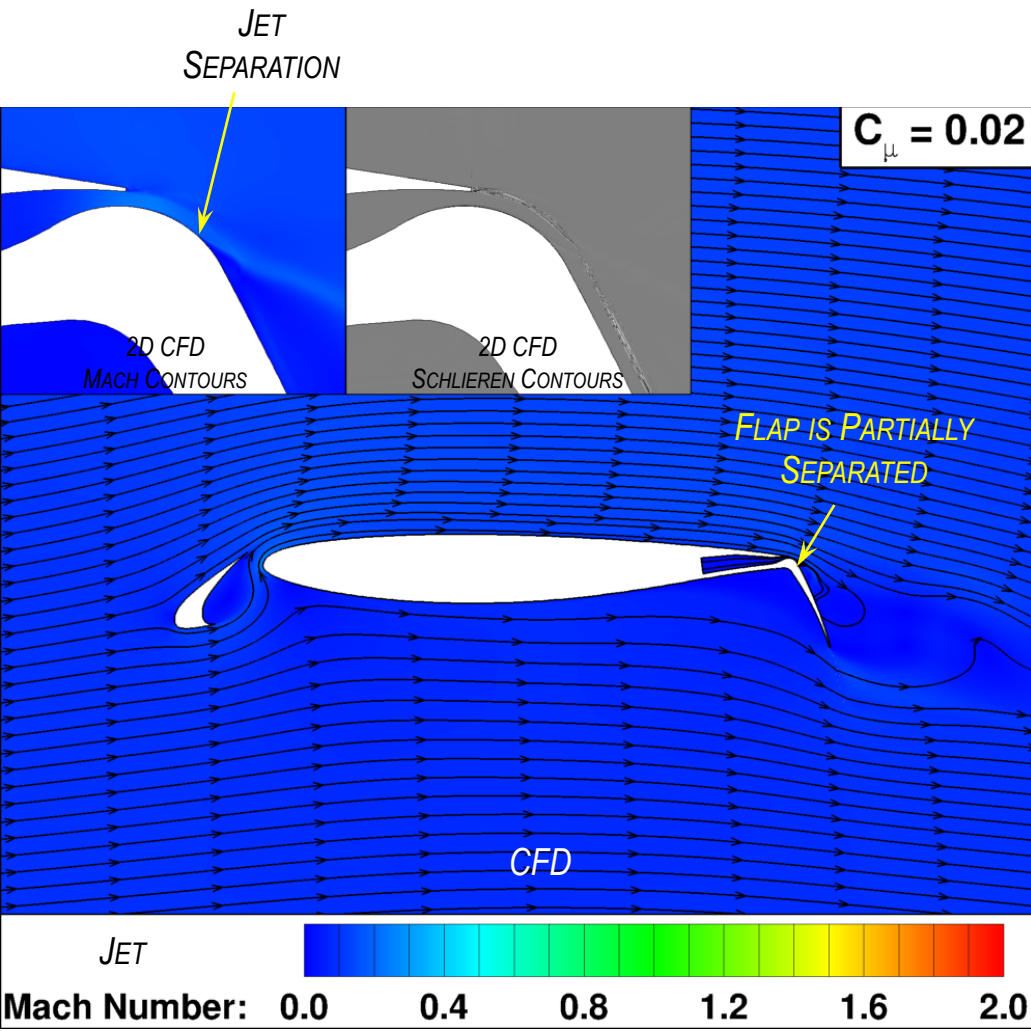
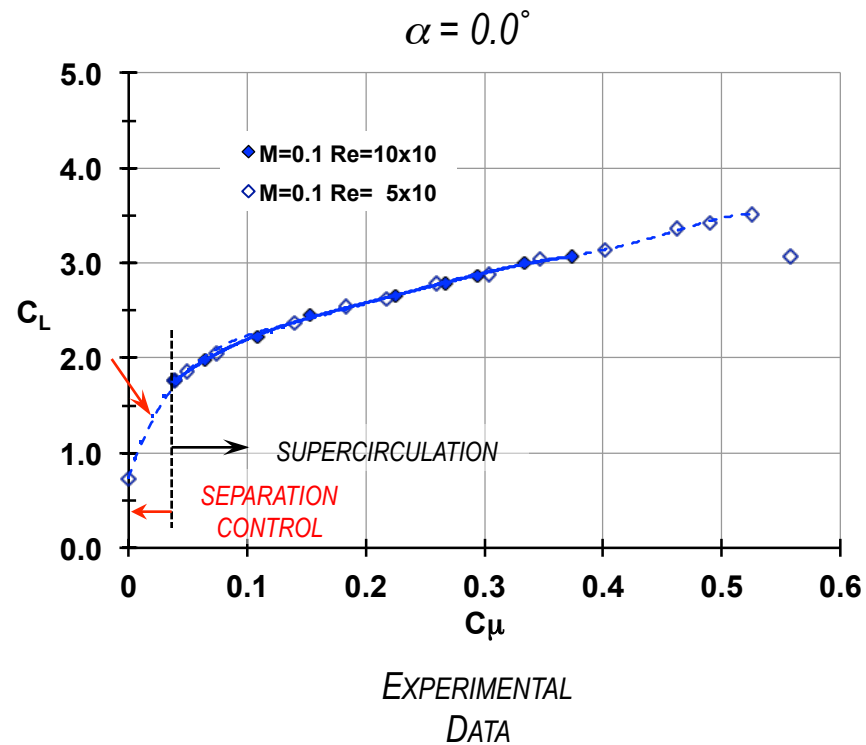


2-D PERFORMANCE WITH BLOWING - $MACH = 0.1$



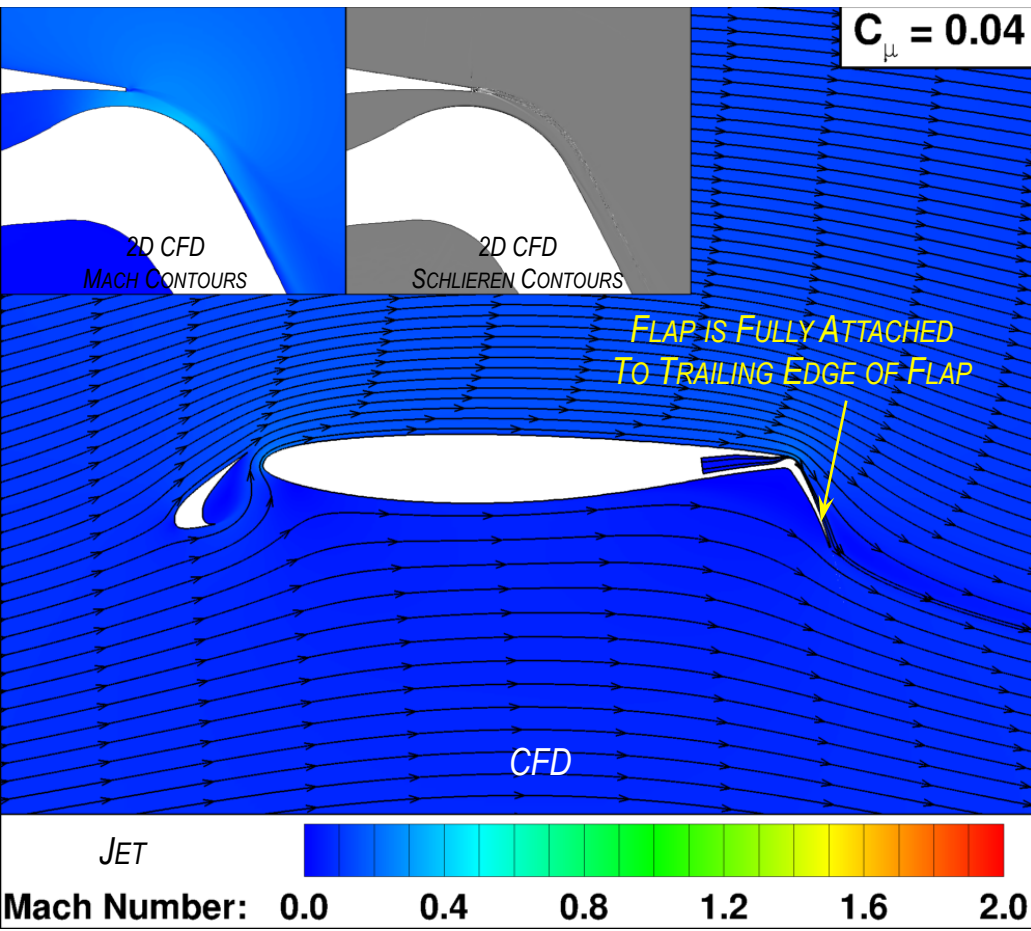
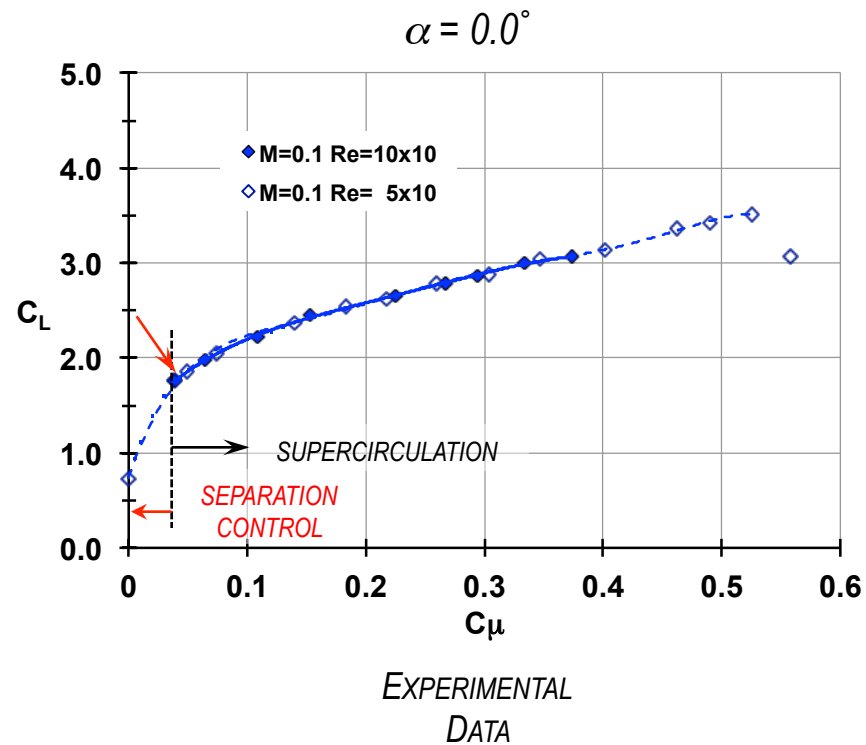


2-D PERFORMANCE WITH BLOWING - MACH = 0.1



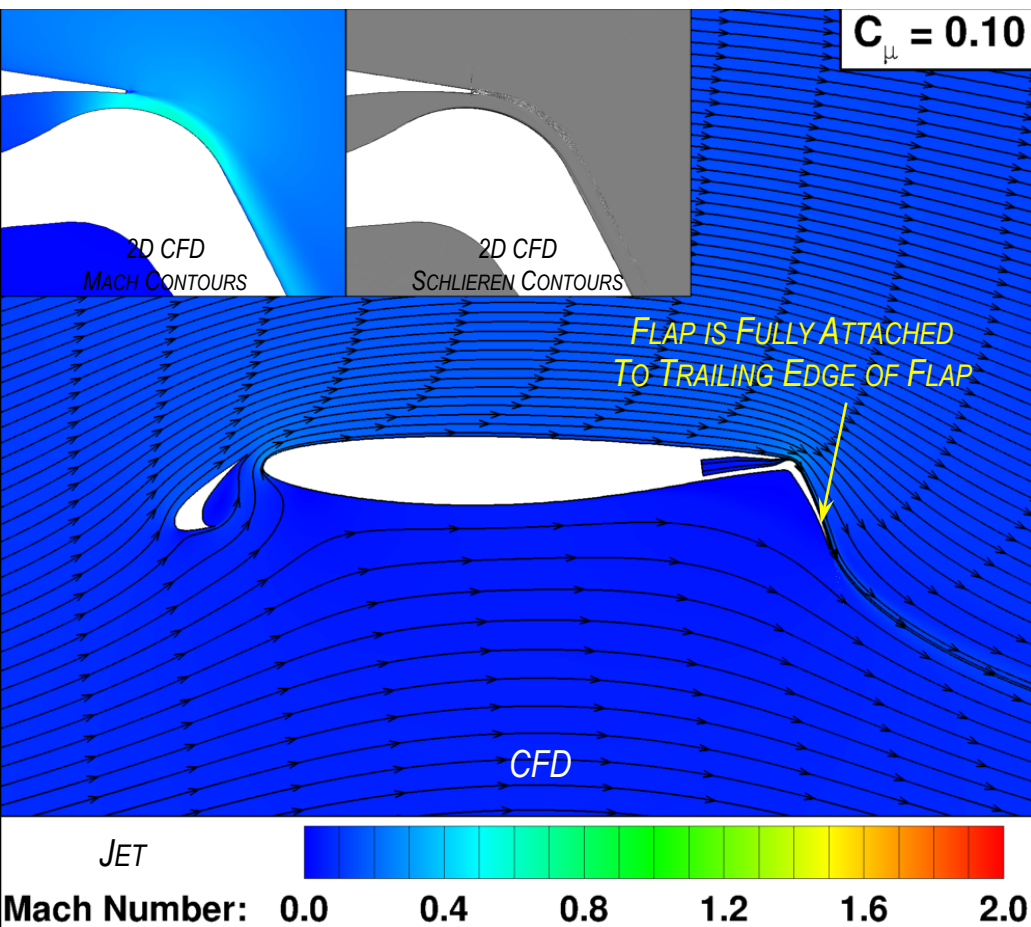
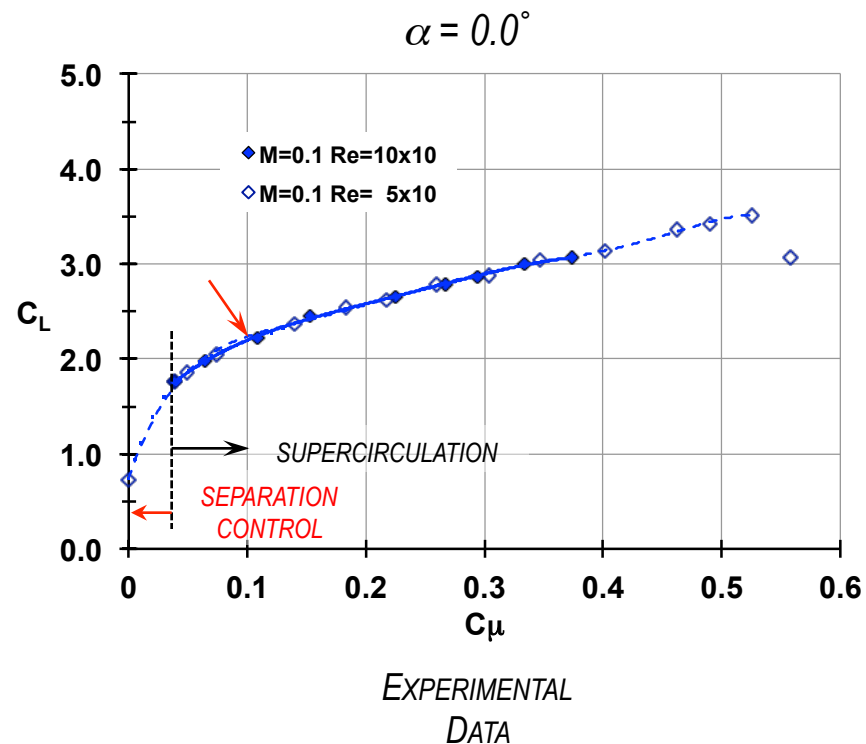


2-D PERFORMANCE WITH BLOWING - MACH = 0.1



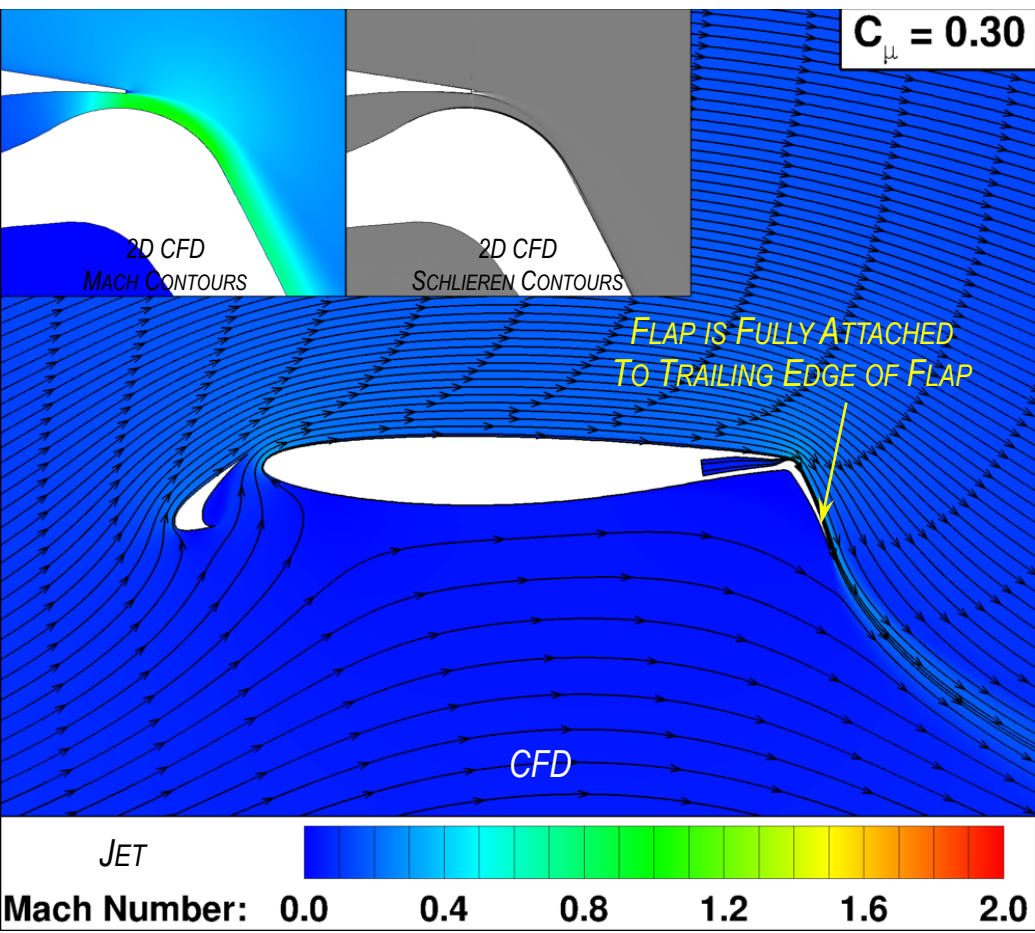
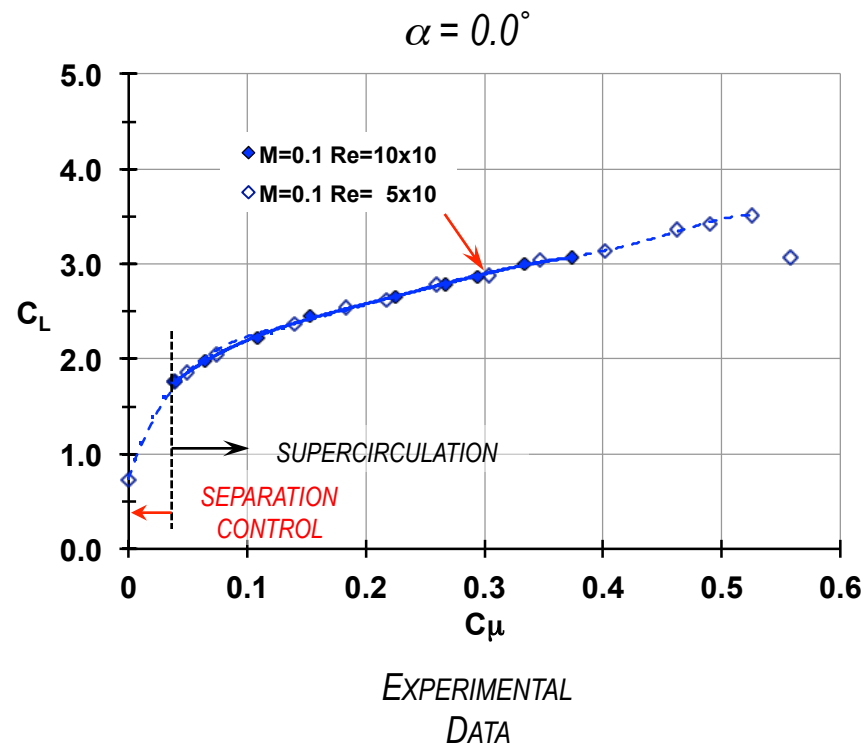


2-D PERFORMANCE WITH BLOWING - MACH = 0.1



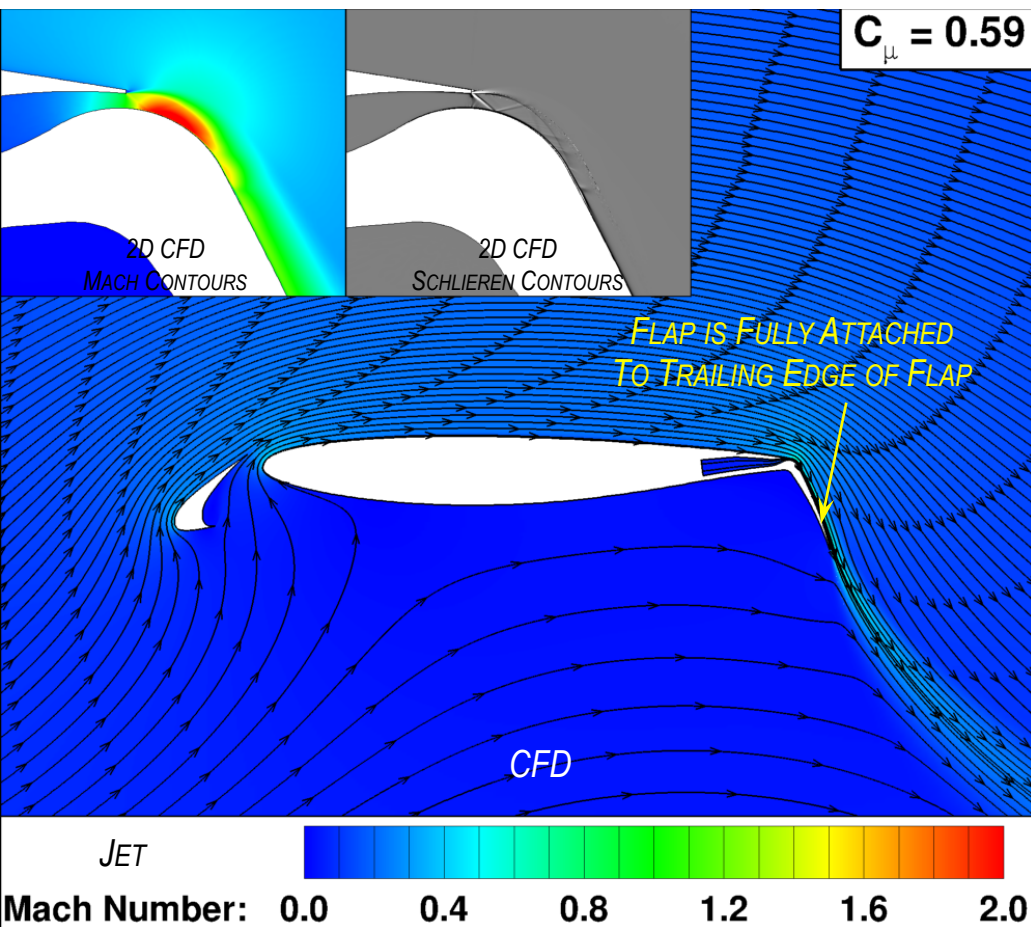
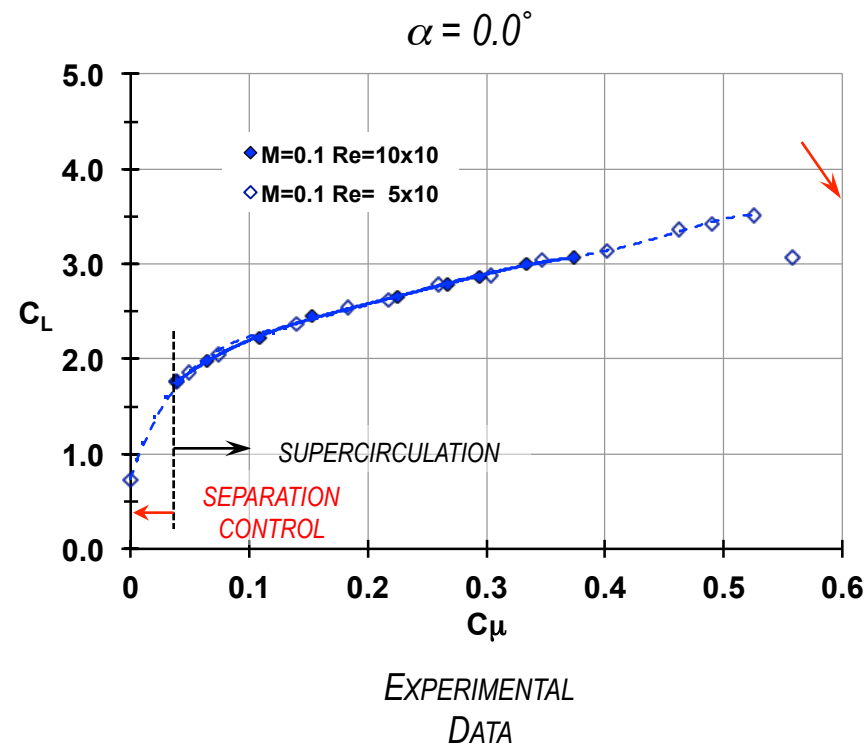


2-D PERFORMANCE WITH BLOWING - $MACH = 0.1$



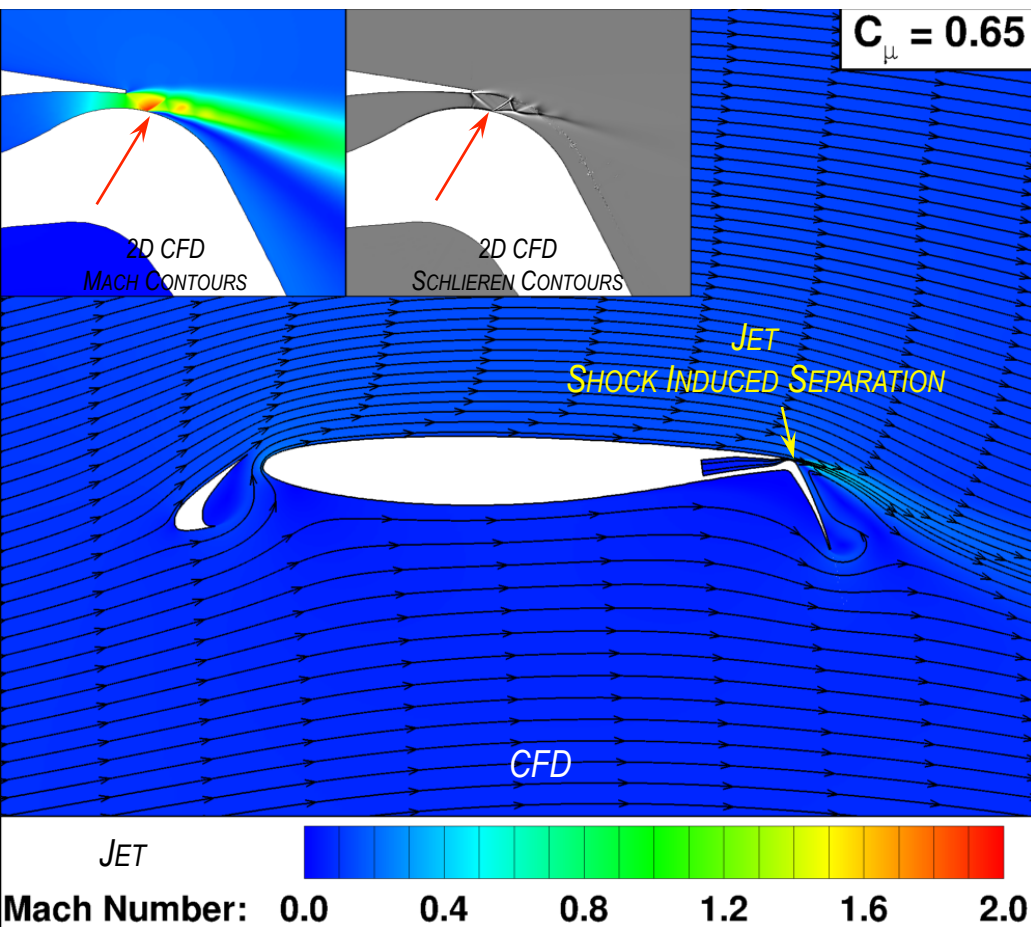
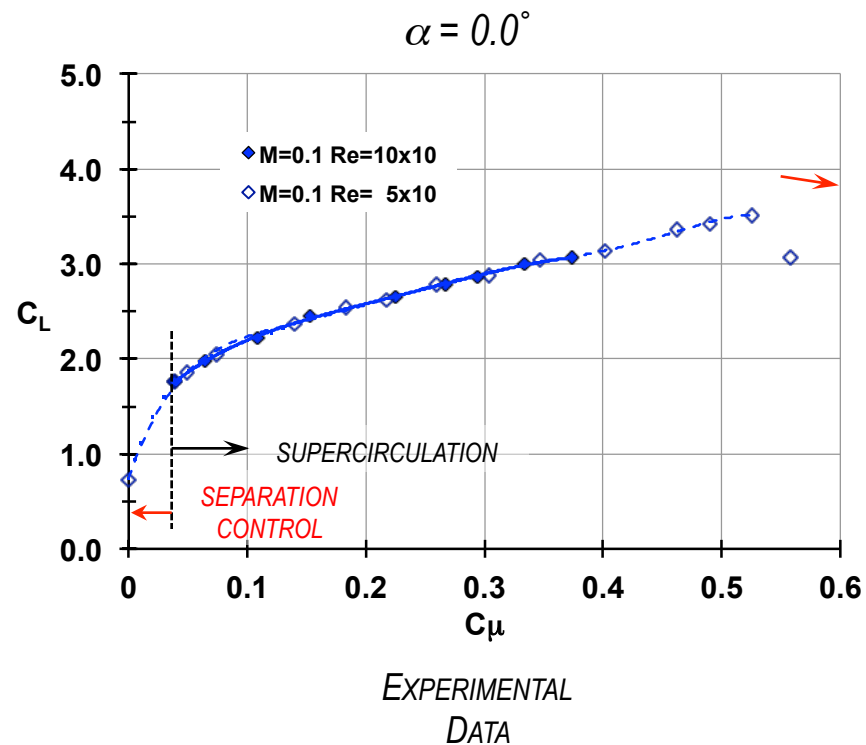


2-D PERFORMANCE WITH BLOWING - $MACH = 0.1$



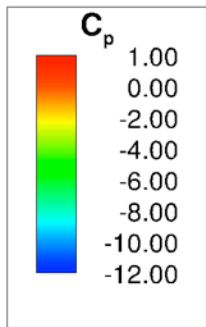


2-D PERFORMANCE WITH BLOWING - $MACH = 0.1$

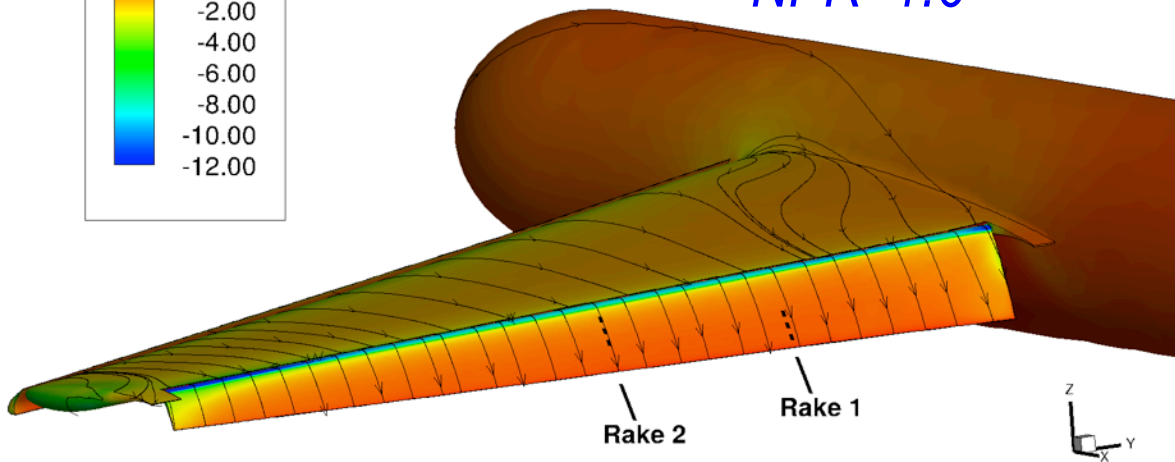




3D SURFACE FLOW WITH BLOWING - $MACH = 0.2$



$NPR=1.6$



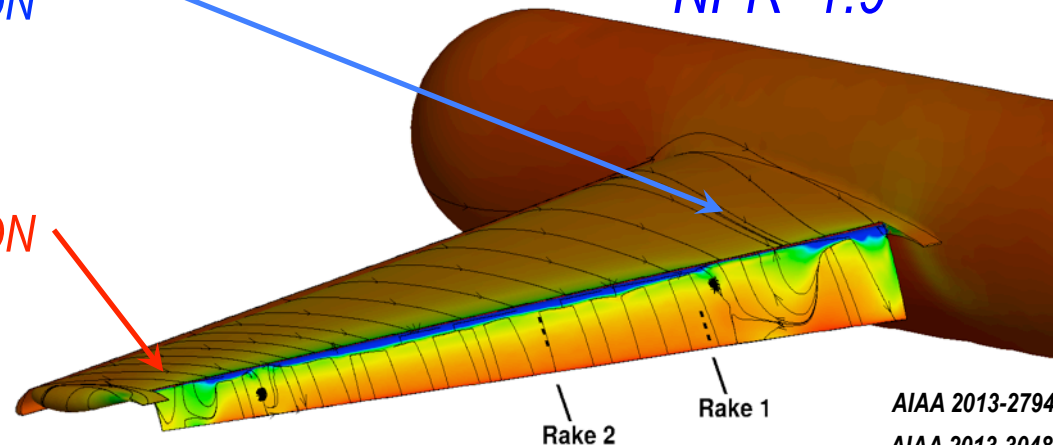
CFD GRID DOES NOT
CONSIDER
AEROELASTIC EFFECTS

FOR THE HIGH LIFT MODE
THE MODEL DEFORMS
 $\sim 0.25''$ AT THE TIP
WITH A TWIST = -0.3°

WING/FUSELAGE JUNCTURE FLOW
INFLUENCES FLAP SEPARATION

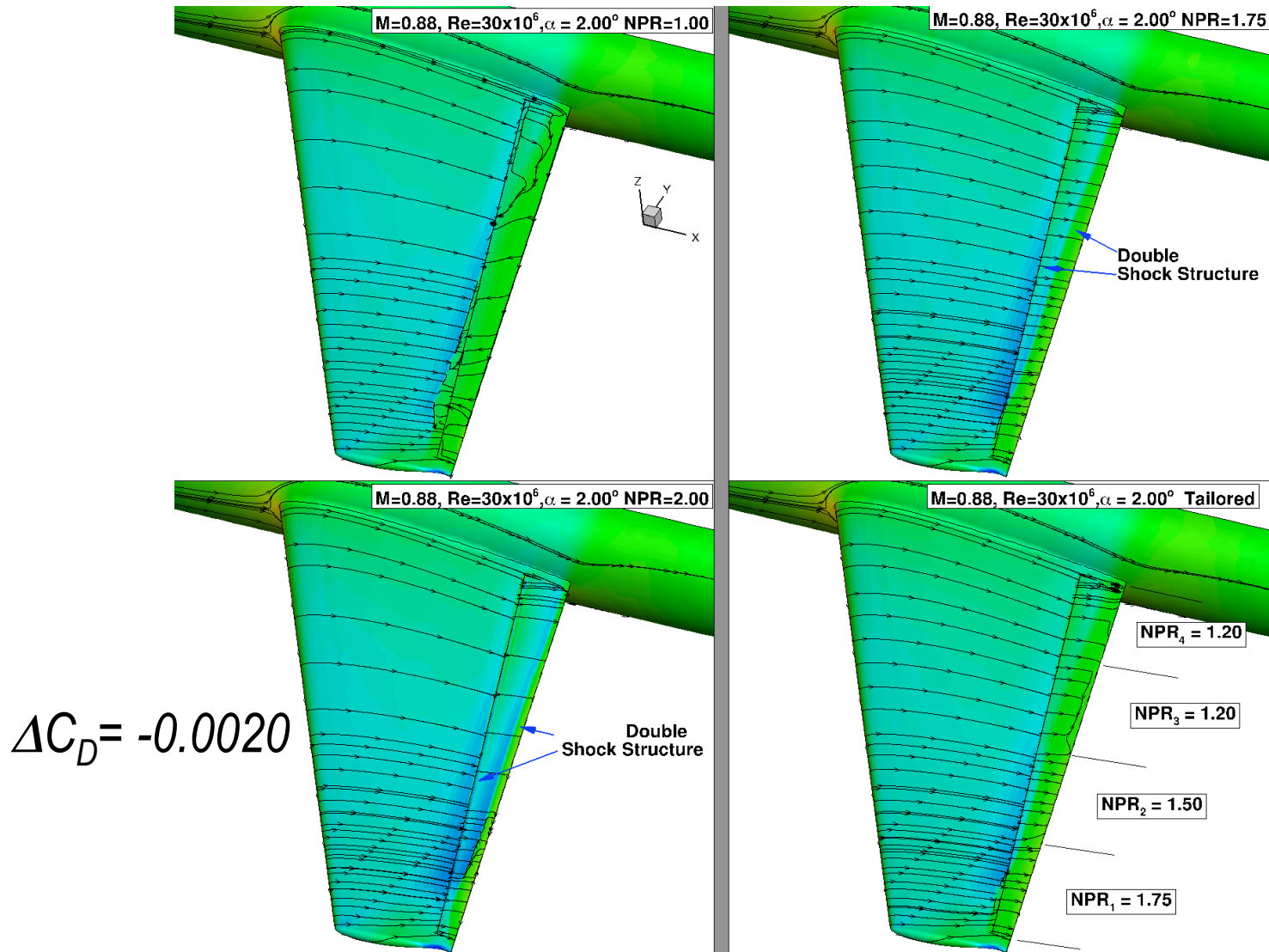
WING TIP FLOW
INFLUENCES FLAP SEPARATION

$NPR=1.9$





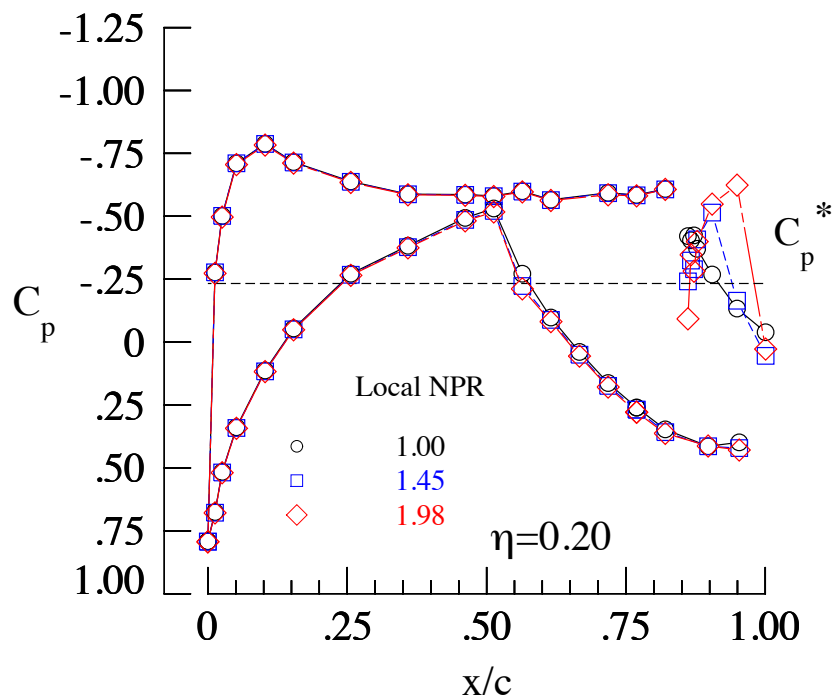
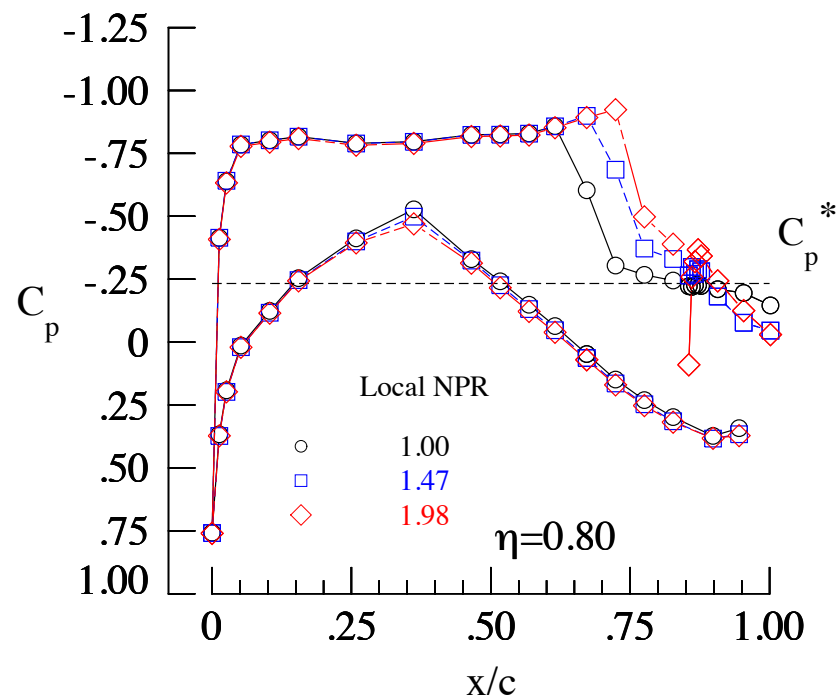
TAILORED BLOWING REDUCES DOUBLE SHOCK CFD PREDICTIONS FROM USM3D





Cp COMPARISONS – w/ BLOWING CHARACTERIZES SHOCK MOVEMENT

	Run	Point	Mach	Re_C	$\alpha(deg.)$	NPR	C_{μ}
○	304	4729	0.879	29.88	3.06	1.00	0.000
□	304	4734	0.879	29.97	3.05	1.46	0.003
◇	304	4737	0.881	29.95	3.05	1.98	0.006



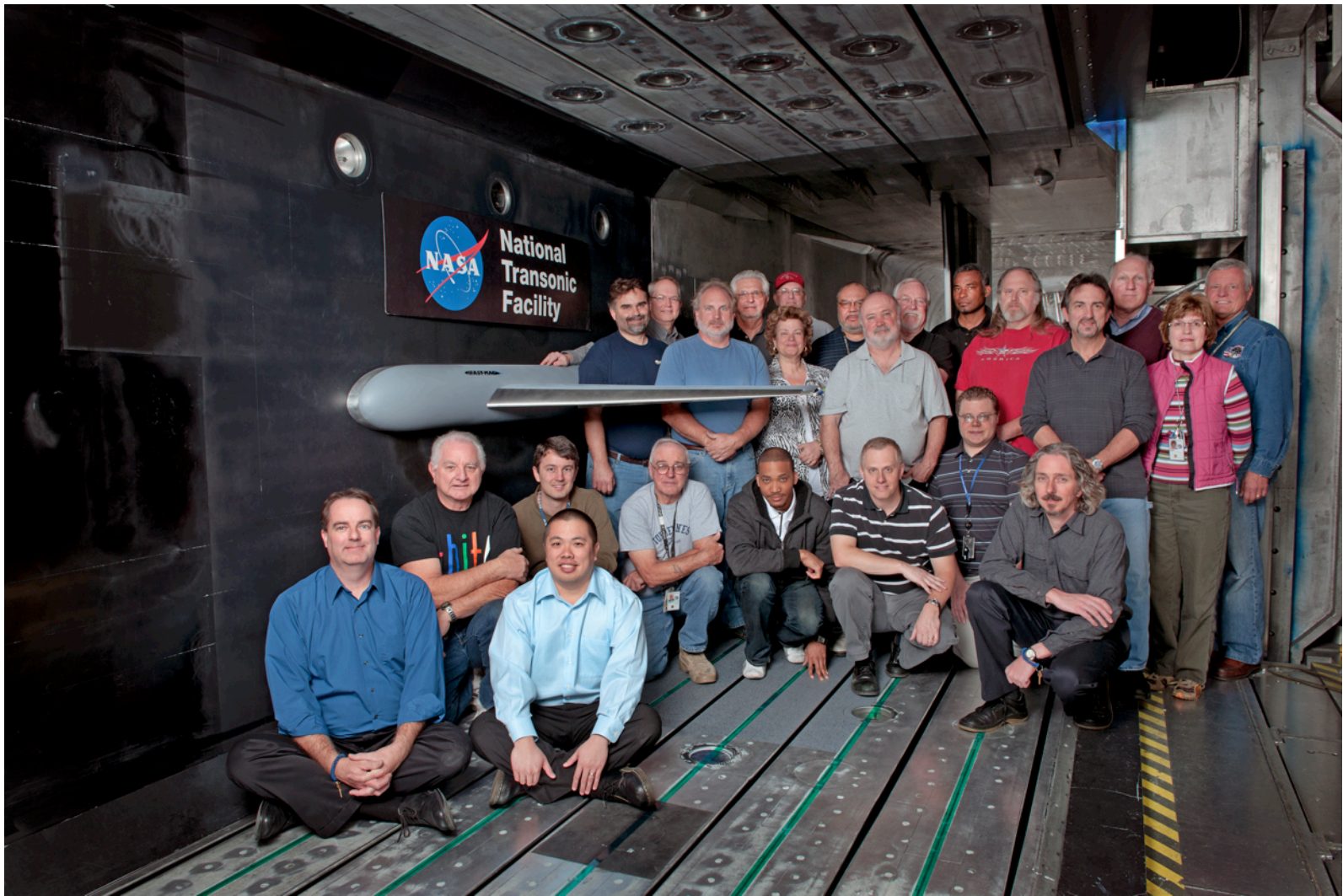


CLOSING REMARKS

- *NASA'S CIRCULATION CONTROL CFD DEVELOPMENT AND VALIDATION IS BASED ON DIFFERENT LEVELS OF SOPHISTICATION AND PHYSICS THAT INCLUDE: UNIT PROBLEMS, BENCHMARK CASES, SUB-SYSTEMS, AND COMPLETE SYSTEMS*
- *CIRCULATION CONTROL IS A CHALLENGING TEST BED FOR CFD AND EXPERIMENTS AND ARE BEING USED TOGETHER TO IMPROVE CONFIDENCE IN OUR RESULTS*
 - *RESULTS FROM THESE EFFORTS HAVE LED TO A GREATER UNDERSTANDING OF THE PHYSICS AND HAVE RESULTED IN IMPROVEMENTS IN OUR CFD AND EXPERIMENTAL TOOLS*
 - *THE IMPROVEMENTS IN CFD IS REALIZED MORE AND MORE AS INDUSTRY UTILIZES CFD AS A AIRCRAFT DESIGN TOOL*
- *VERIFICATION AND VALIDATION AT REALISTIC MACH AND REYNOLDS NUMBERS IS ONE OF THE FINAL STEPS IN THE AIRCRAFT DESIGN PROCESS.*
- *THE HIGH REYNOLDS NUMBER FAST-MAC RESULTS SHOW GOOD CORRELATION BETWEEN CFD AND EXPERIMENT. IN ADDITION TO THIS POSITIVE OUTCOME, THE CRUISE RESULTS ARE PROMISING AND MAY BE ENOUGH TO HELP THIS TECHNOLOGY BUY IT'S WAY ONTO THE NEXT GENERATION AIRCRAFT*



Questions?







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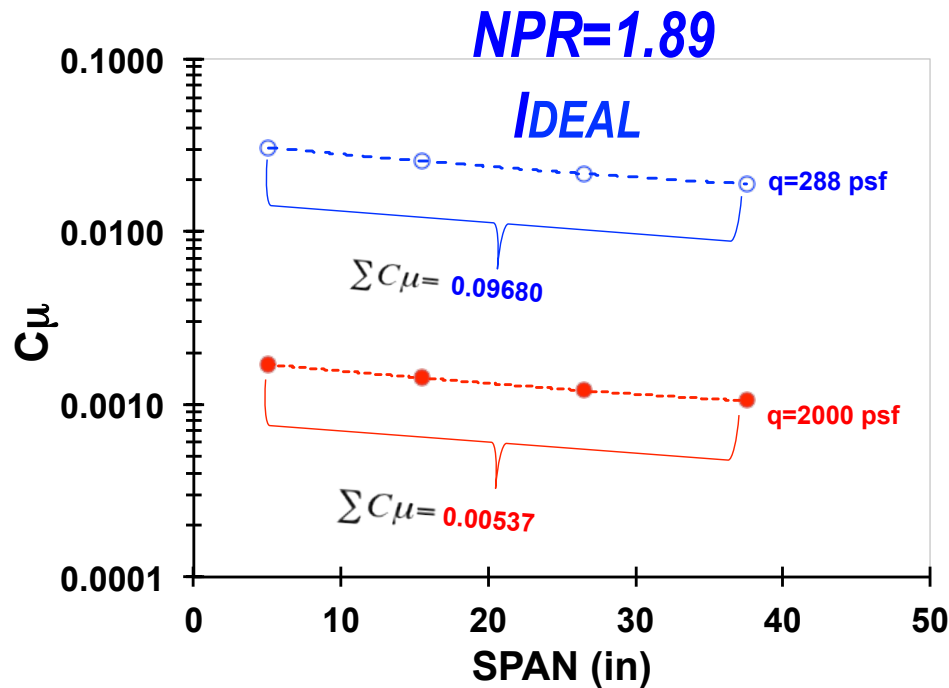
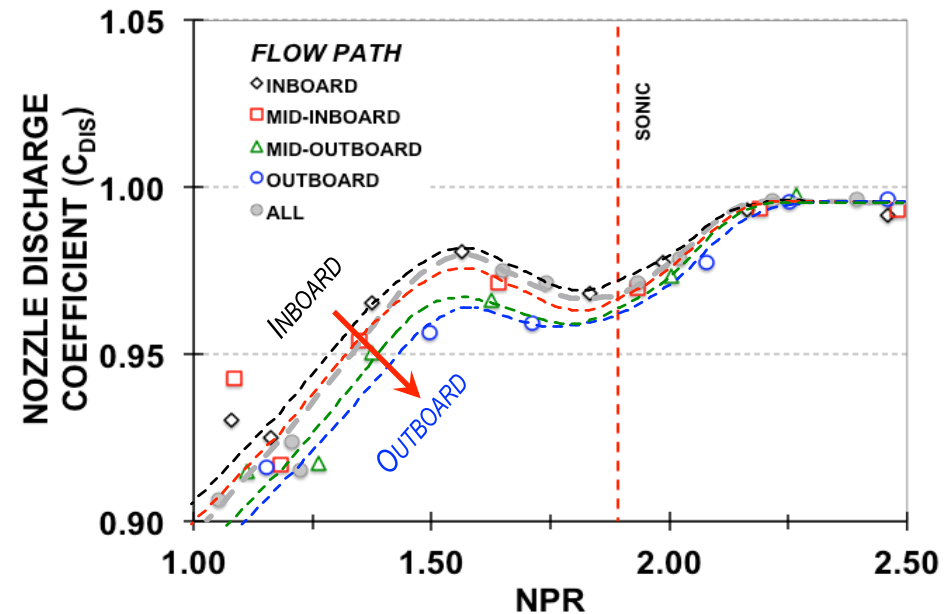


CC NOZZLE EFFICIENCY

$$C_{\mu} = \frac{THRUST}{q_{\infty} S} = \frac{2hb_{JET}}{cb} \frac{\rho_{JET}}{\rho_{\infty}} \frac{U_{JET}^2}{U_{\infty}^2}$$

$$C_{\mu} = \frac{C_{DIS} \dot{W} U_{JET}}{q_{\infty} S}$$

$$C_{DIS} = \frac{\dot{W}_{MEASURED}}{\dot{W}_{IDEAL}}$$



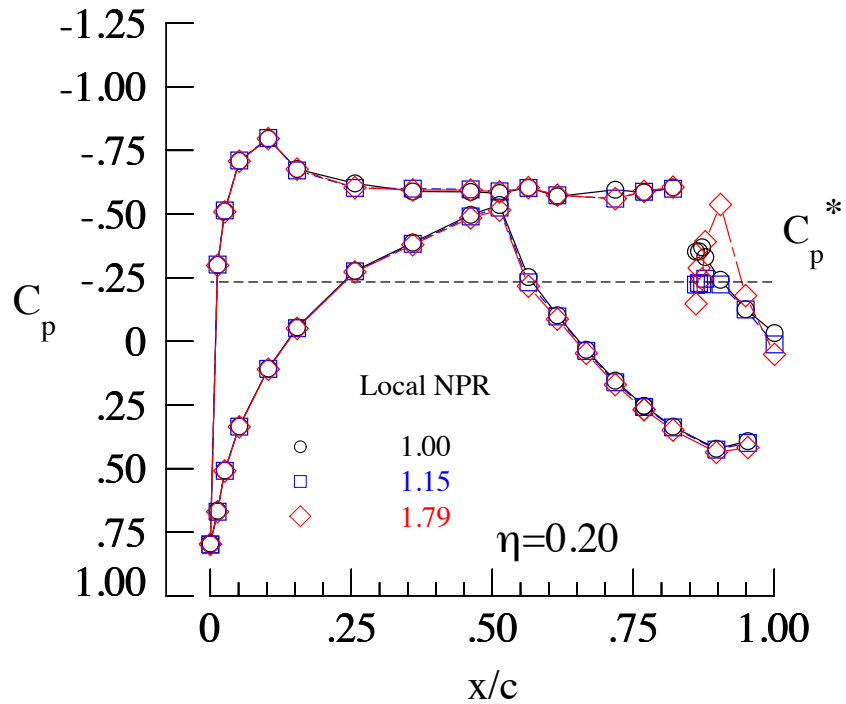
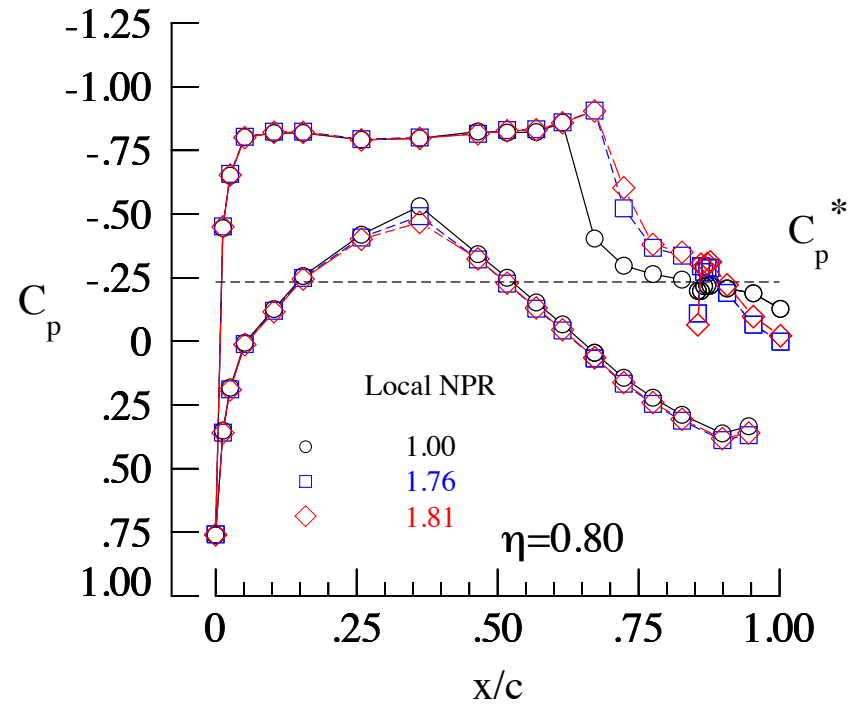
**Nozzle Discharge Coefficients for the 60° flap,
 $h/c=0.0022$ Configuration, $P_o=1\text{ATM}$, $T_{JET}=40^{\circ}\text{F}$**



Cp COMPARISONS

TAILORED BLOWING CRUISE FLAP

	Run	Point	Mach	Re_C	$\alpha(deg.)$	NPR	C_{μ}
○	337	5266	0.879	15.20	3.02	1.00	0.000
□	347	5436	0.879	14.96	3.04	1.46	0.003
◇	346	5420	0.880	14.95	3.04	1.79	0.005





JET PROFILES - MACH = 0.2

