AIAA Paper 2005-1260

High Performance Airfoil Using Co-flow Jet Flow Control: Wind Tunnel Tests and Analysis

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Overview of Airfoil Flow Control

- Rotating Cylinder at LE and TE
- Circulation Control Airfoil, LE or TE Blowing
- Synthetic Jet, Pulsed Jet
- Closed Loop Feed Back, Actuation and Sensor System
- Multi-Element High Lifting System

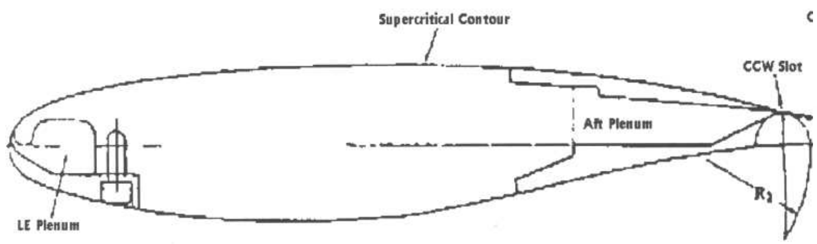


Figure 1. Dual Radius CCW Airfoil with LE Blowing [2]

Circulation Control Airfoil with TE Flap (Englar, et al. J. Aircraft, V.31,09/1994)

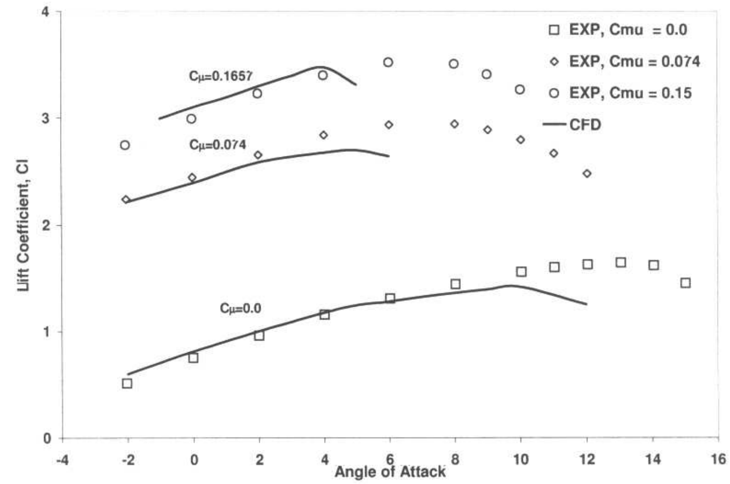


Figure 4. Variation of the Lift Coefficient with Angle of Attack

CC Airfoil C_L vs AoA (Liu, et al. AIAA Paper 2004-56)

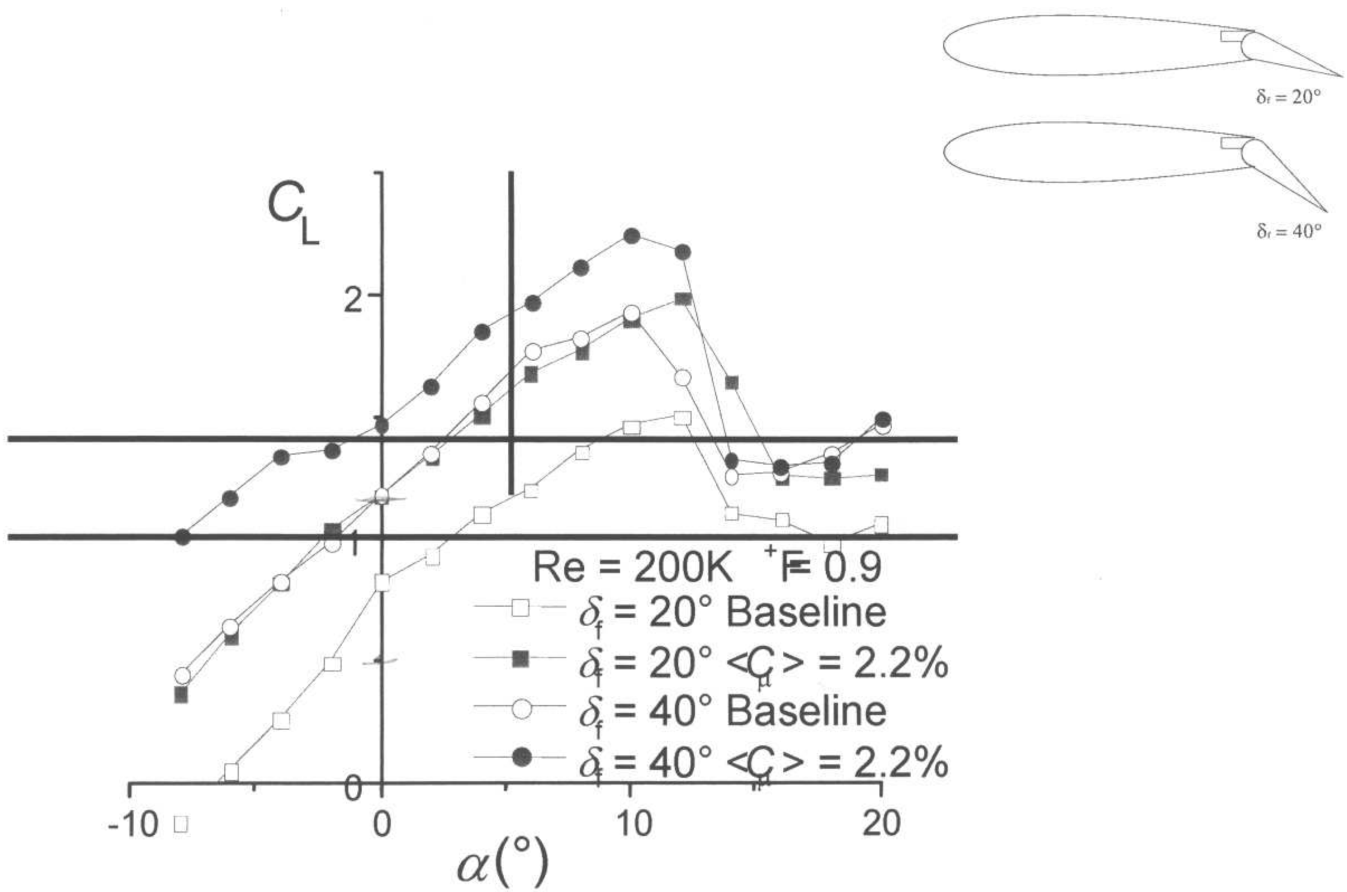


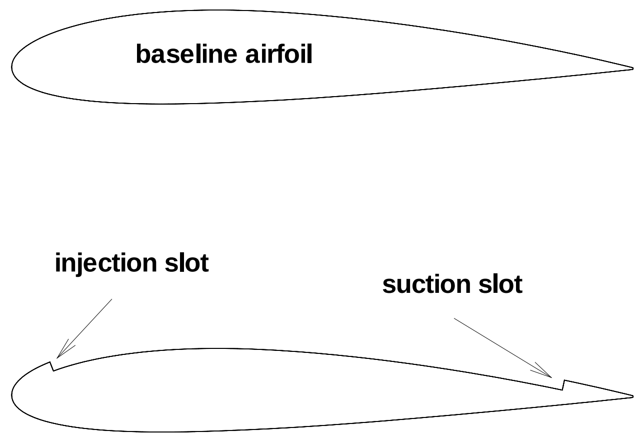
Figure 4 C_L vs α sweep on a flapped NACA 0015 for $\delta_f = 20°$ & $40°$

Synthetic Jet (Wygnanski, AIAA Paper 2004-2505)

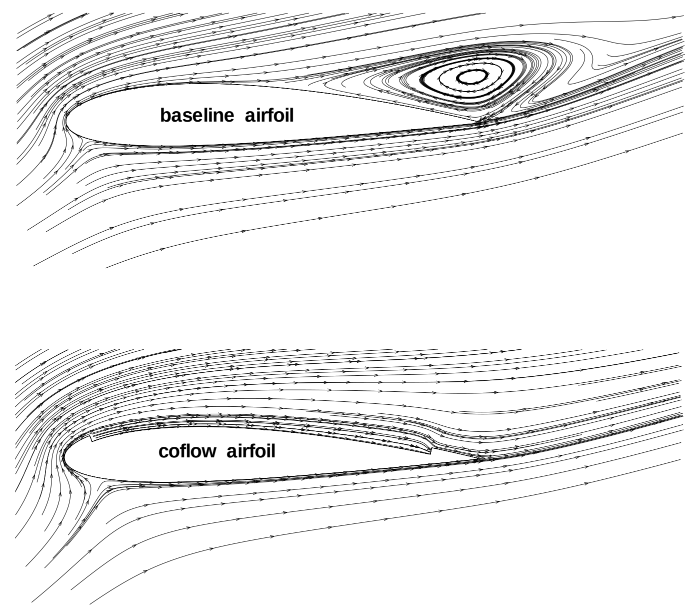
Objective

- Develop A New Airfoil Flow Control Technology:
- **Highly Effective**: High Lift, Low Drag, High Stall Margin
- **Energy Efficient**: Small Penalty to Propulsion System
- **Easy Implementation**

Co-Flow Jet(CFJ) Airfoil Concept

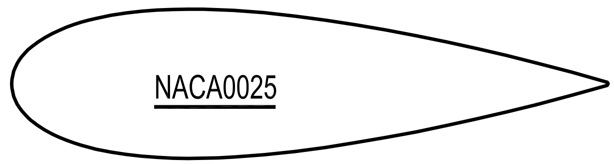


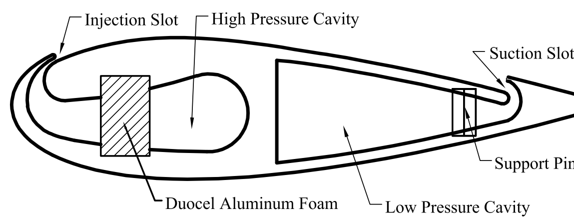
Baseline NACA2415 and CFJ Airfoil



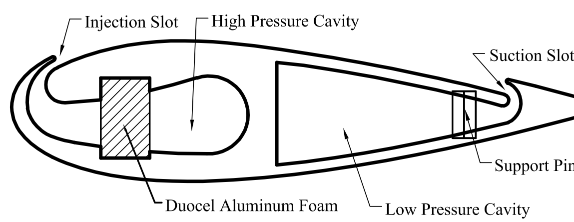
Streamlines at High AoA

The Tested CFJ Airfoil Geometry



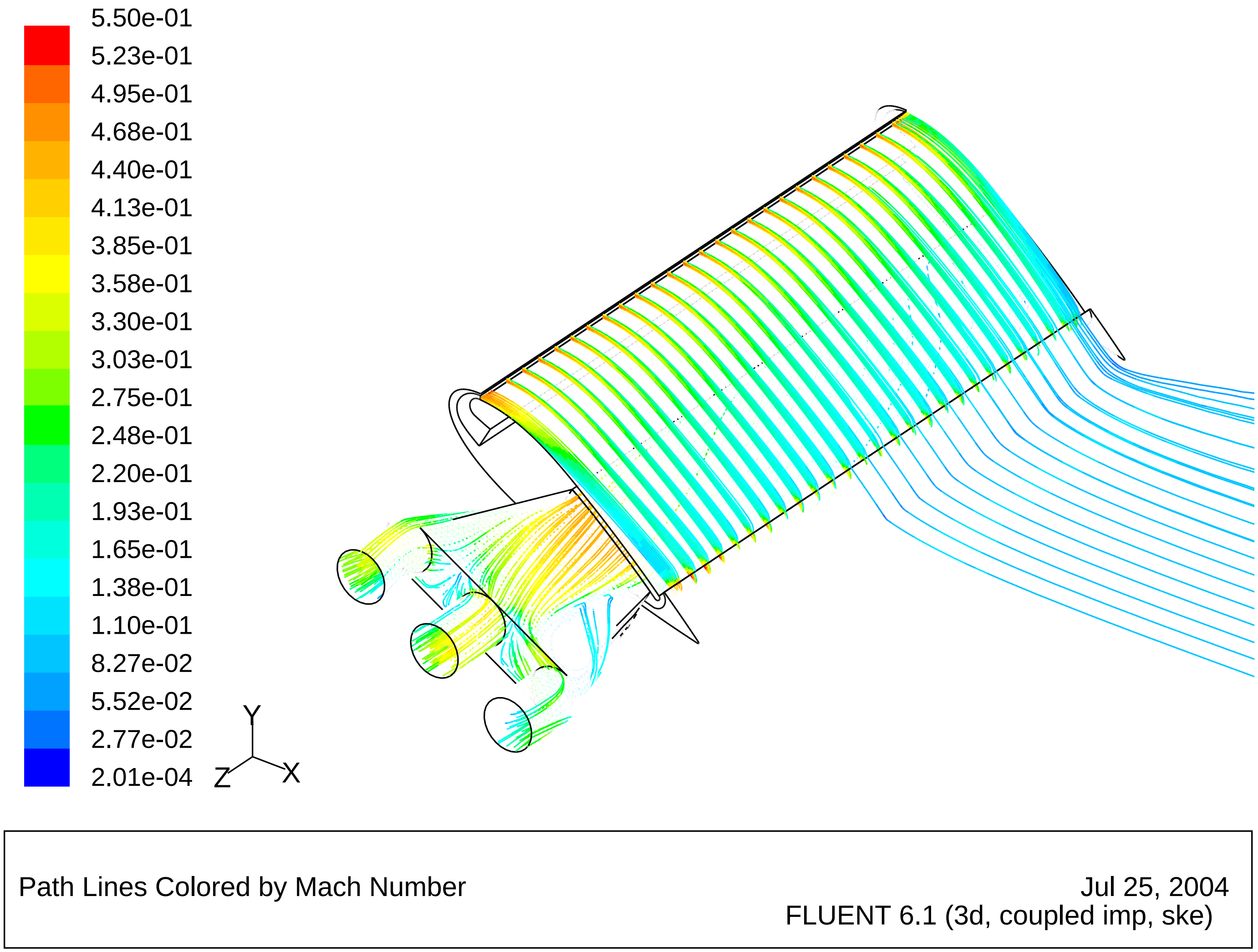


CFJ0025-065-196



CFJ0025-131-196

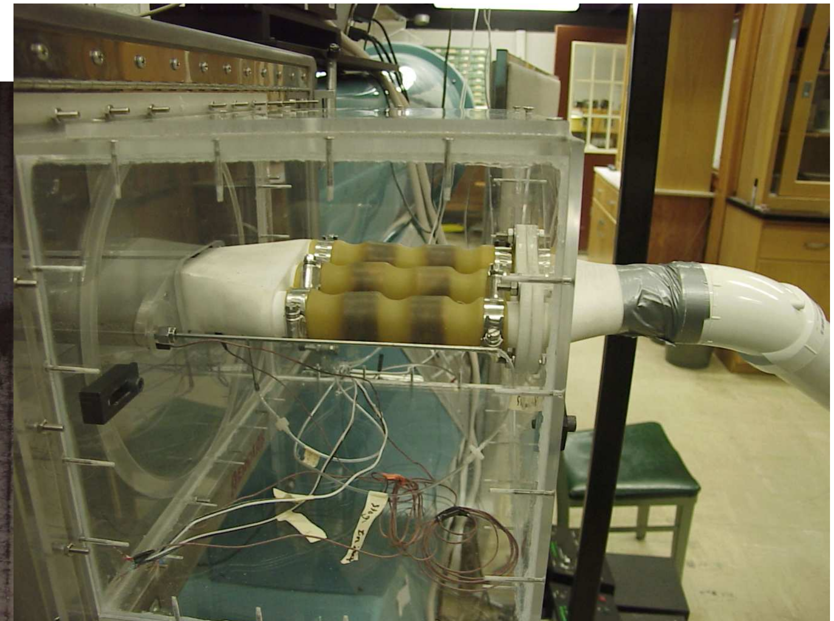
Baseline NACA0025, CFJ0025-065-192, CFJ0025-131-192,



Streamlines released from the injection jet at AoA=30^0, CFJ0026-131-192 airfoil

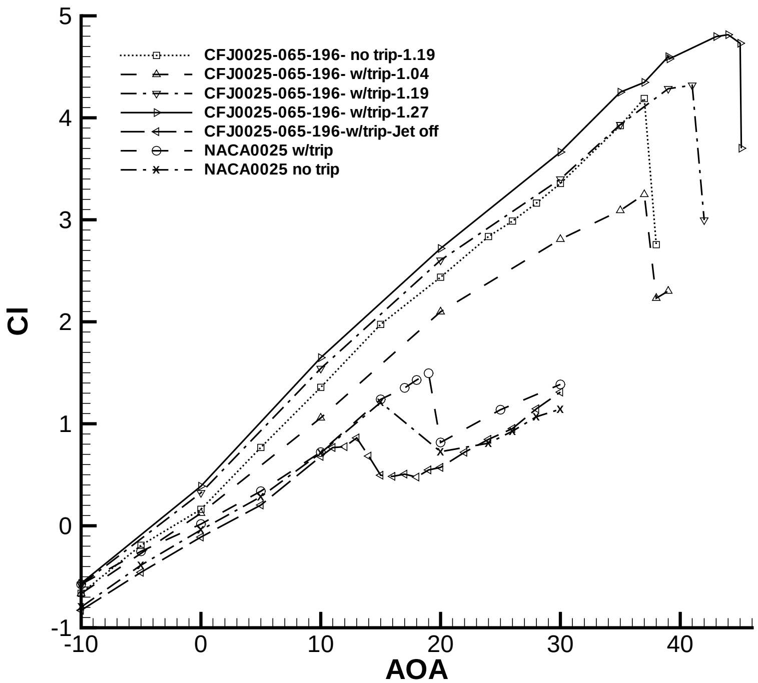
Wind Tunnel Setup

CFJ airfoil showing the injection side

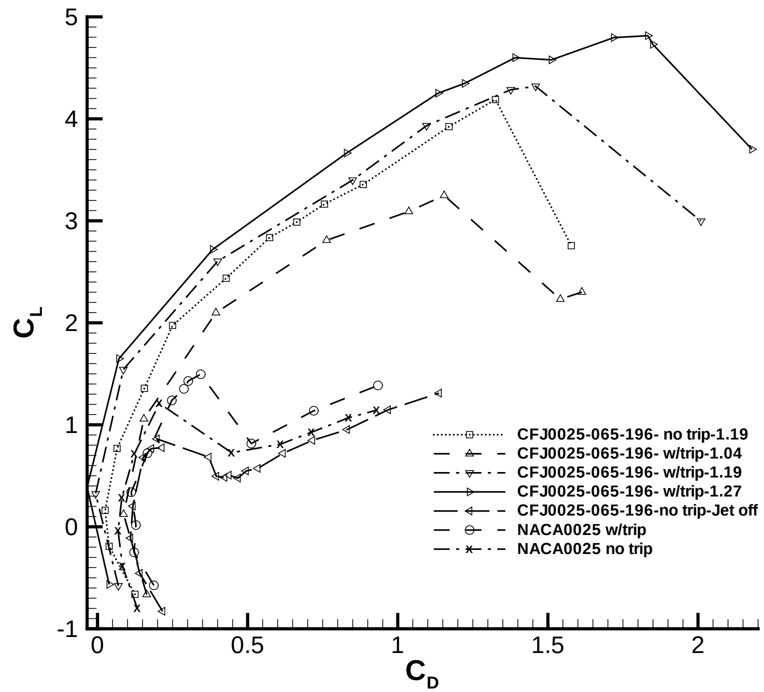


Soft latex tubes and surrounding box on suction side to remove force translation

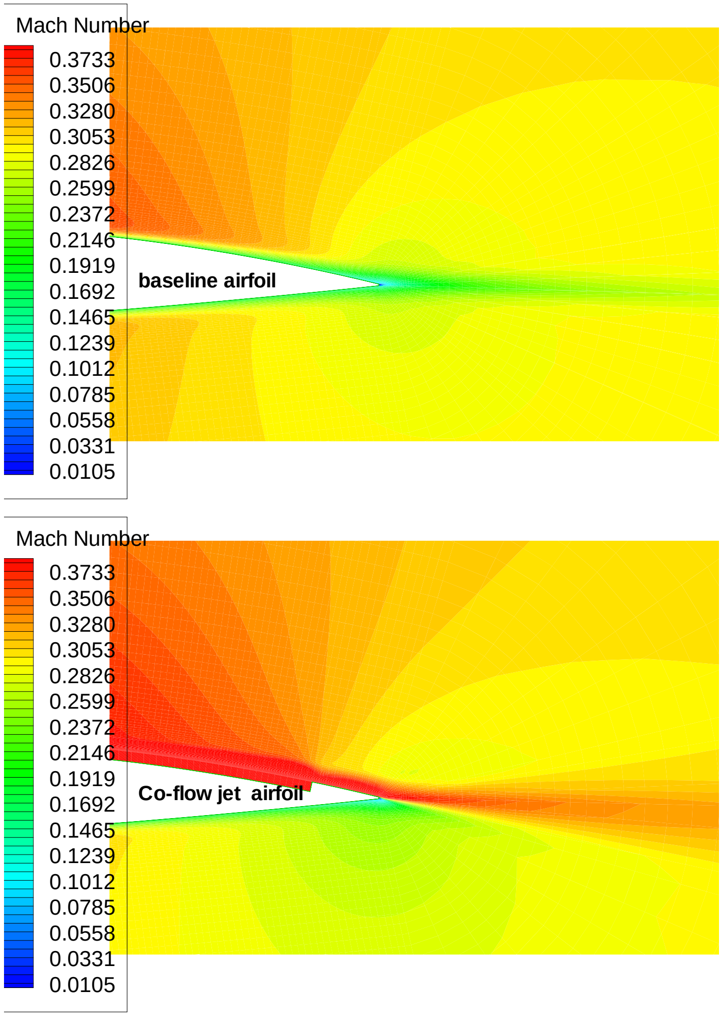
Wind Tunnel Test Results



tested lift coefficient for baseline NACA0025 and CFJ0025-065-196 airfoil

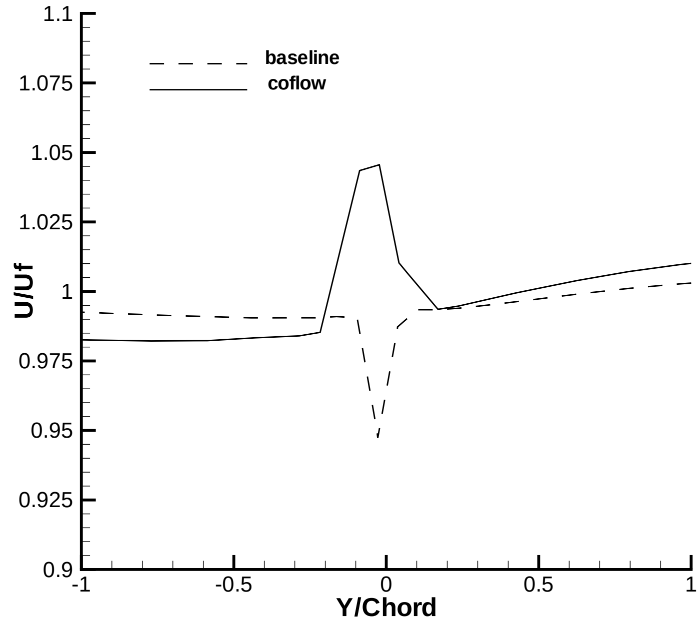


Measured drag polar, CFJ0025-065-196 airfoil



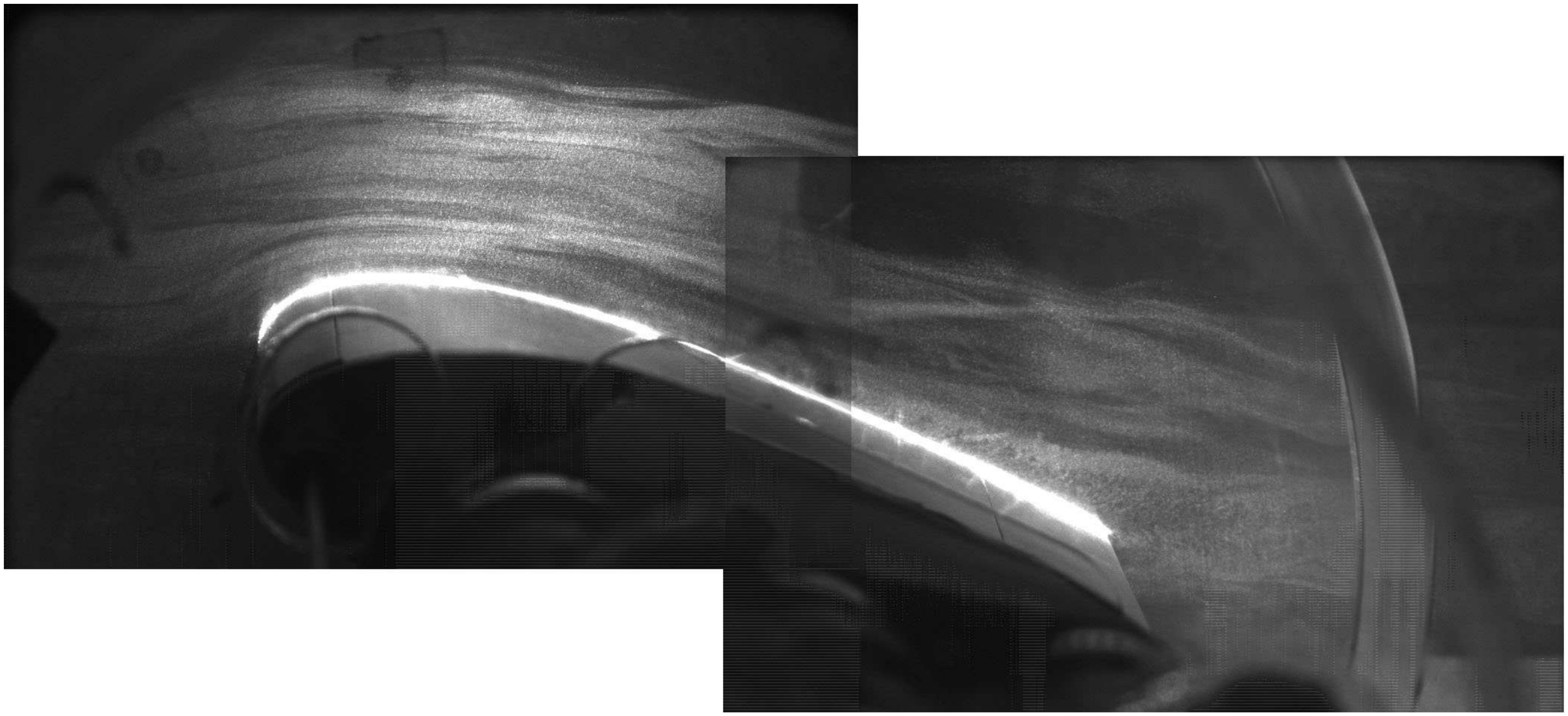
CFD,wake Mach number contours

$$D = \int \int \rho U (U_\infty - U) dA$$



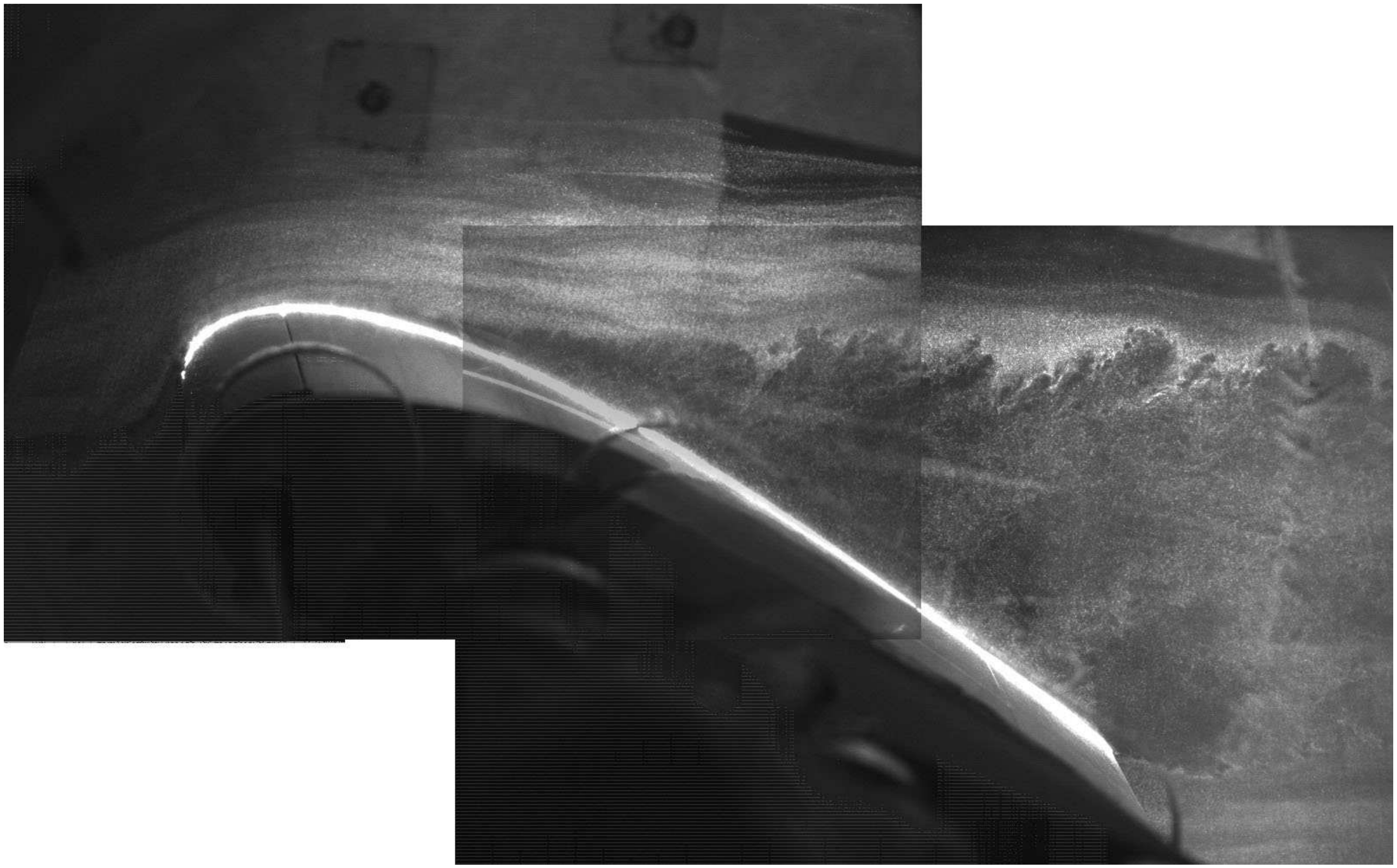
CFD, wake shape

Wind Tunnel Test Results

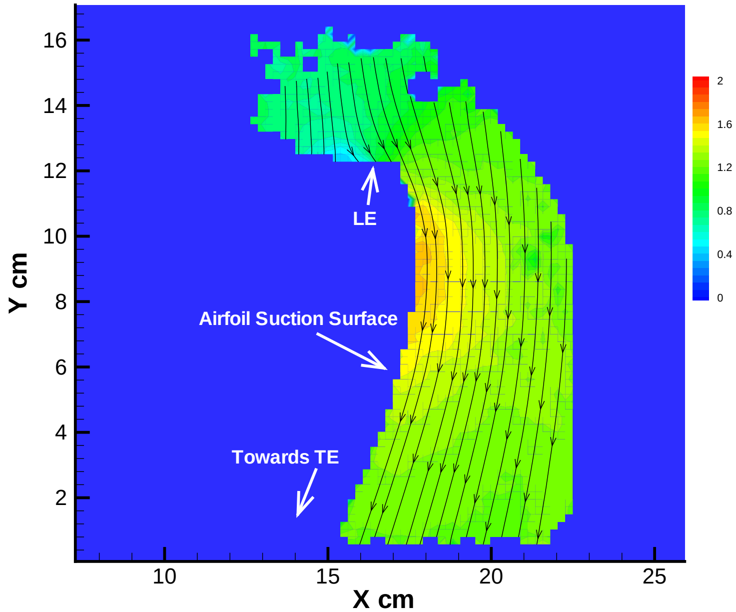


Flow visualization of attached flow, baseline NACA0025 airfoil, AoA = 10^0

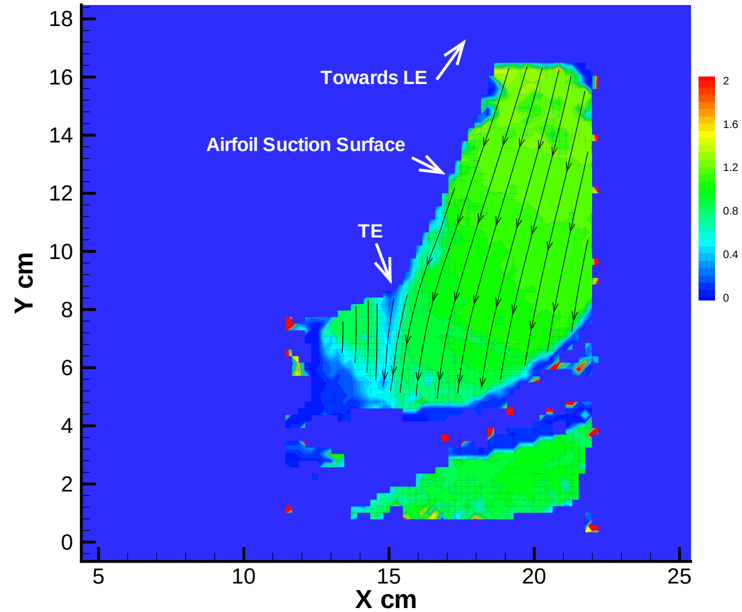
Wind Tunnel Test Results



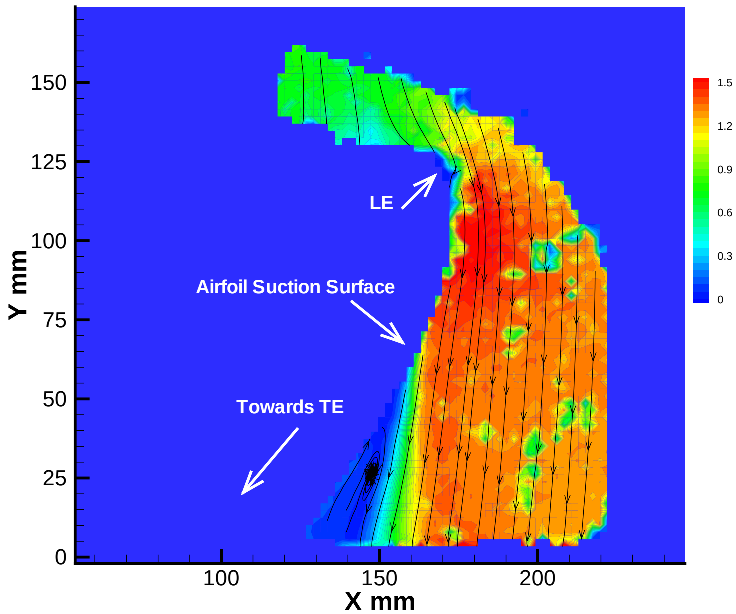
Flow visualization of separated flow, baseline NACA0025 airfoil, AoA $=20^0$



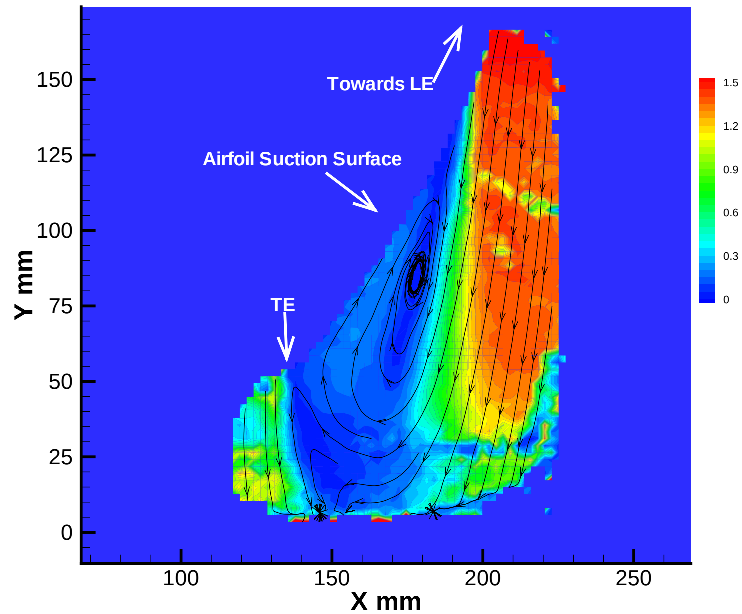
PIV, V/V_∞, Streamline, attached, baseline, AoA $= 10^0$, Front



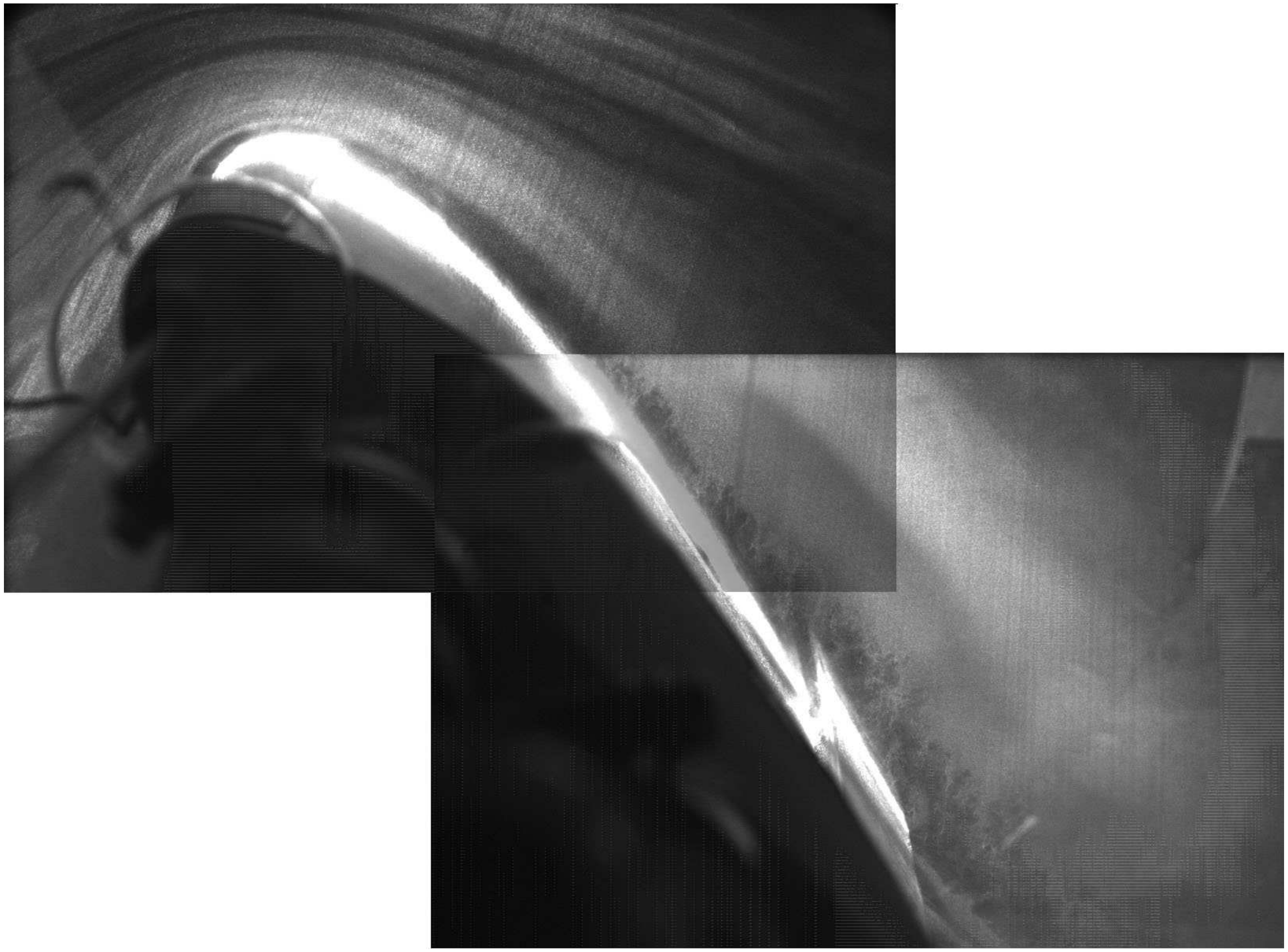
PIV, V/V_∞, Streamline, attached, baseline, AoA $= 10^0$, Rear



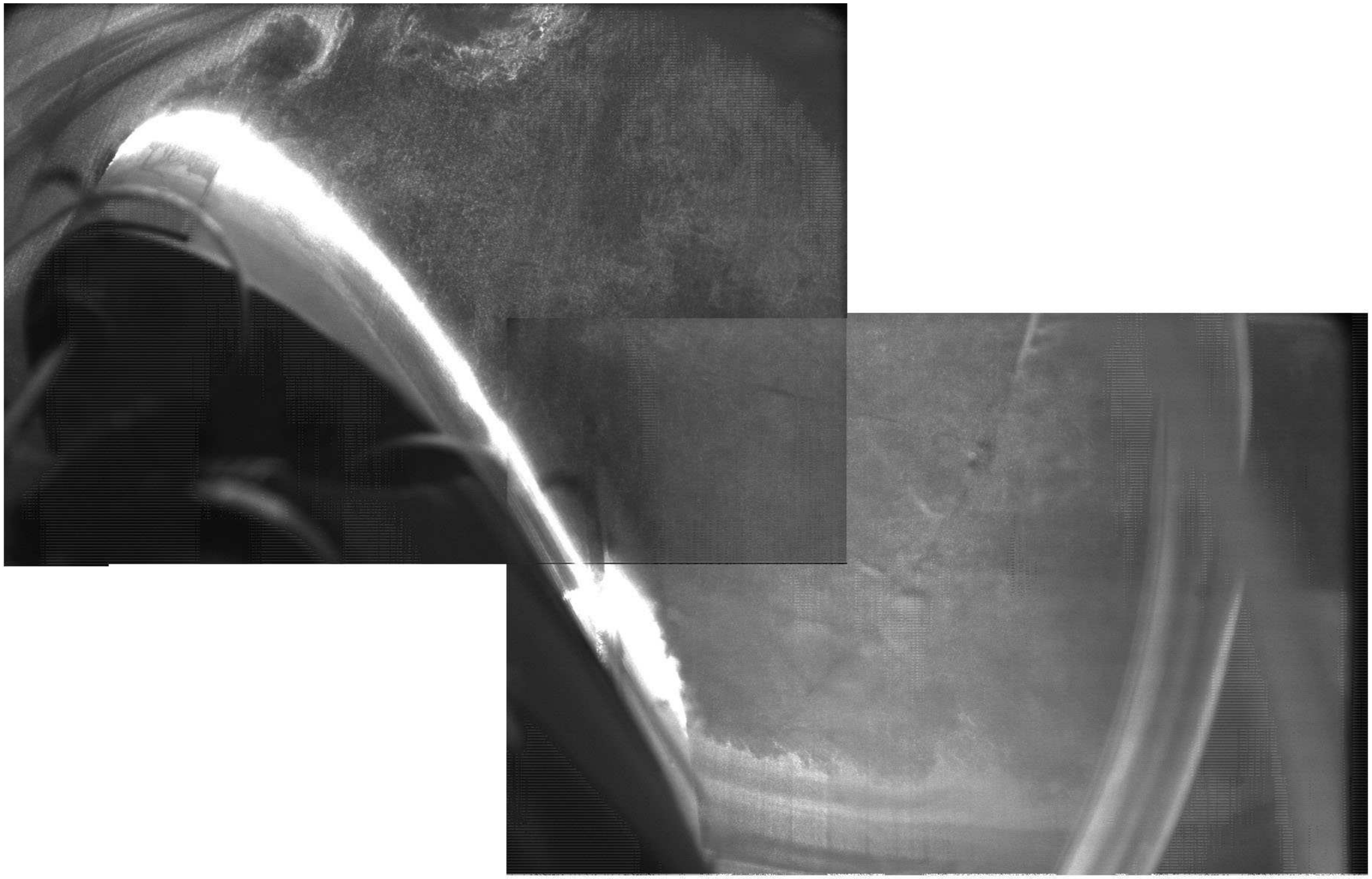
PIV, V/V_{∞}, Streamline, separated, baseline, AoA = 20^0, Front



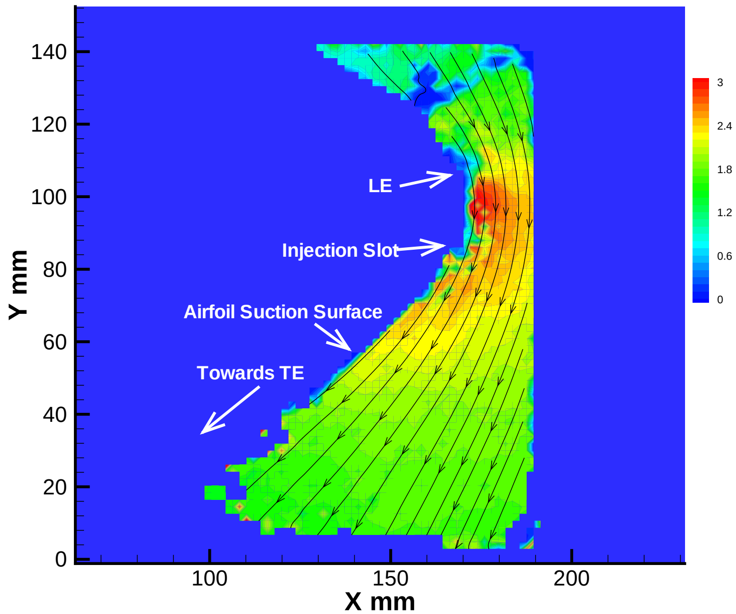
PIV, V/V_{∞}, Streamline, separated, baseline, AoA = 20^0, Rear



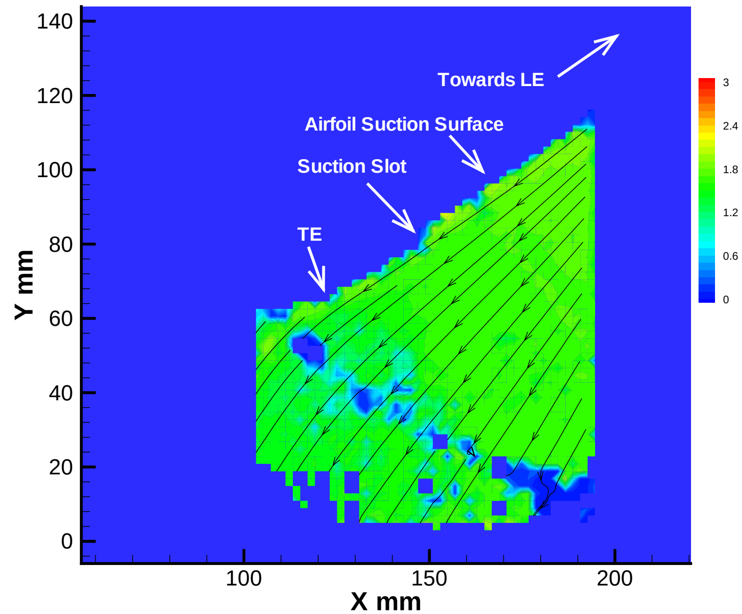
Flow visualization, attached flow, CFJ0025-065-196 airfoil, AoA=43^0



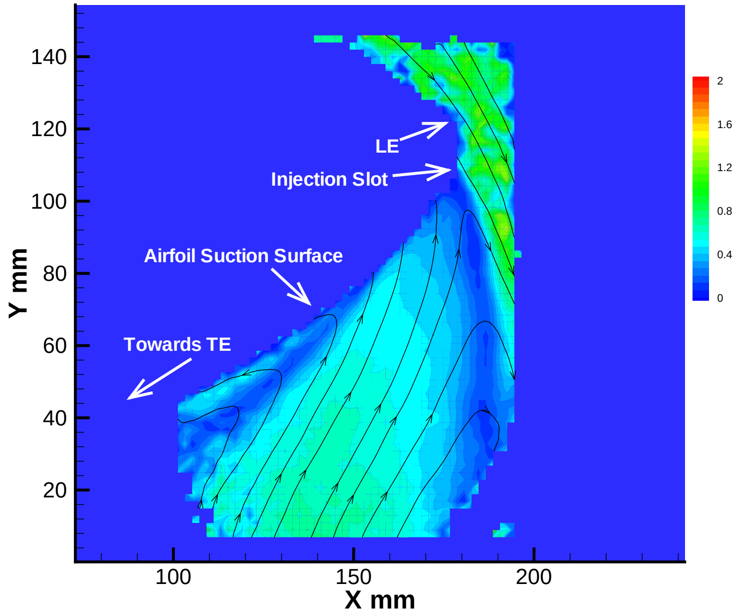
Flow visualization,separated flow, CFJ0025-065-196 airfoil, AoA=46^0



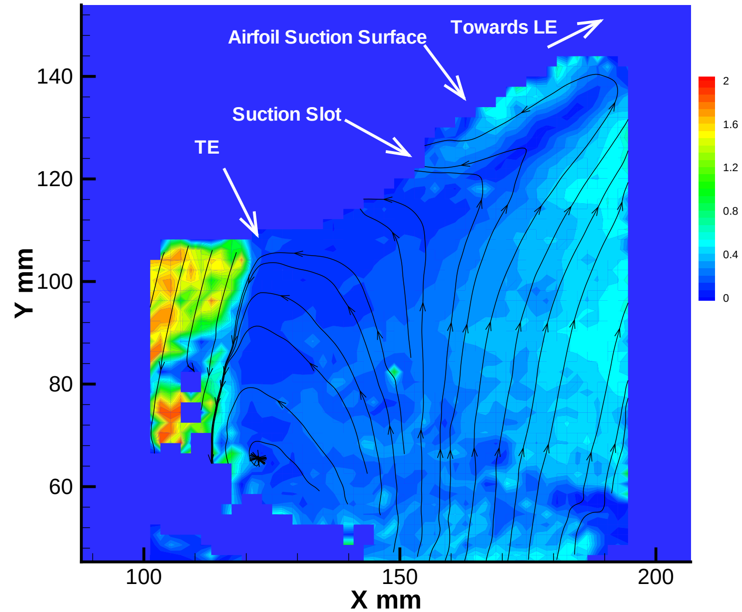
PIV, V/V_∞, Streamline, attached, CFJ0025-065-196, AoA $= 43^0$, Front



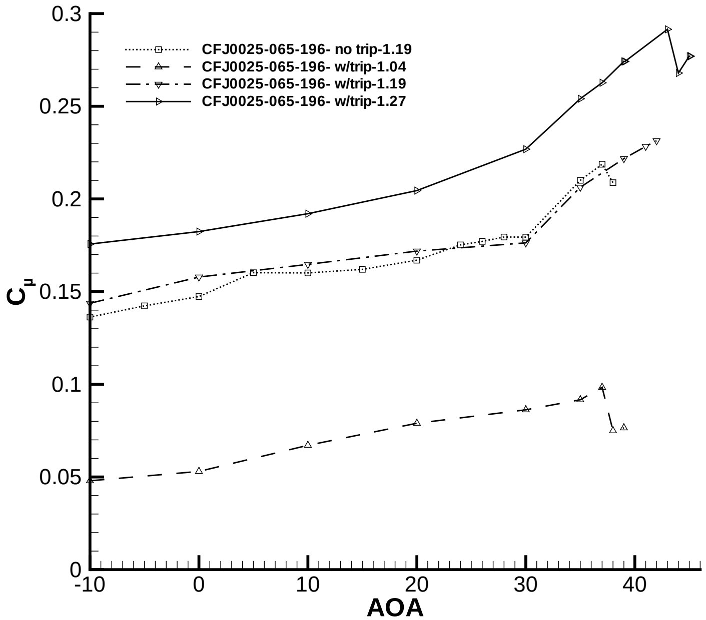
PIV, V/V_∞, Streamline, attached, baseline, AoA $= 43^0$, Rear



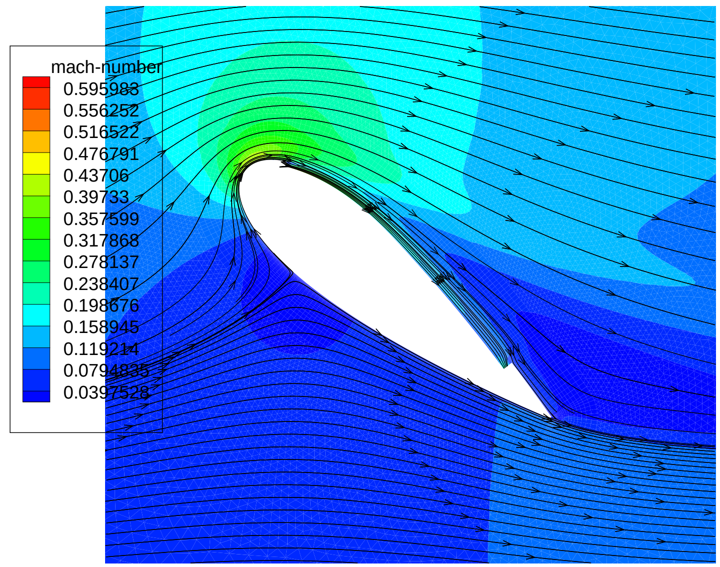
PIV, V/V_∞, Streamline, separated, CFJ0025-065-196, AoA $= 46^0$, Front



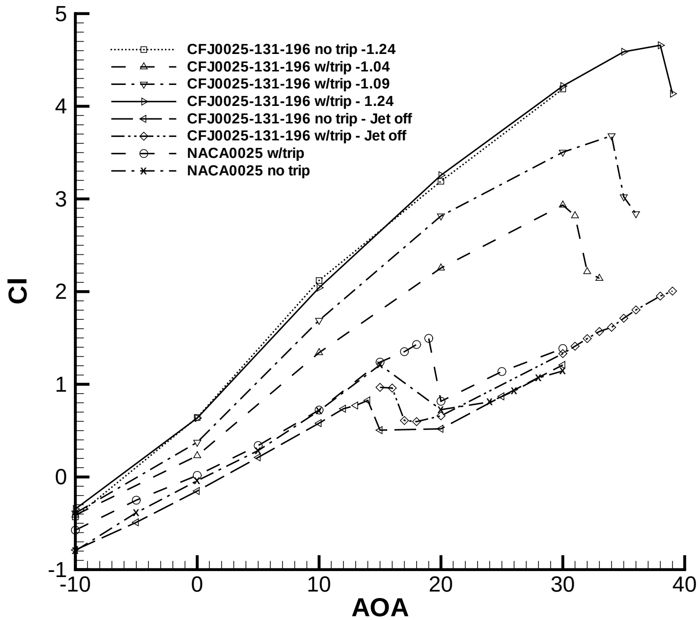
PIV, V/V_∞, Streamline, separated, baseline, AoA $= 46^0$, Rear



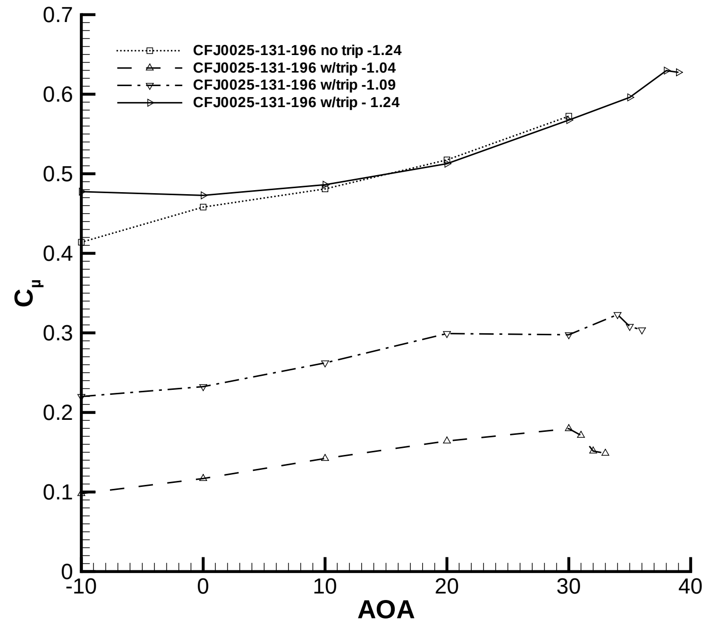
Measured injection momentum coefficient, CFJ0025-065-196 airfoil



CFD,streamlines, Mach contours, CFJ0025-065-196 AoA = 39^0.

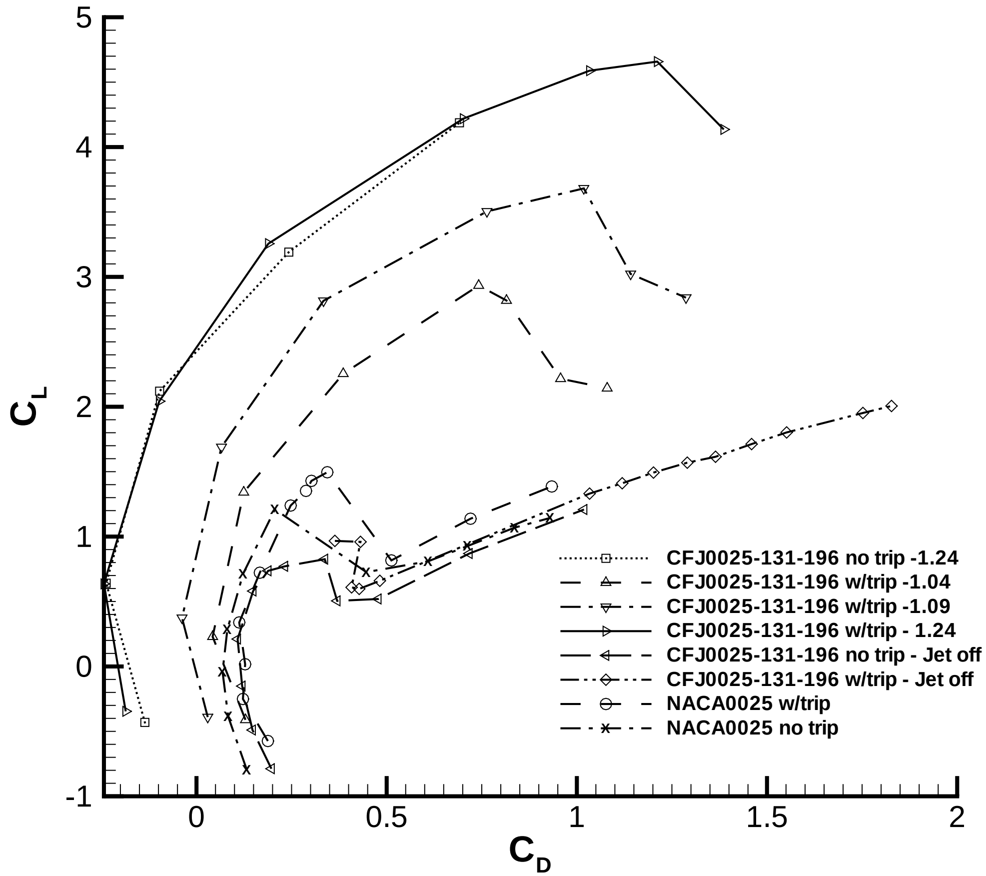


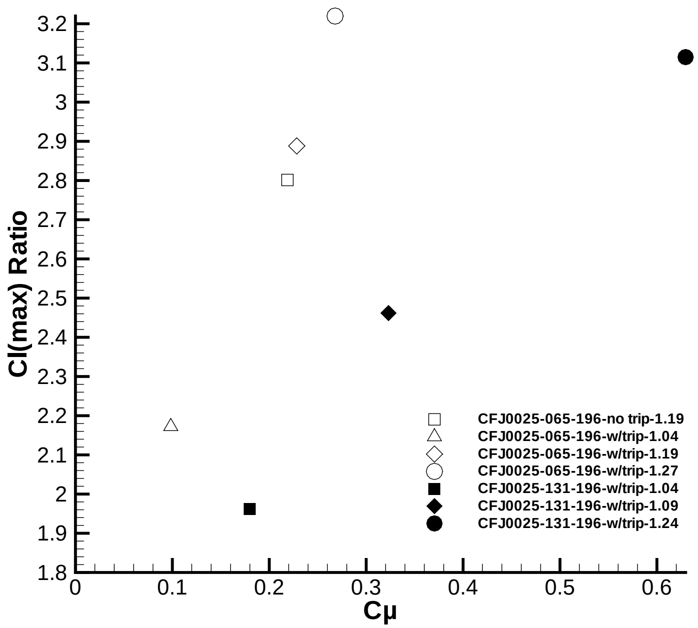
Measured lift coefficient for baseline NACA0025 and CFJ0025-131-196 airfoil



Measured momentum coefficient, CFJ0025-131-196 airfoil

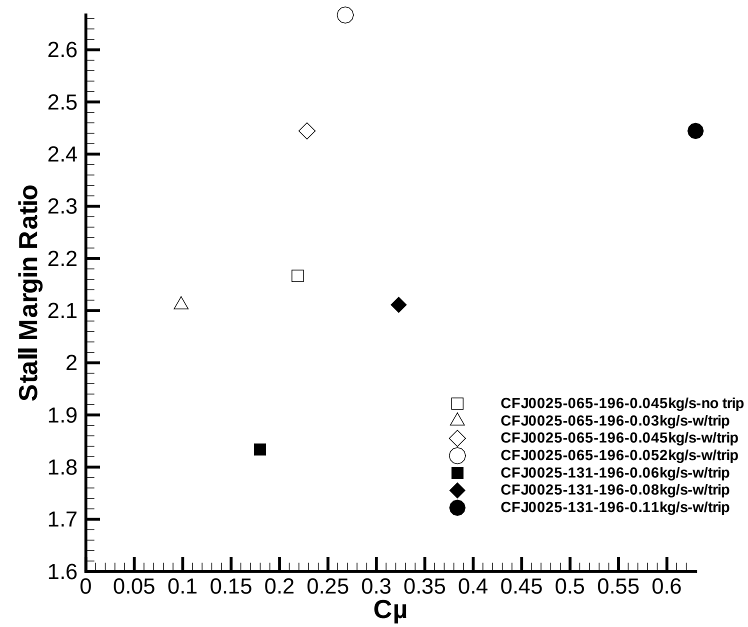
Measured drag polar of CFJ0025-131-196 airfoil





Measured

$C_{Lmax\,cfj}/C_{Lmax\,baseline}$ vs C_μ

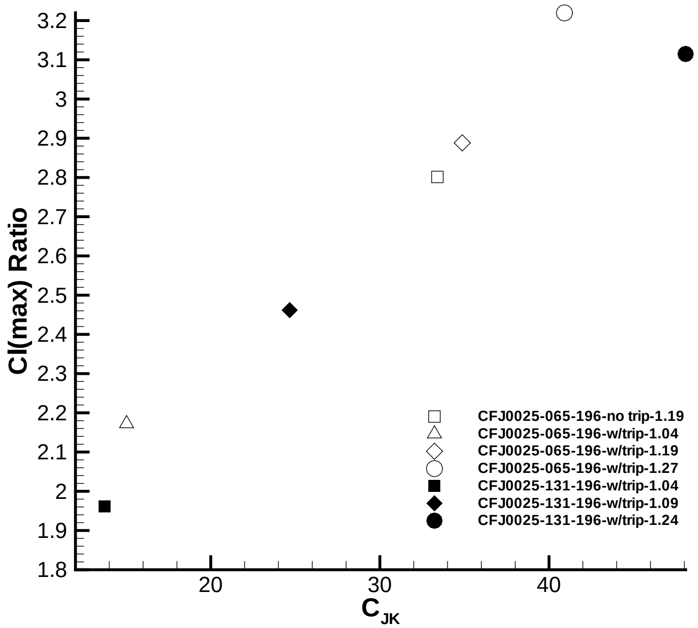


Measured

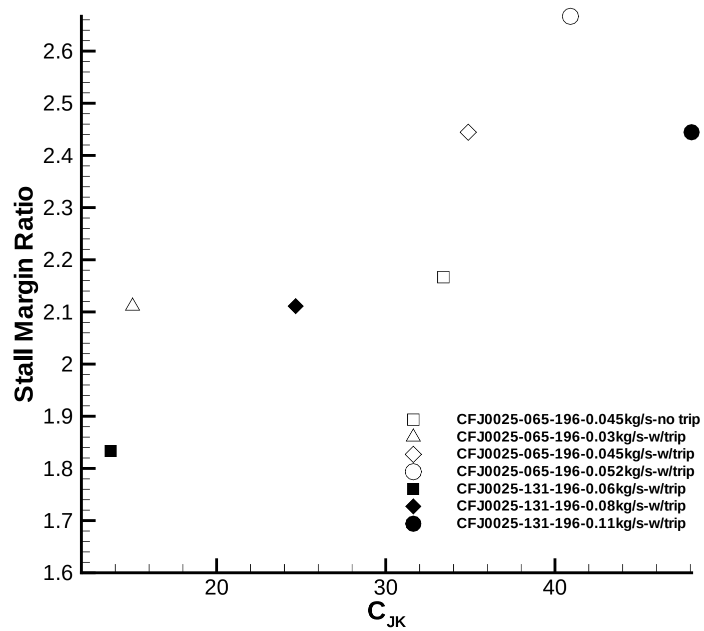
$stallmargin_{cfj}/stallmargin_{baseline}$

vs C_μ

$$C_{jk} = \frac{\dot{m}_j V_j}{0.5 \rho_\infty U_\infty^2 S_{slot}}$$

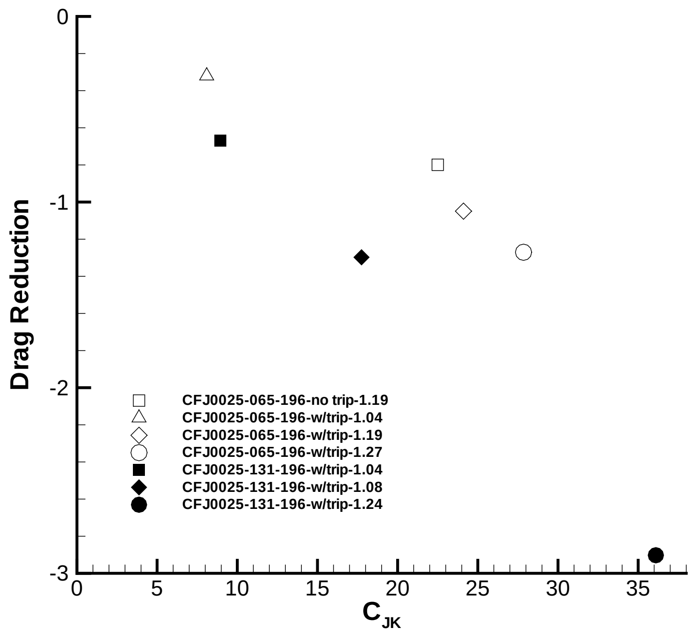


Measured $C_{Lmax\,cfj}/C_{Lmax\,baseline}$ vs C_{jk}

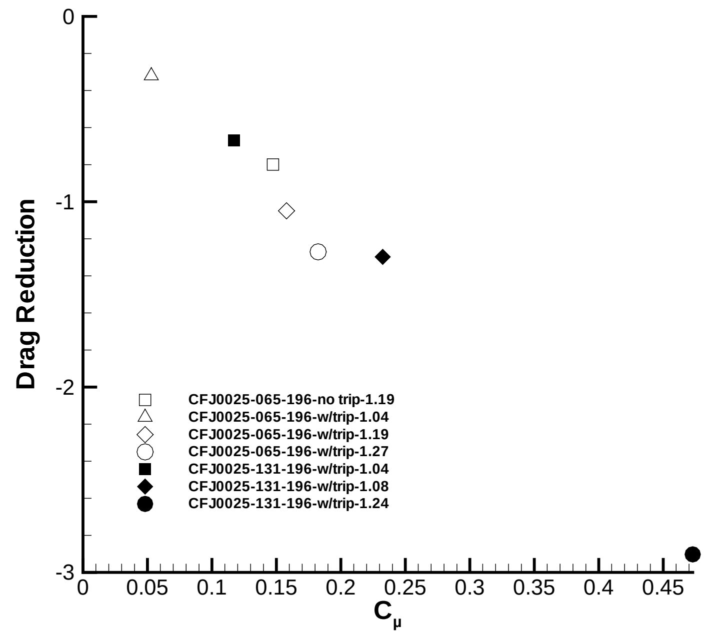


Measured $stallmargin_{cfj}/stallmargin_{baseline}$ vs C_{jk}

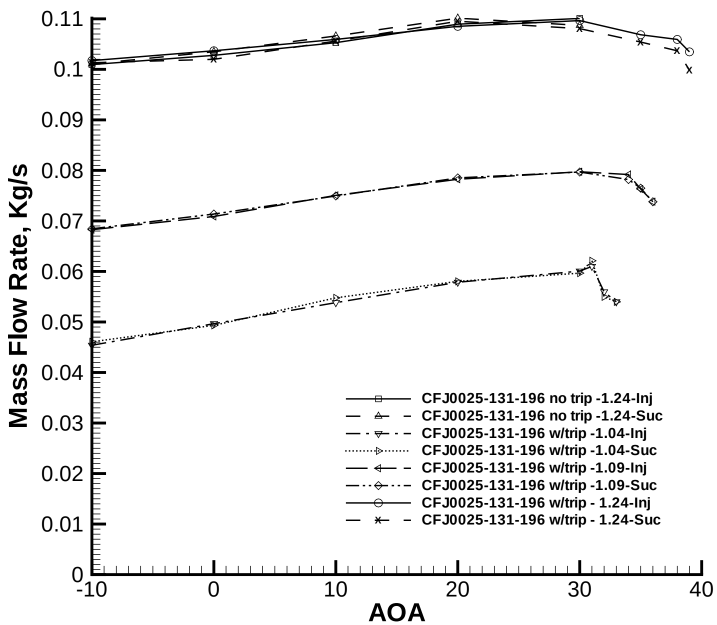
$$Drag\ Reduction = (Cd_{cfj} - Cd_{baseline})/Cd_{baseline}$$



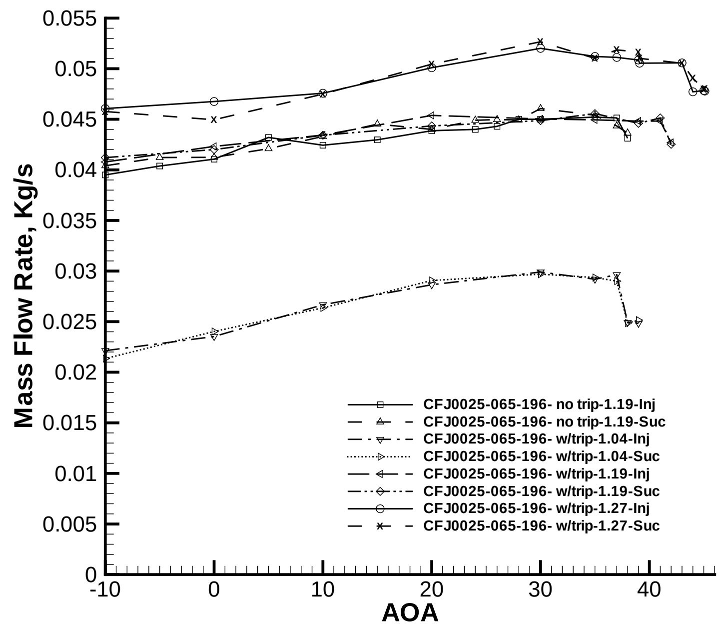
Measured Minimum Drag Reduction vs C_{jk}



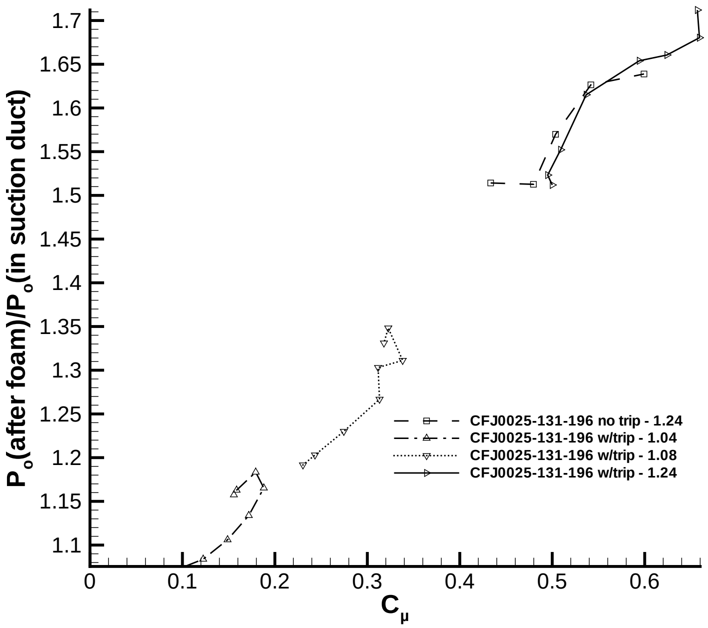
Measured Minimum Drag Reduction vs C_{μ}



Measured injection,suction $\dot{m}$, CFJ0025-131-196

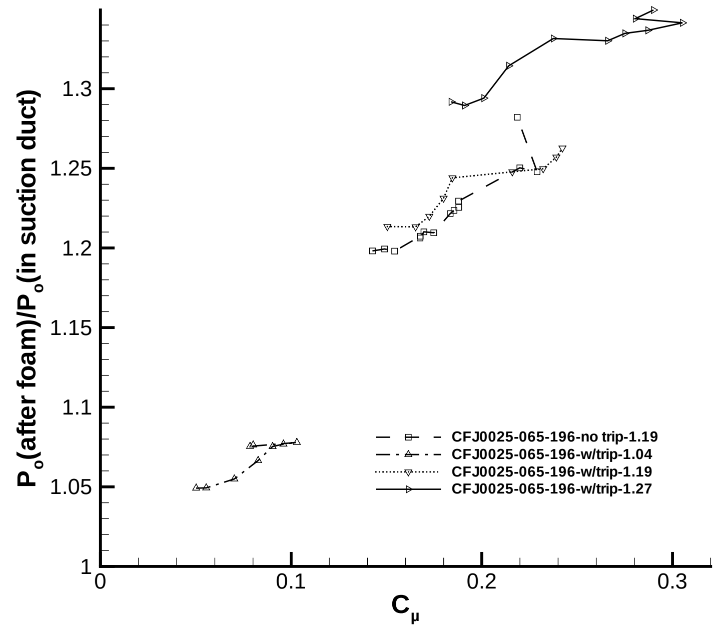


Measured injection,suction $\dot{m}$, CFJ0025-131-196



Measured Pt Ratio

CFJ0025-131-196



Measured Pt Ratio

CFJ0025-131-196

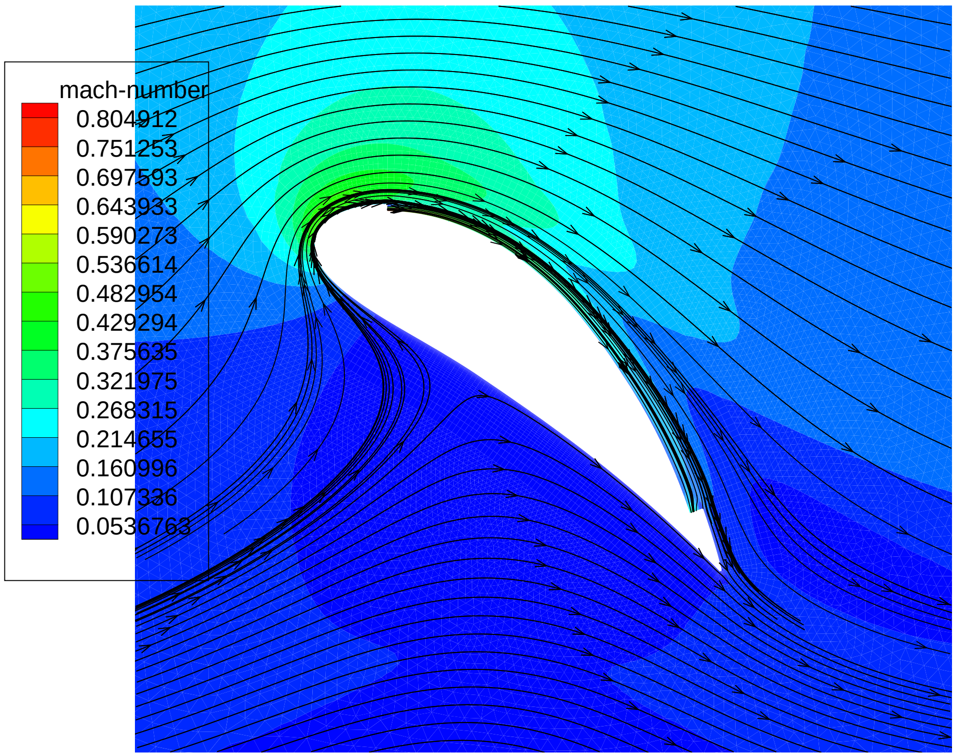
Comparison of power required to achieve $C_L = 4.22$ for the two CFJ airfoils

Airfoil	C_L	$\dot{m}$ (kg/s)	PR	AoA	Power Required
CFJ0025-065-196	4.42	0.051254	1.33	34.7^0	1
CFJ0025-131-196	4.42	0.11	1.65	30^0	3.9

- Great Potential to Improve CFJ Airfoil Performance

Super-Circulation Airfoil

C_L=9.7, CFJ11425-065-196, AoA=39^0, M=0.1, CFD Simulation, Inviscid Limit $C_{Lmax} = 2\pi(1 + t/c)$



CFJ Aircraft Benefit Assessment

- Energy Expenditure

$$Loss = \frac{POWER_{cfj}}{POWER_{compressor}}$$

$$= \overline{\dot{m}_{cfj}} \frac{\eta_{compressor}}{\eta_{cfj}} \frac{(PR_{cfj}^{\frac{\gamma-1}{\gamma}} - 1)}{(PR_{compressor}^{\frac{\gamma-1}{\gamma}} - 1)} \tag{1}$$

- Loss is small

Thrust

$$\begin{aligned} F &= (\dot{m}_{engine} + \dot{m}_{fuel})V_{nozzle} - \dot{m}_{engine}V_{inlet} \\ &= \dot{m}_{nozzle}V_{nozzle} - \dot{m}_{engine}V_{\infty} \end{aligned} \tag{2}$$

On Ground

$$F = m_{nozzle} V_{nozzle} \tag{3}$$

Penalty to Thrust $\propto \dot{m}$ Dumped

Fuel Consumption Suffer Same Penalty

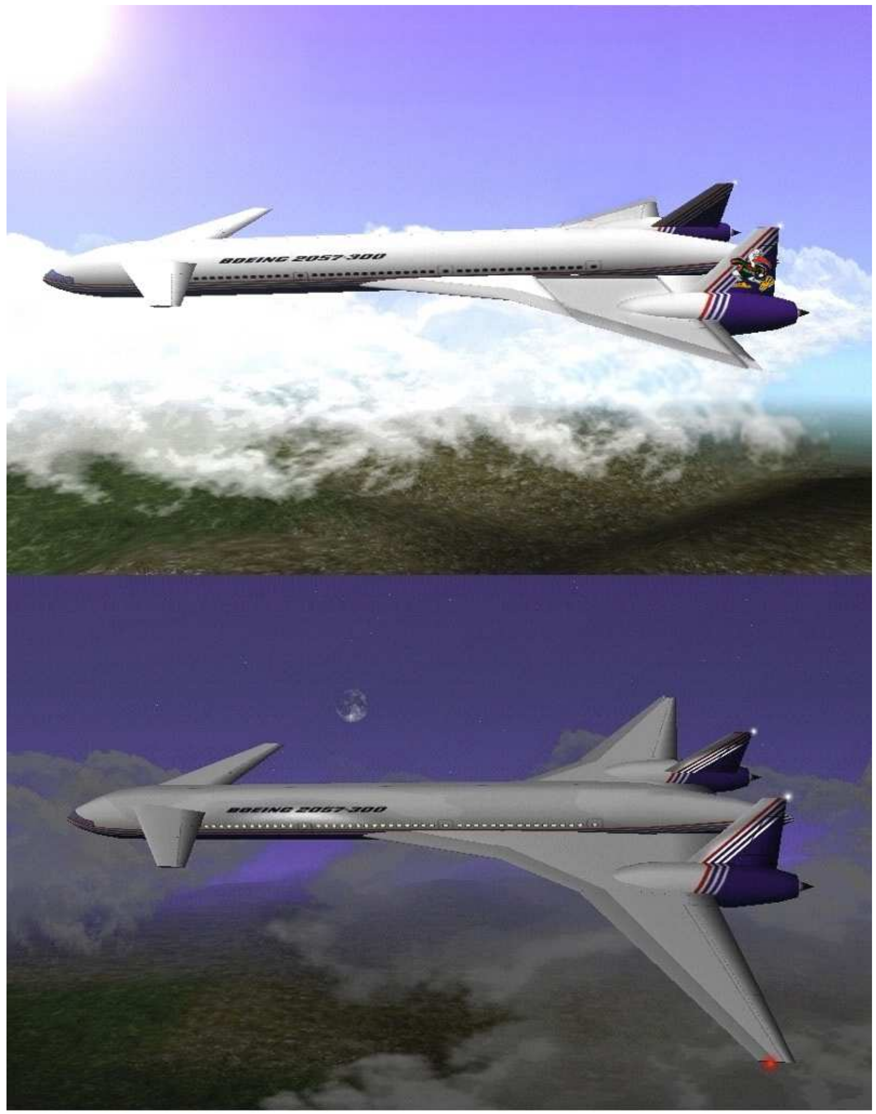
$$SFC = \dot{m}_{fuel}/F \tag{4}$$

CFJ X-47UM in Cruise (Fiction)

CFJ X-47UM Taking Off in Aircraft Carrier(Fiction)

CFJ Personal Aircraft, (Fiction), adapted form www.flug-revue.rotor.com

Boeing CFJ Sonic Cruiser,(Fiction), adapted form www.vigilanceaero.com



Conclusions

• Wind tests successfully demonstrated the Superior Performance of CFJ Airfoil

• CFJ Airfoil Significantly Increase Lift , Stall Margin, and Reduce Drag

• Low Penalty to Propulsion System

• No Large LE and TE Required, Can be used for Thin and Thick Airfoil

• Can be Used for Low and High Speed Aifcraft

• No moving Parts Needed

• Two CFJ Airfoil Tested in Wind Tunnel, CFJ0025-065-196, CFJ0025-131-196,

• Smaller Injection Size Perform Better for C_{Lmax}, Stall Margin, Power Consumed

• Larger Injection Size Reduce More Drag

• Jet Mass Limit and Jet Instability Observed in Experiment

• Super-Circulation Airfoil Possible

CFJ Airfoil Promising for:

• Aircraft Required Short Take Off/Land Distance (Aircraft Carrier)

• Personal Aircraft to Have Short Take Off/Land Distance, Compact Wingsize, Small Drag

• Long Range Cruiser to Save Fuel

• Combat Aircraft for Fast Acceleration and High Maneuverability

• Quiet Airplane with Low Noise

• Military Aircraft (UAVs) Need Loitering and Supersonic Dash (suggested by G. Hill, NASA LaRC)

• Increase Supersonic Delta Wing Lift at Subsonic Take off and Landing(suggested by G. Hill, NASA LaRC)

Thank NASA LaRC for Support

NASA LaRC Contract NNL04AA39C
NRA-03-LaRC-02