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Numerical Investigations of Co-Flow Jet Airfoil with and without Suction

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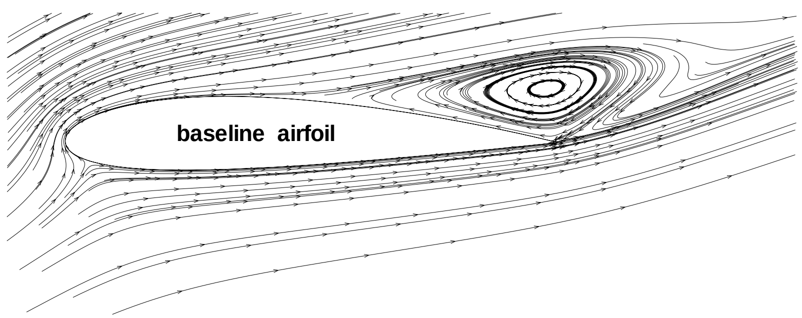
Overview of Airfoil Flow Control

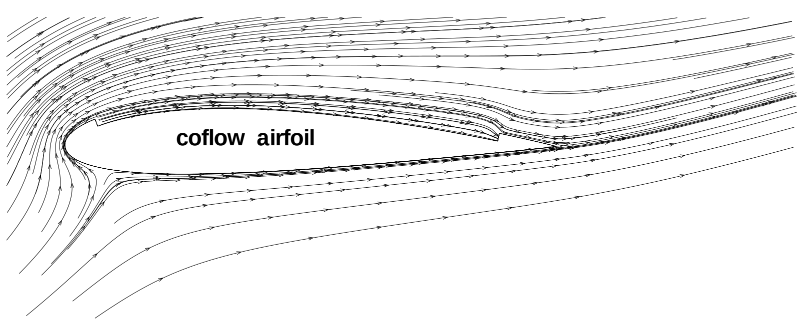
- Rotating Cylinder at LE and TE
- Circulation Control Airfoil, Coanda Effect (IBF)
- Synthetic Jet, Pulsed Jet
- Externally Blown Flaps
- Upper Surface Blowing
- Co-Flow Jet Airfoil (2005)

Co-Flow Jet(CFJ) Airfoil

- AIAA Book Series, 2006, AIAA J. of Aircraft, 2006
- AIAA Paper: 2004-2208,2005-1260, 2006-1060, 2006-0102,

2006-1061, NASA/CP-2005-213506, 2005





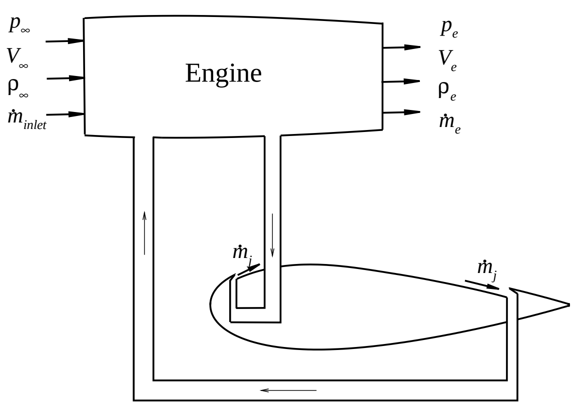
CFJ Airfoil

- **Highly Effective**: High Lift, Low Drag, High Stall Margin
- **Energy Efficient**: Small Penalty to Propulsion System
- **Easy Implementation**

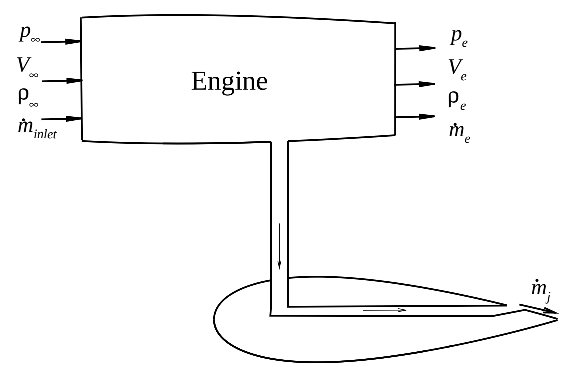
Objectives: Study the suction effect on CFJ airfoil performance

Q1: What is the equivalent drag?

Q2: Where is better off for the jet suction to occur, on airfoil or engine?

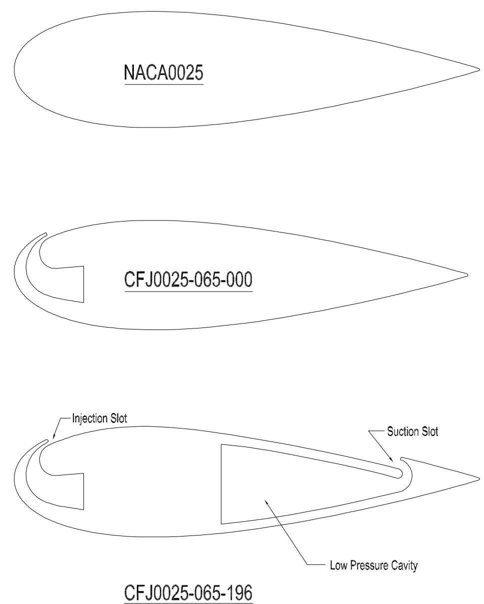


CFJ Airfoil, injection-suction



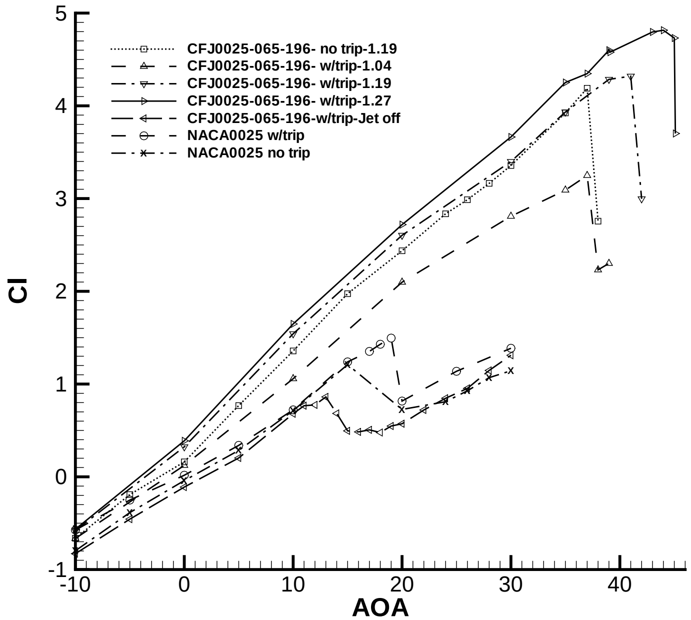
CC Airfoil, injection only

CFJ Airfoil Geometry

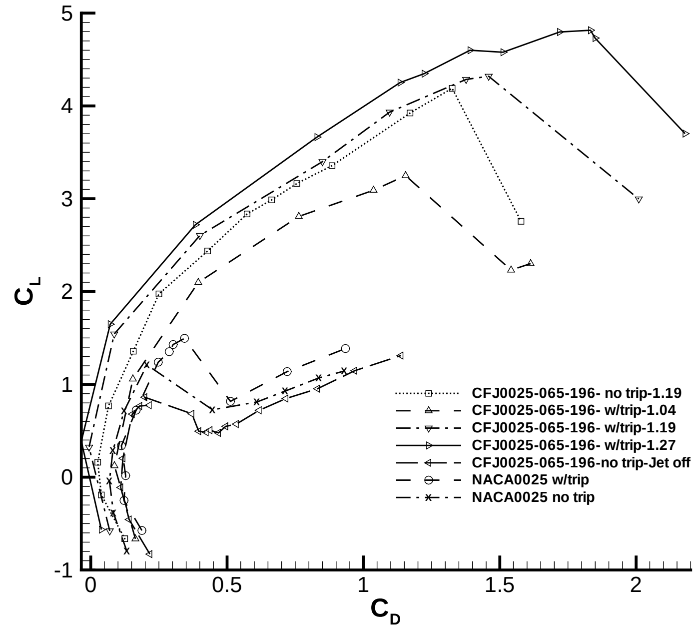


Baseline NACA0025, CFJ0025-065-000, CFJ0025-065-196,

Wind Tunnel Test Results, CFJ0026-065-196 airfoil

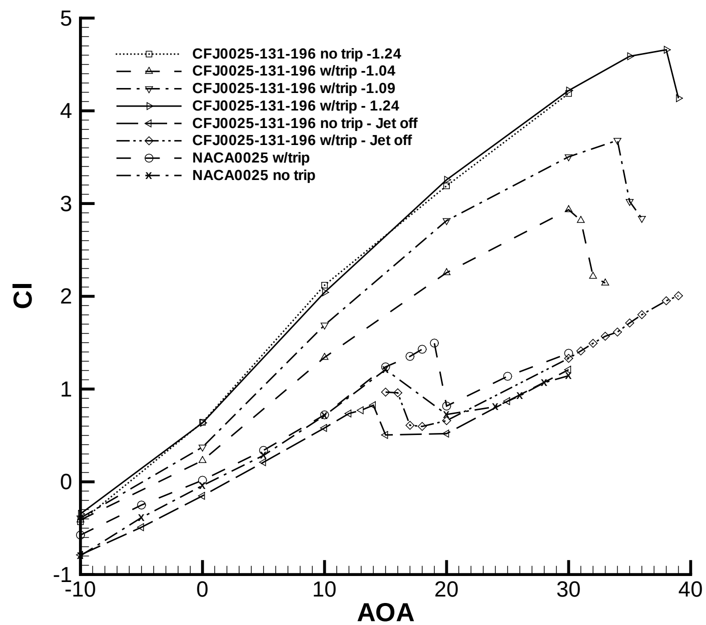


Measured Lift vs AoA

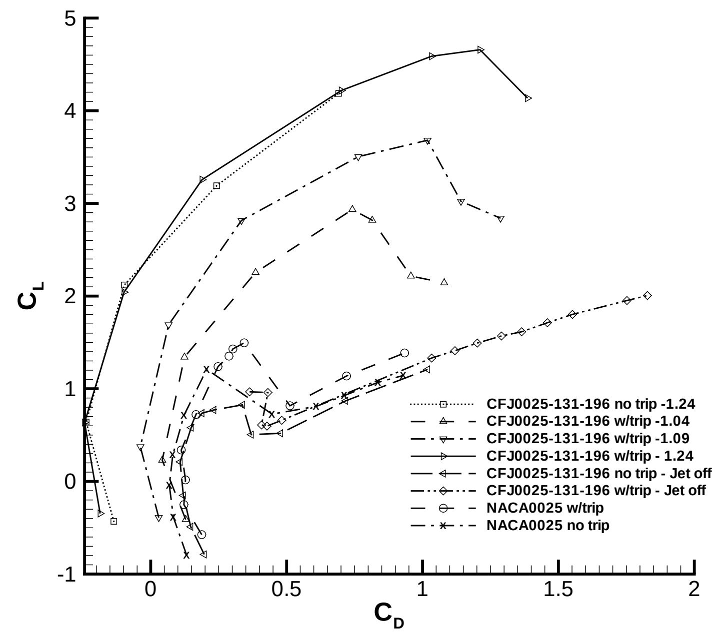


Measured Drag Polar

Wind Tunnel Test Results, CFJ0026-131-196 airfoil

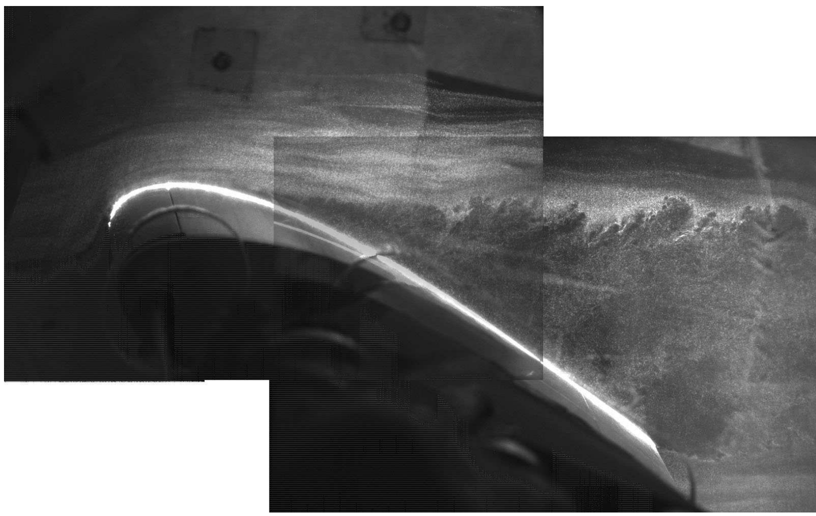


Measured Lift vs AoA

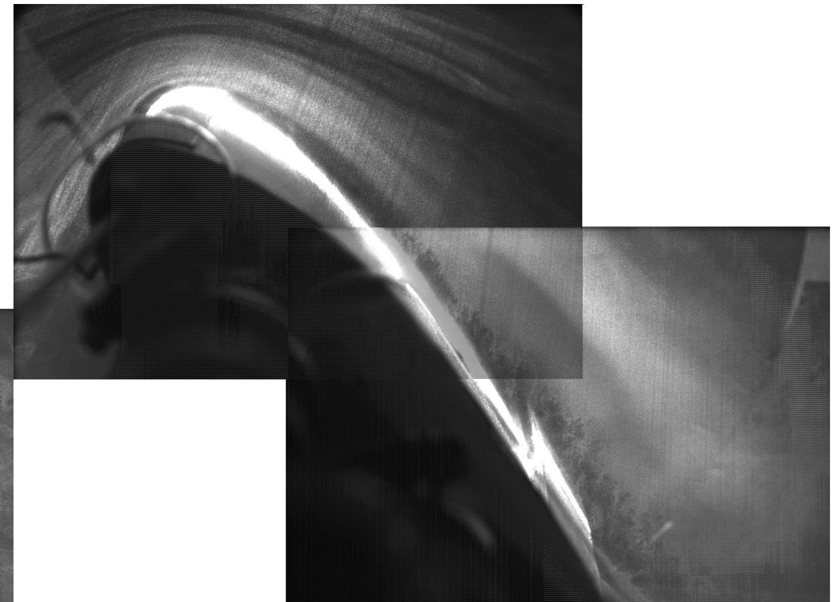


Measured Drag Polar

Wind Tunnel Test Results

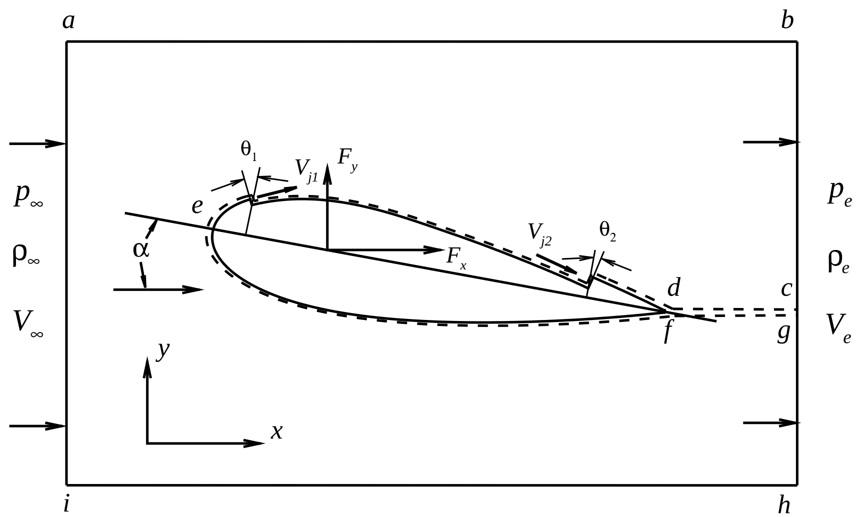


baseline airfoil, AoA $=20^0$



CFJ0025-065-196 airfoil, AoA$=43^0$

Control Volume AIAA Paper 2006-0102, Zha et al.



F_{xcfj}: duct reaction force in x-direction

$$F_{xcfj} = (\dot{m}_{j1}u_{j1} + (p_{j1}A_{j1})_x) - \gamma(\dot{m}_{j2}u_{j2} + (p_{j2}A_{j2})_x)$$

$$= (\dot{m}_j V_{j1} + p_{j1}A_{j1}) * cos(\theta_1 - \alpha) - \gamma(\dot{m}_j V_{j2} + p_{j2}A_{j2}) * cos(\theta_2 + \alpha) \quad (1)$$

$$D = R'_x - F_{xcfj} = \int_h^b \rho V_e (V_\infty - V_e) dy \quad (2)$$

or

$$C_D = C_{Drake} \quad (3)$$

Lift

$$L = R'_y - F_{y_{cfj}} \tag{4}$$

R'_y: Surface pressure and shear stress integral in y-direction

$$F_{y_{cfj}} = (\dot{m}_{j1}v_{j1} + (p_{j1}A_{j1})_y) - \gamma(\dot{m}_{j2}v_{j2} + (p_{j2}A_{j2})_y)$$

$$= (\dot{m}_j V_{j1} + p_{j1}A_{j1}) * sin(\theta_1 - \alpha) + \gamma(\dot{m}_j V_{j2} + p_{j2}A_{j2}) * sin(\theta_2 + \alpha) \tag{5}$$

Airfoil with Jet Injection Only

Mass Conservation

$$\int_i^a \rho V_\infty \cdot dy + \dot{m}_j = \int_h^b \rho V_e \cdot dy \tag{6}$$

Momentum Equation

$$D_{windtunnel} = R'_x - (\dot{m}_j u_j + (p_j A_j)_x)$$

$$= R'_x - (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * cos(\theta_1 - \alpha)$$

$$= \int_h^b \rho V_e (V_\infty - V_e) dy - m_j V_\infty \tag{7}$$

$$C_{D windtunnel} = C_{D rake} - C_\mu \frac{V_\infty}{V_j} \tag{8}$$

Equivalent Drag (Actual Drag)

Assume drawing in flow from engine inlet (ei),

$$D_{equiv} = R'_x - (\dot{m}_j u_j + (p_j A_j)_x) + \dot{m}_j V_{ei} + p_{ei} A_{j\,ei} \tag{9}$$

$$D_{equiv} = D_{windtunnel} + \dot{m}_j V_{ei} + p_{ei} A_{j\,ei} \tag{10}$$

$$\rho_{ei} V_{ei} A_{j\,ei} = \dot{m}_j \tag{11}$$

$$p_{ei} A_{j\,ei} = \frac{\dot{m}_j V_{ei}}{\gamma M_{ei}^2} \tag{12}$$

$$C_{D\,equiv} = C_{D\,windtunnel} + C_\mu \frac{V_{ei}}{V_j} + C_\mu \frac{V_{ei}}{V_j \gamma M_{ei}^2} \tag{13}$$

Lift

$$L = R'_y - (\dot{m}_{j1} v_{j1} + (p_{j1} A_{j1})_y) = R'_y - (\dot{m}_j V_{j1} + p_{j1} A_{j1}) * sin(\theta_1 - \alpha) \tag{14}$$

The equivalent drag used by Jones(2005) and Wilson(1979):

$$C_{Dequiv} = C_{Dwindtunnel} + C_\mu \frac{V_\infty}{V_j} + C_\mu \frac{V_j}{2V_\infty} \tag{15}$$

Using Eq.(8),

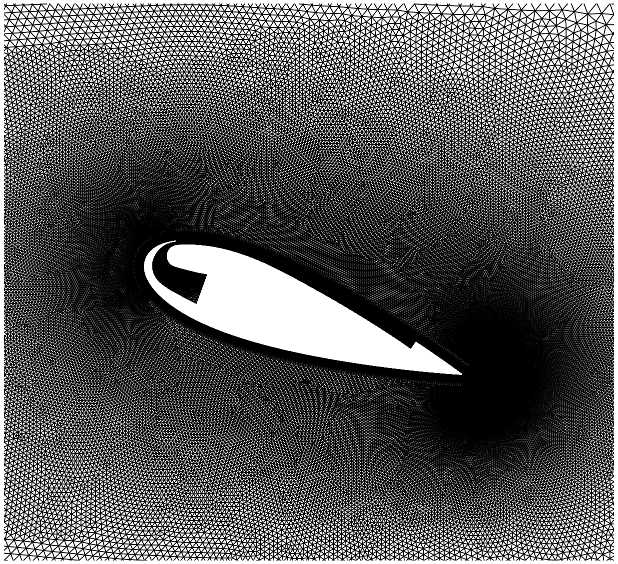
$$C_{Dequiv} = C_{Drake} + C_\mu \frac{V_j}{2V_\infty} \tag{16}$$

CFD Solver: Fluent

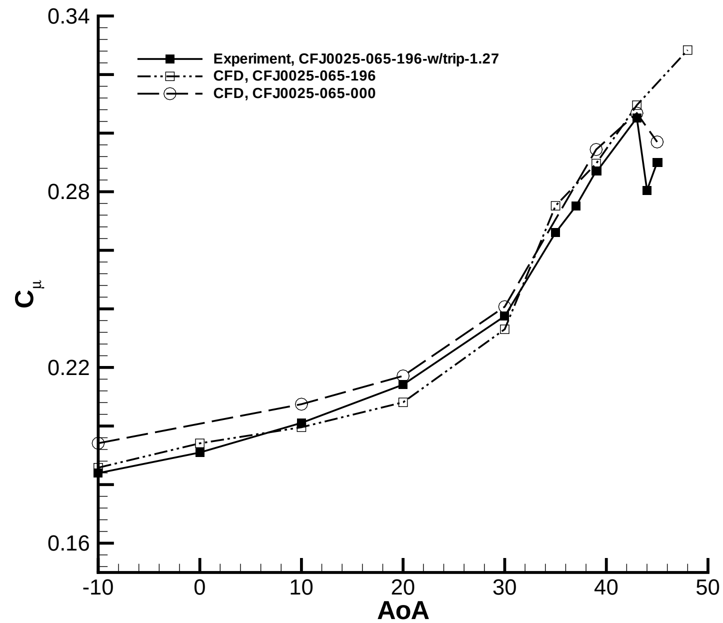
- 2nd Order Upwind Scheme, Pressure Based
- $k - \epsilon$ model integrated to wall, $y^+ \approx 1$
- Structured mesh around airfoil, unstructured mesh far field

Boundary Conditions

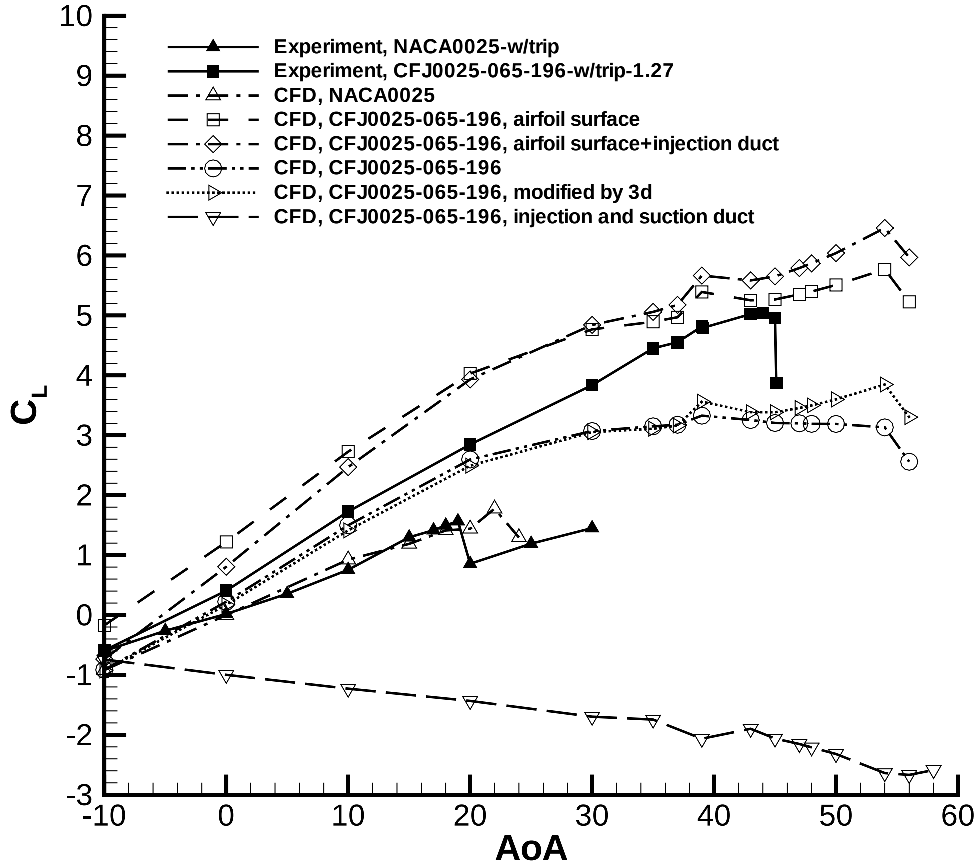
- Far field
- Injection: Iterate P_0, T_0, matching experiment C_μ
- Suction: Iterate p, matching $\dot{m}_j$



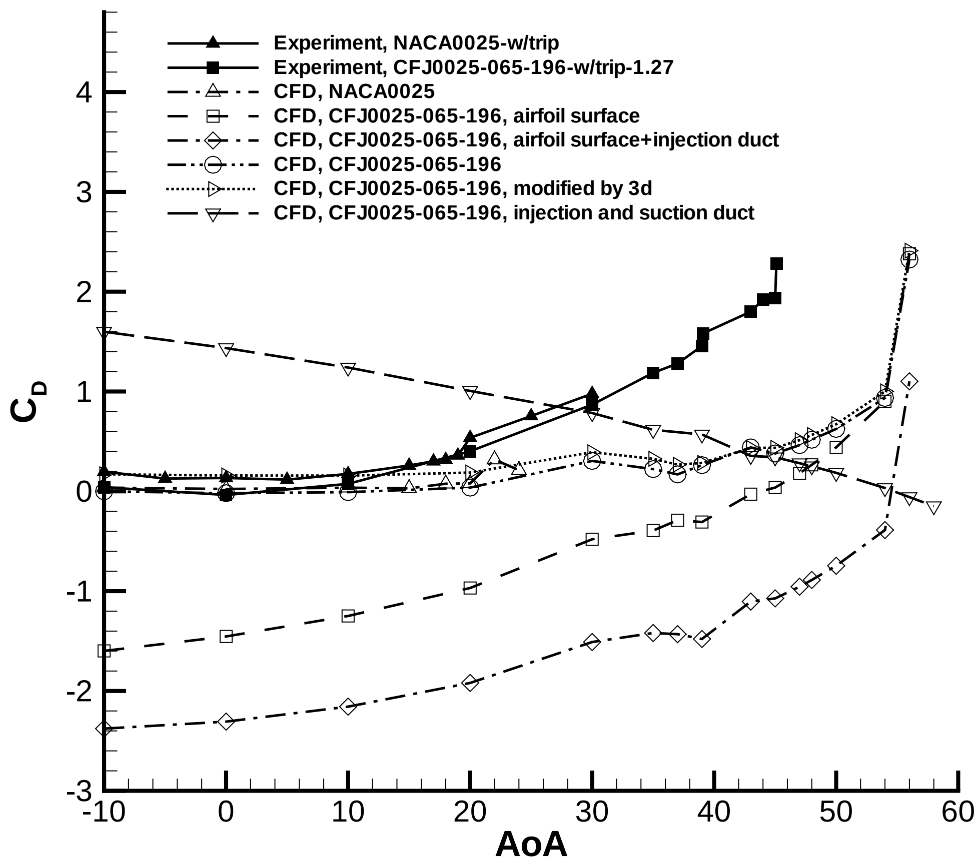
2D Mesh


Experiment, CFJ0025-065-196-w/trip-1.27
CFD, CFJ0025-065-196
CFD, CFJ0025-065-000
0.34
0.28
0.22
0.16
C_μ
-10
0
10
20
30
40
50
AoA

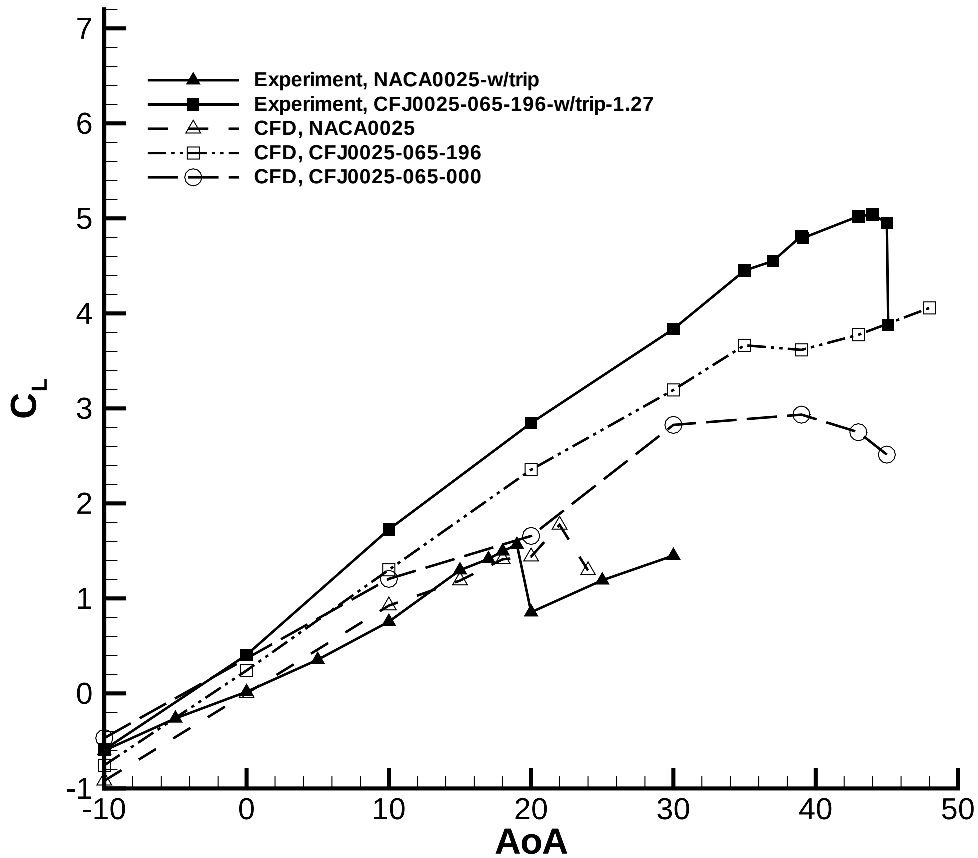
Lift Breakdown



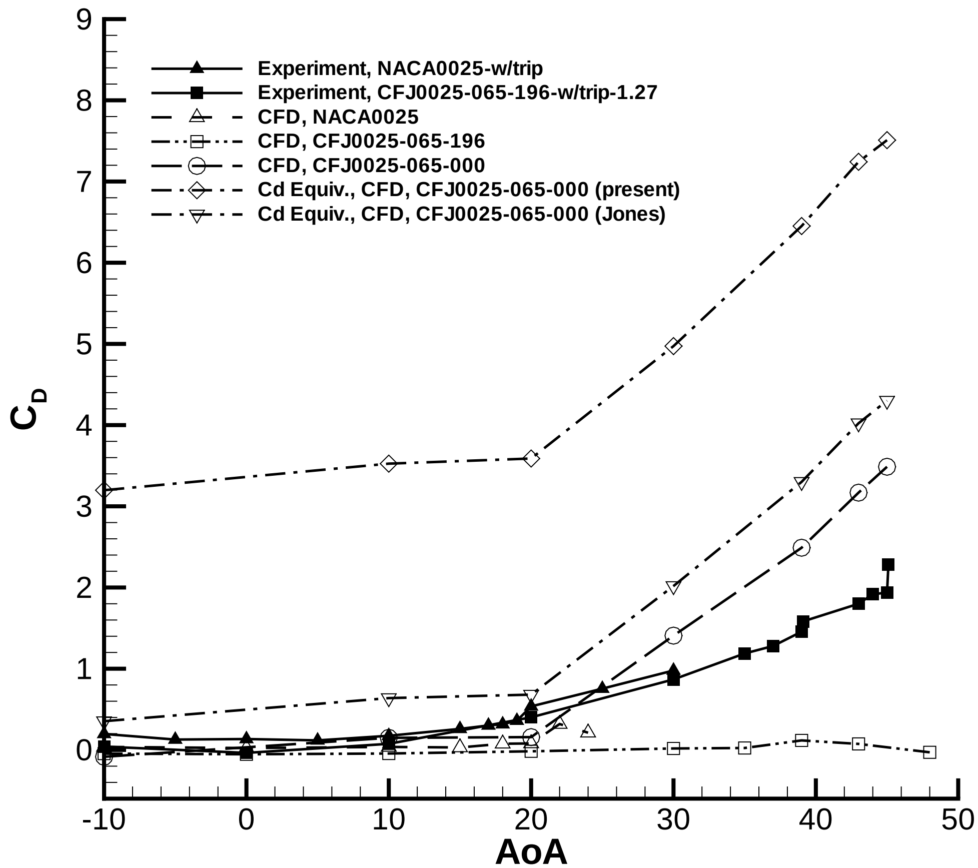
Drag Breakdown



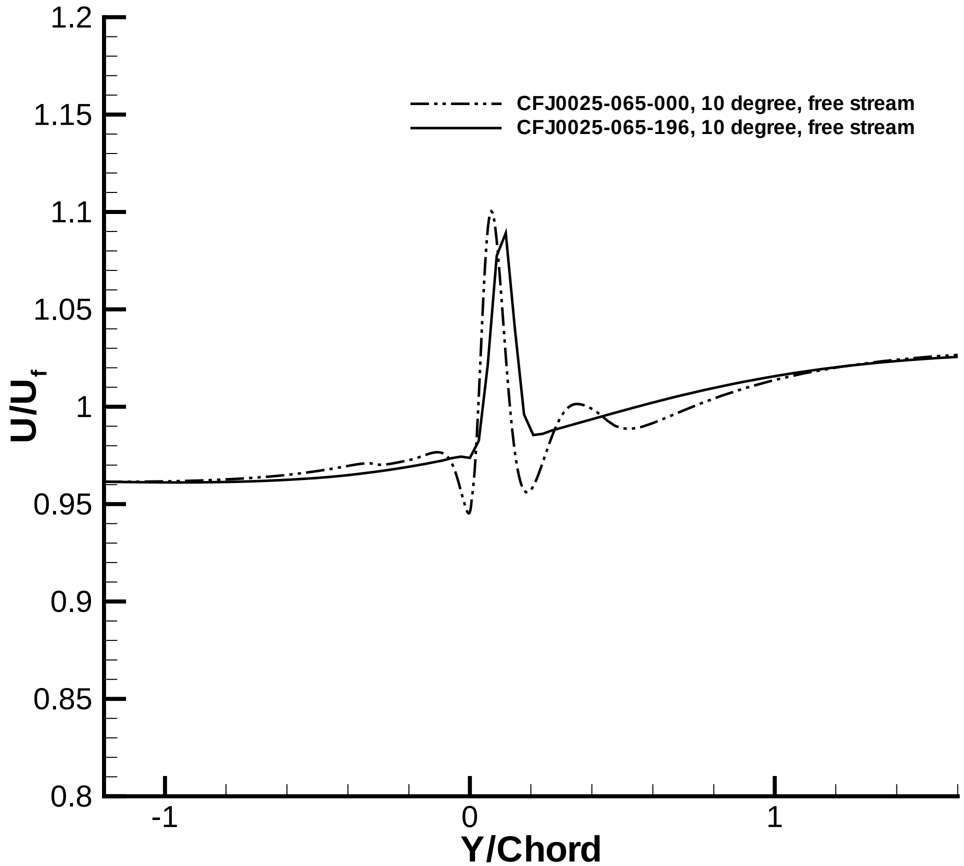
Computed lift coefficient



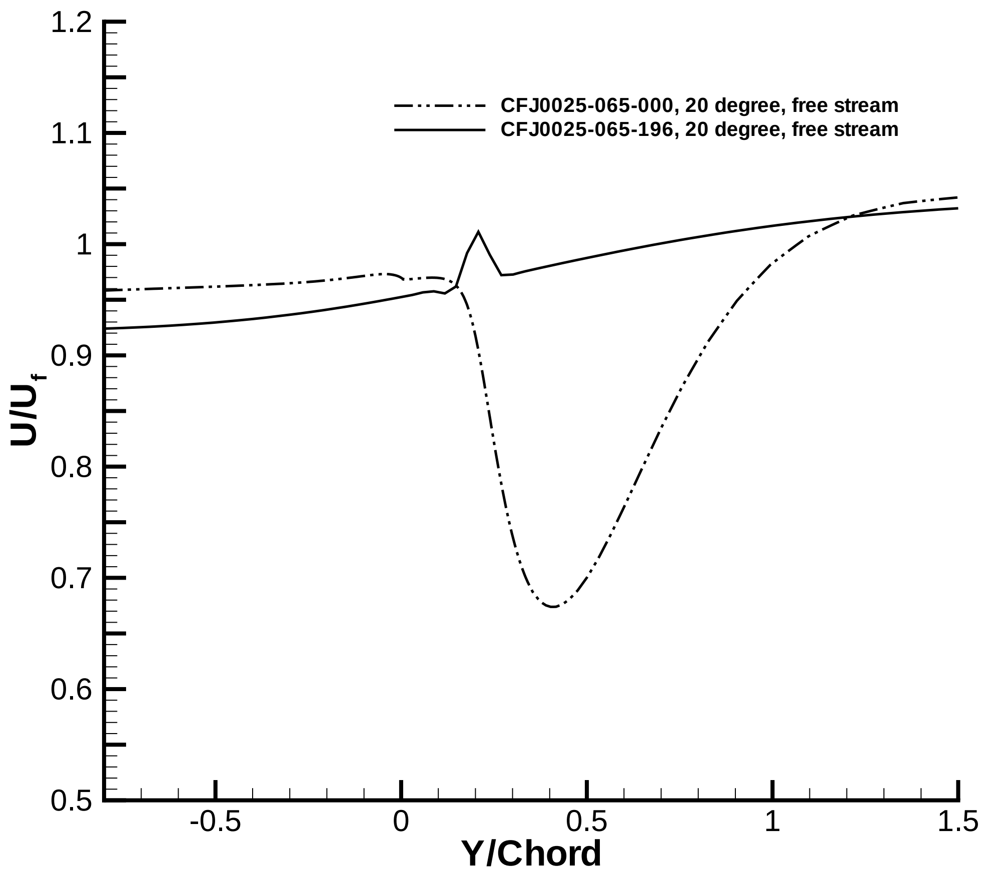
Computed drag coefficient



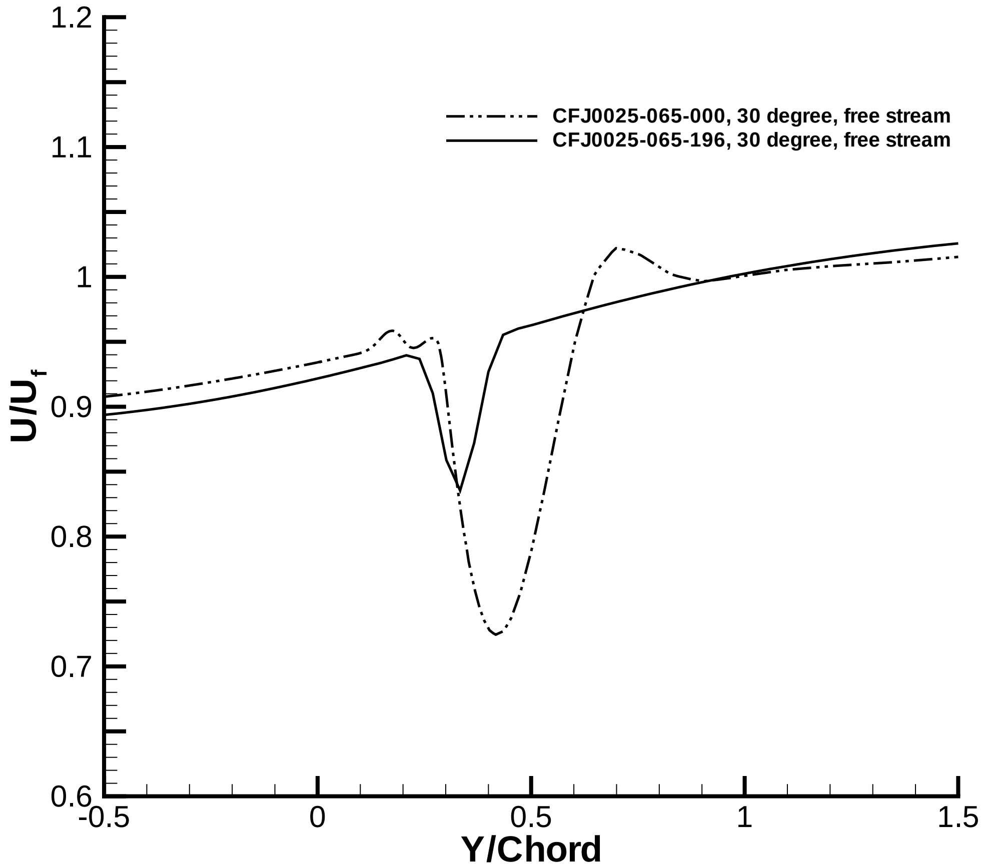
Computed wake profiles at AoA=10°.



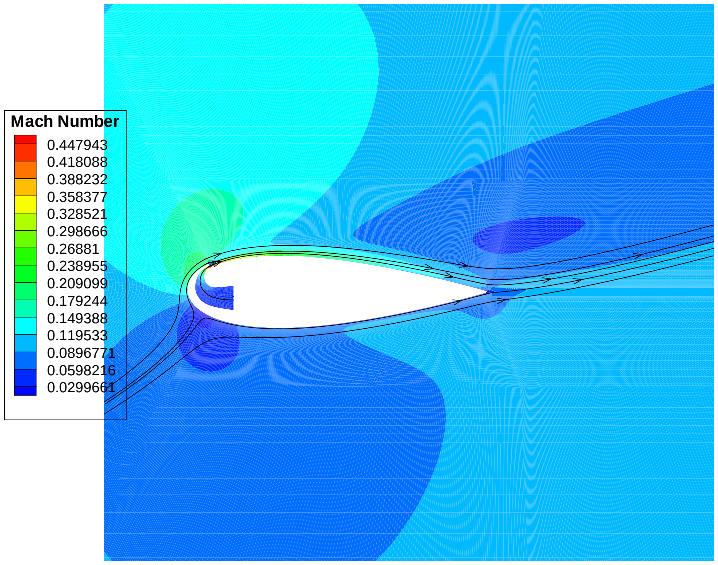
Computed wake profiles at AoA=20°.



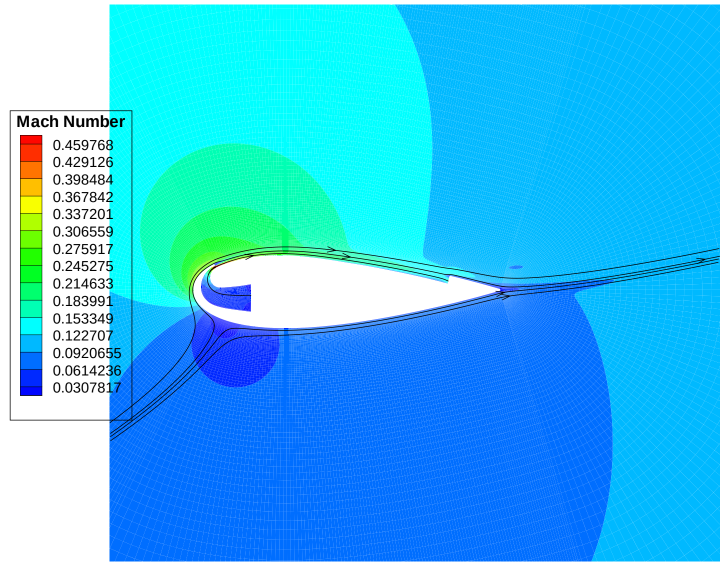
Computed wake profiles at AoA=30°.



Mach contours with streamlines, AoA=20°

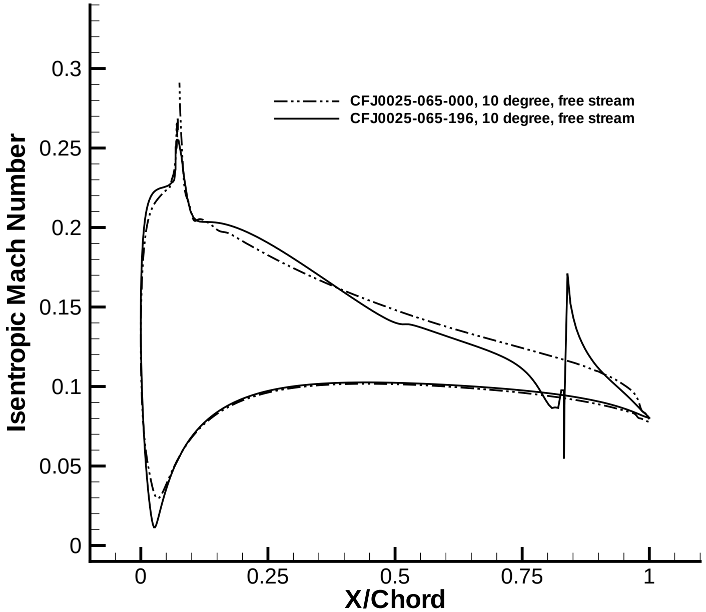


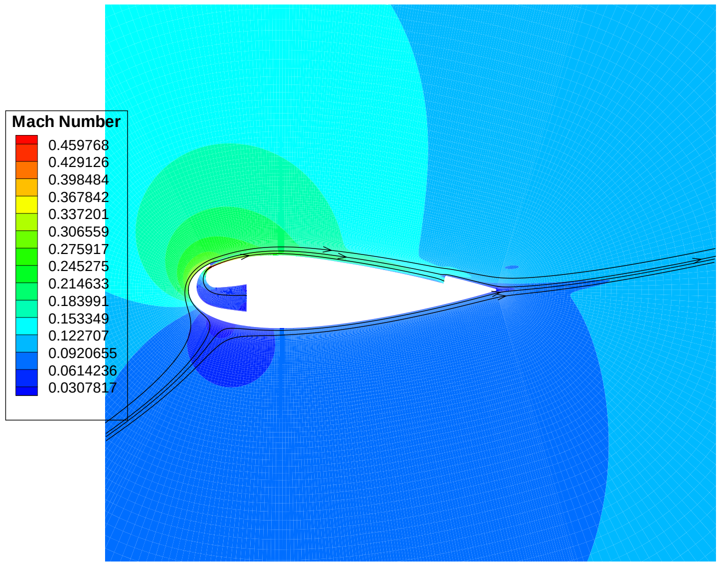
CFJ0025-065-000 airfoil



CFJ0025-065-196 airfoil

Surface Isentropic Mach number





AoA=10°

AoA=20°

A1: For CFJ Airfoil, $D_{equiv} = D_{windtunnel}$

For Airfoil with injection only,

$$C_{D equiv} = C_{D windtunnel} + C_{\mu} \frac{V_{ei}}{V_j} + C_{\mu} \frac{V_{ei}}{V_j \gamma M_{ei}^2} \tag{17}$$

A2: Suction on airfoil is better than suction on engine.

Conclusions

- Jet injection reduce drag, increase lift if downward, decrease drag if upward
- Jet suction increase drag and decrease lift
- Jet suction is necessary as long as jet injection is used.
- For CFJ airfoil, the wind tunnel measured drag is the actual drag.
- Jet suction on airfoil surface is more beneficial than jet suction on engine inlet
- For CFJ airfoil, jet suction penalty is off set by higher circulation, lower drag due to stronger LE suction.
- The airfoil with injection only needs to add suction drag. The equivalent drag is significantly larger than the measured drag and the CFJ airfoil drag.

- Compared with the airfoil with injection only, the CFJ airfoil has higher lift, higher stall margin, lower drag and lower energy expenditure.

- For the CFJ0025-065-196 airfoils, the RANS model predict lift and drag fairly well when AoA $\leq 20^\circ$, significantly under-predicts lift and drag when AoA is higher.

- The jet ducts force contributions from control volume analysis agree well with 3D CFD calculation.