Aerodynamics, Flow Separation, Frost & Paint

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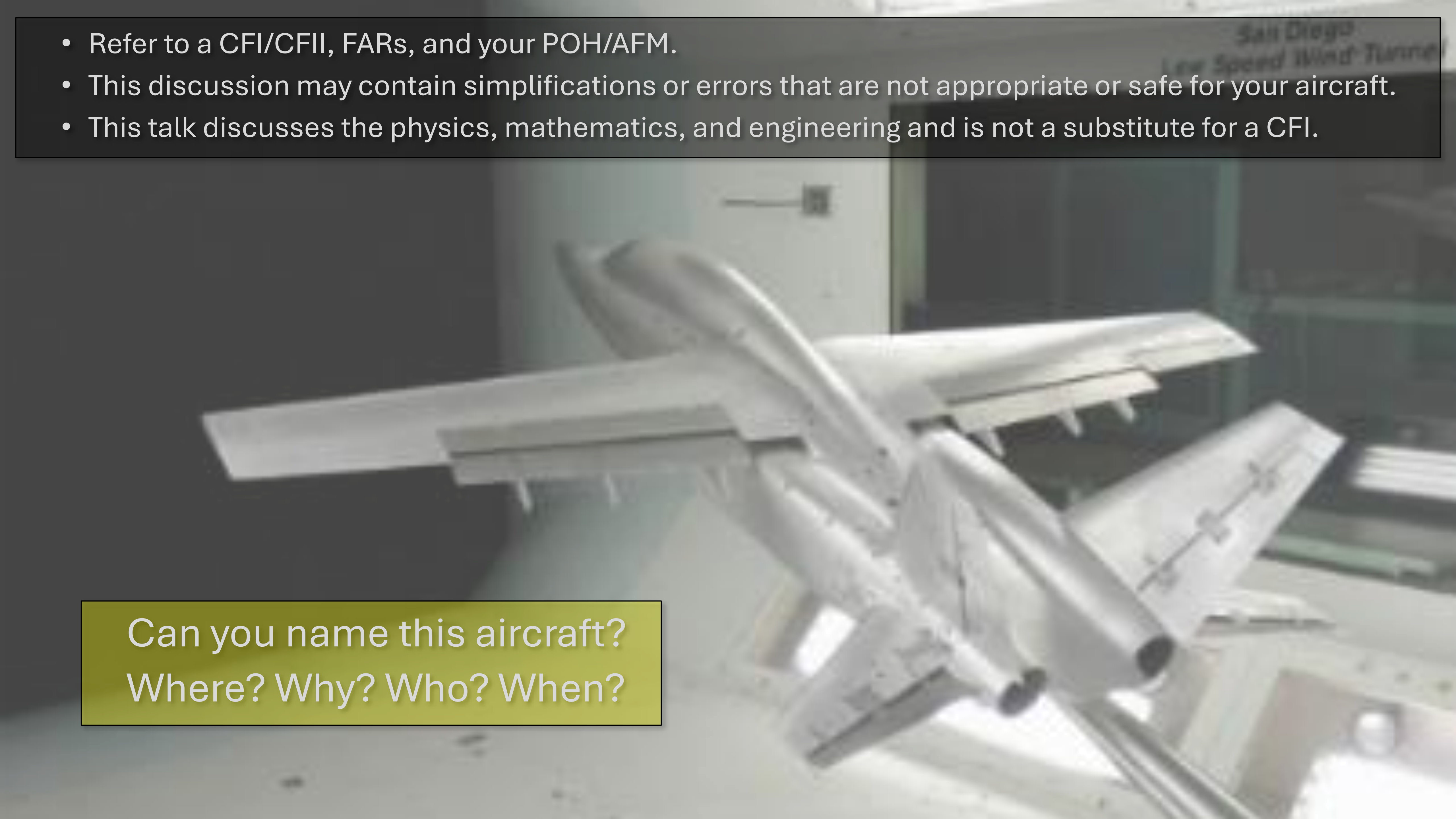
Justus Milligan (CFI/CFII)

9 June 2025
Posted at: https://charles-oneill.com

How this discussion is structured:

1) Start with an interesting question or observation.
2) Dig into the physics, TTPs, and details.
3) Zoom out and give actionable knowledge.

- Refer to a CFI/CFII, FARs, and your POH/AFM.
- This discussion may contain simplifications or errors that are not appropriate or safe for your aircraft.
- This talk discusses the physics, mathematics, and engineering and is not a substitute for a CFI.



Can you name this aircraft?
Where? Why? Who? When?

Q: Is Frost Dangerous?

Q2: Why bring this up now? Summer in TX!

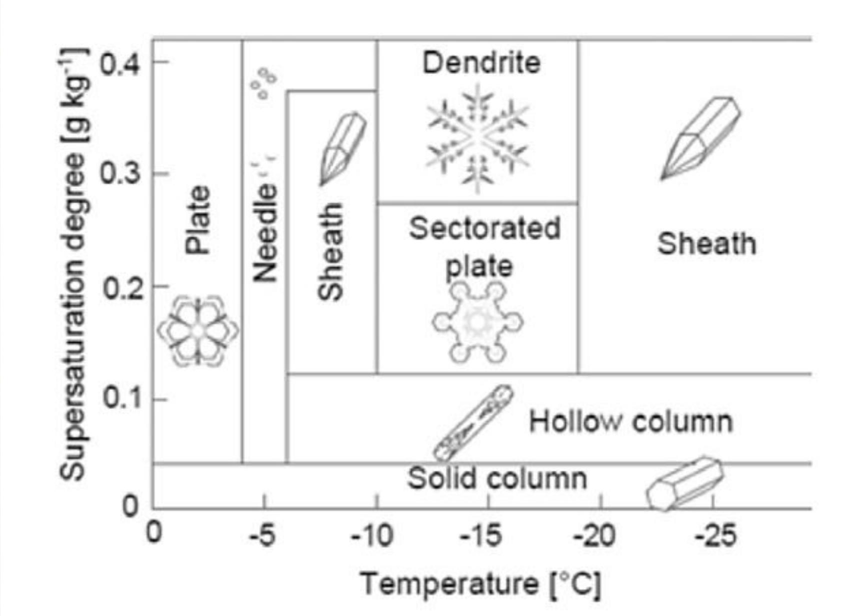
Frost is water vapor freezing on a surface. Frost "*grows*" away from the surface.

AOPA Photo

NASA Photo

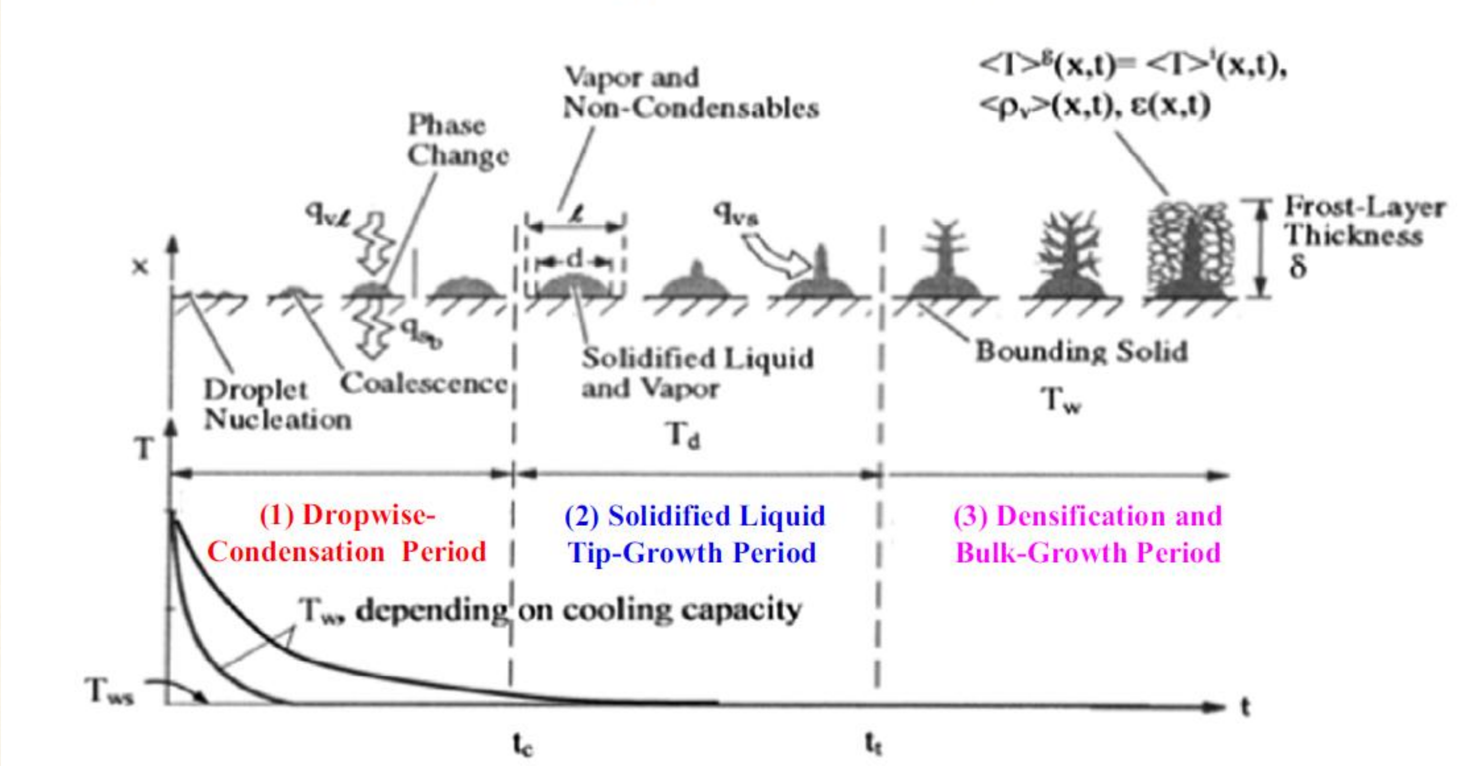
Airworthy? Physics? Why?

Frost Physics



(a) Kobayashi's (1958) map of frost morphology

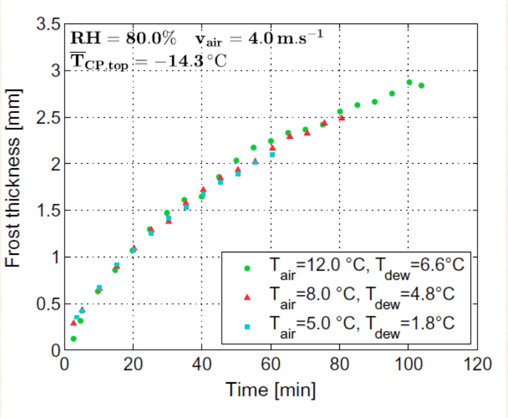
M. Song, C. Dang / International Journal of Heat and Mass Transfer 124 (2018) 586–614



A. Leoni et al. / Experimental Thermal and Fluid Science 88 (2017) 220–233

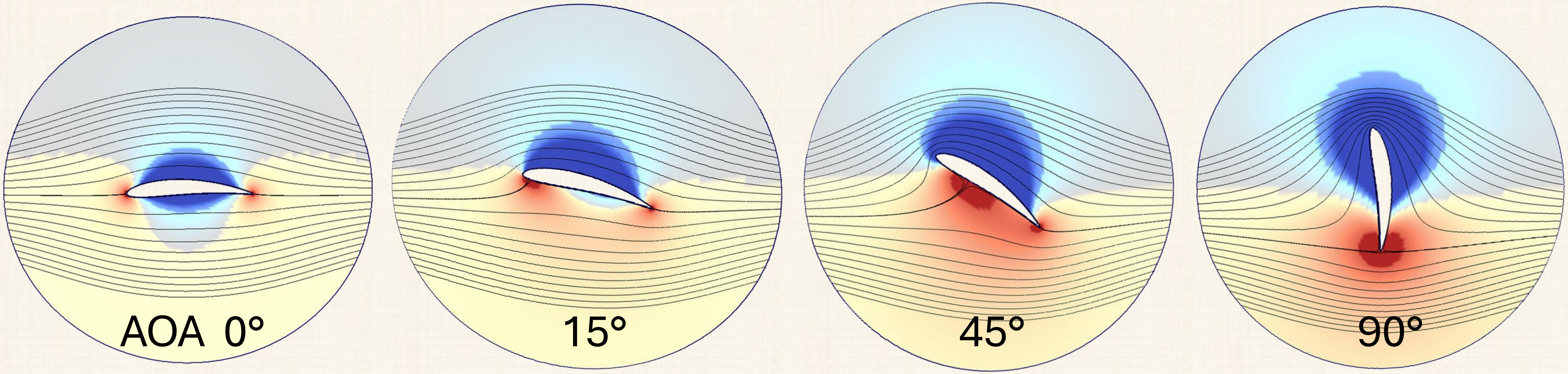
Frost layer growth depends on the surface temperature, humidity, and heat transfer (reverse of cooling fins!).

Frost growth can be 0.1 inch (3 mm) even over a short time (2 hr).



Idealized Airfoil Lift Generation

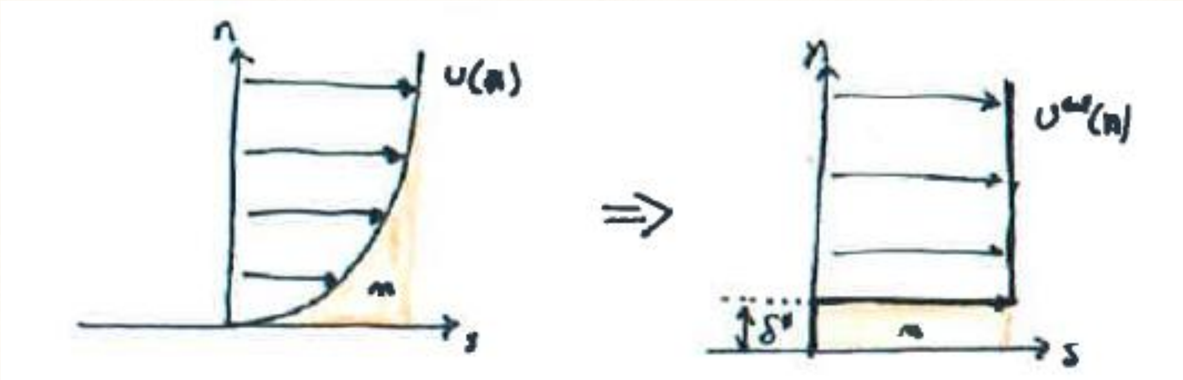
- Ideal & Inviscid Aerodynamics. What is physically wrong with these?



Engineer: Viscous flows with boundary layers and flow separation.

Pilot: Reality | Surface Drag | Stall

Boundary Layer Growth

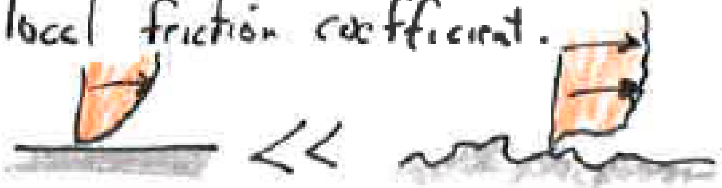


Boundary layer growth depends on the roughness, thickness, and the pressure variation.

$$\frac{d\theta}{ds} = \frac{C_f}{2} + \left(H + 2 - M_e^2\right) \frac{\theta}{\rho_e U_e^2} \frac{dp}{ds}$$

θ is a measure of the boundary layer thickness and impact on drag. "Momentum thickness"

C_f : local friction coefficient.



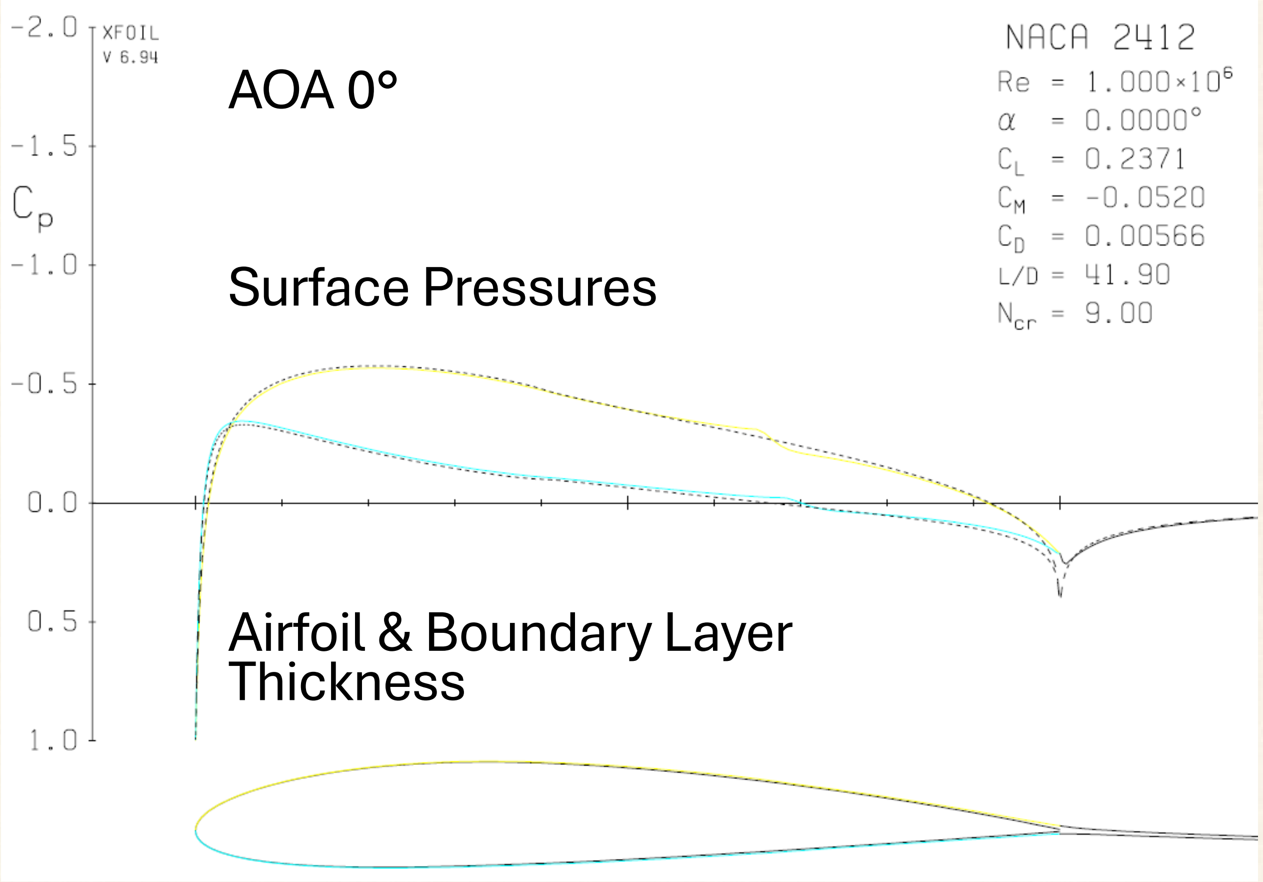
H ≡ shape parameter
≈ 1.4 turb

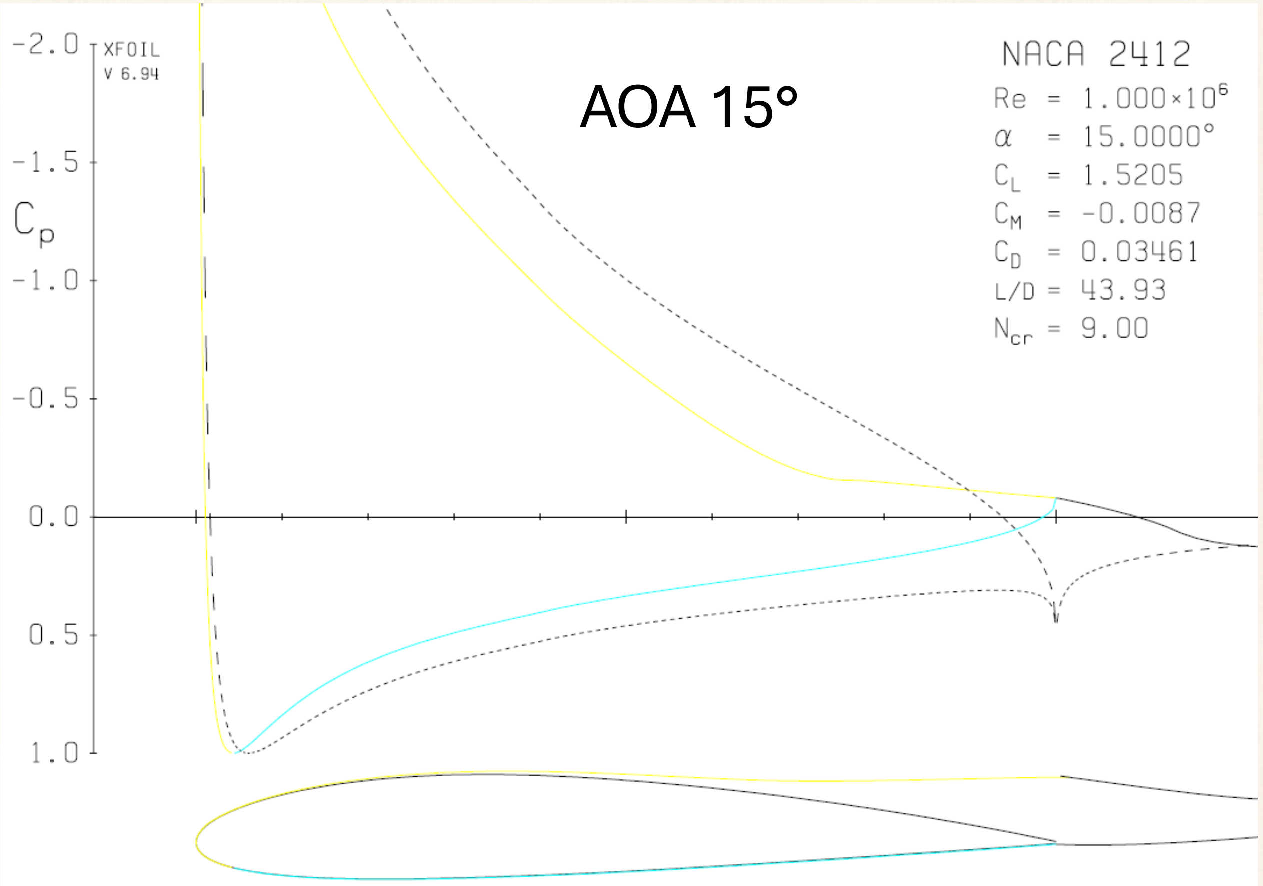
$\frac{dp}{ds}$: pressure gradient along streamline at surface

Actual Airfoil Lift Generation

$$\frac{d\theta}{ds} = \frac{C_f}{2} + \left(H + 2 - M_e^2\right) \frac{\theta}{\rho_e U_e^2} \frac{dp}{ds}$$

- Viscosity & No-slip surfaces = Boundary layers & Separation

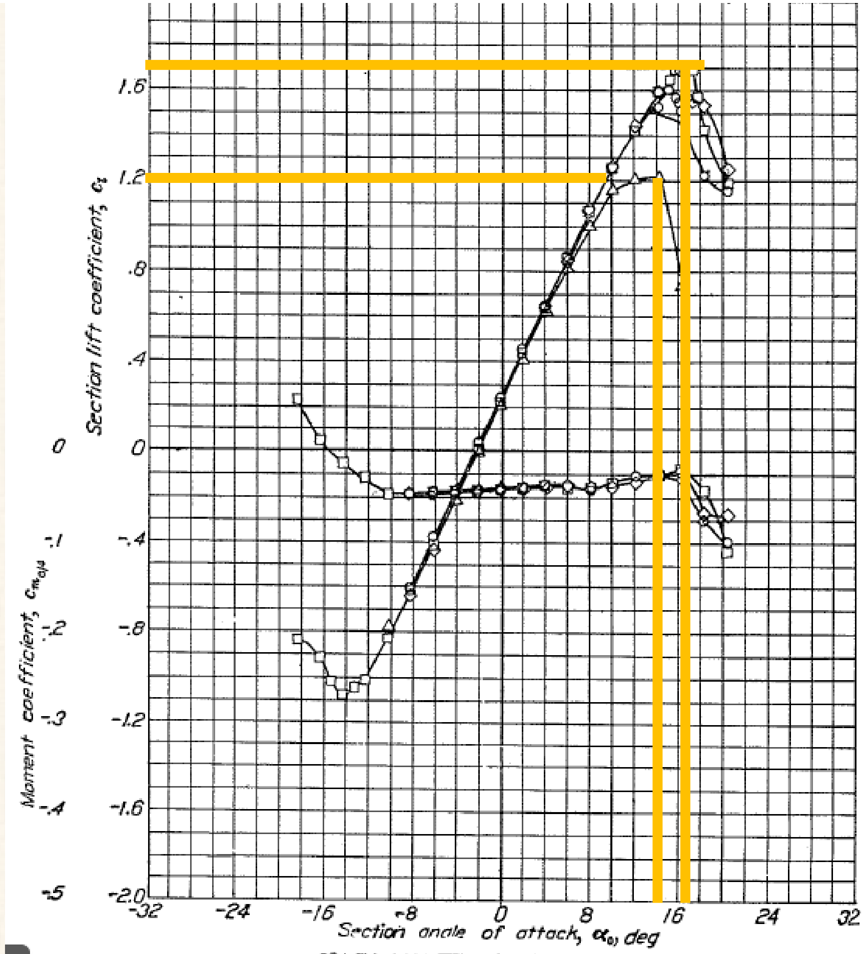




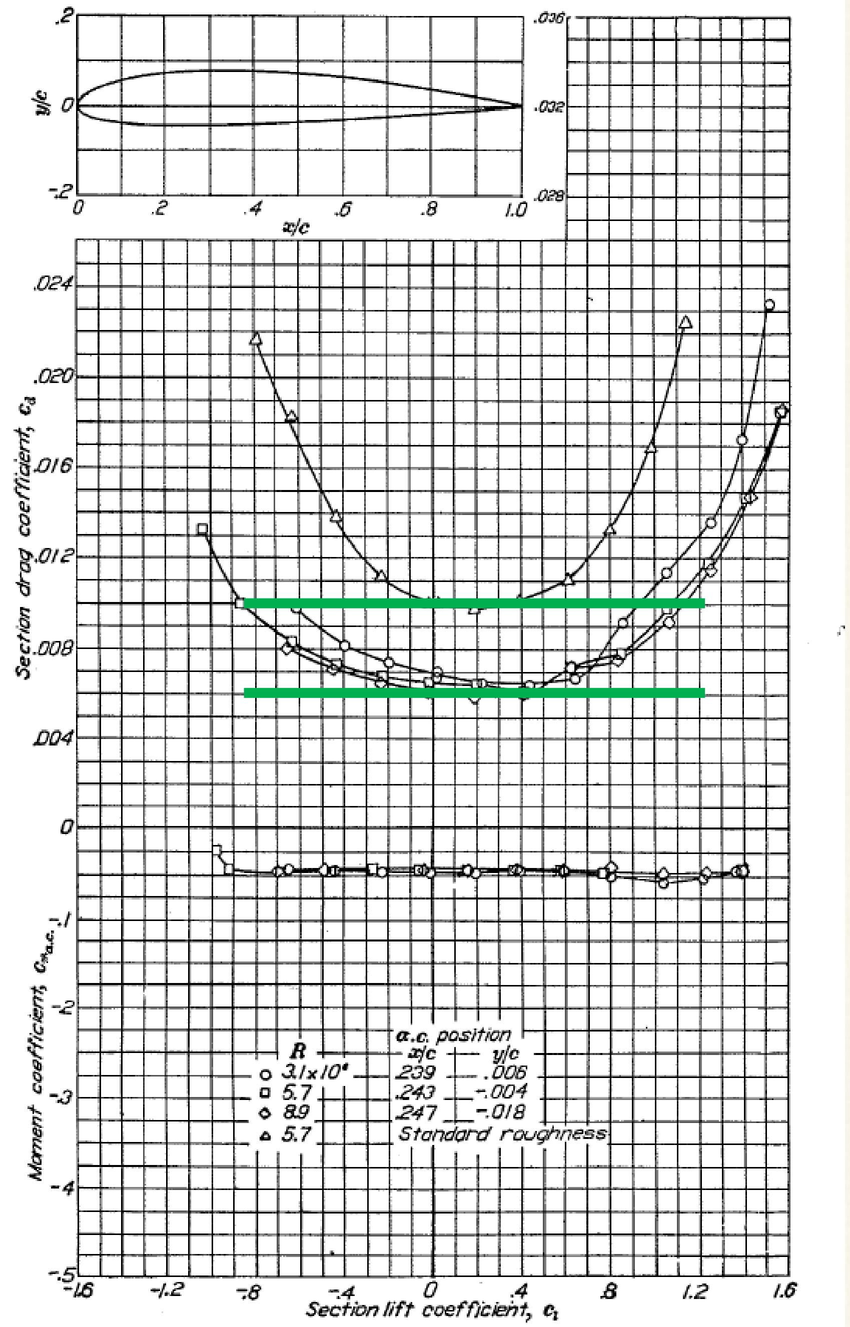
The wake is small at low AOA and increases in thickness up to stall.

NACA Standard Roughness = 0.011” sand grain over 5% to 10% of LE area up to 8% chord. Thickness is ~3 sheets of paper. Standard roughness is NOT frost!

Max Lift: 30% lower.
Stall AOA: 2° lower
Drag: 60% higher

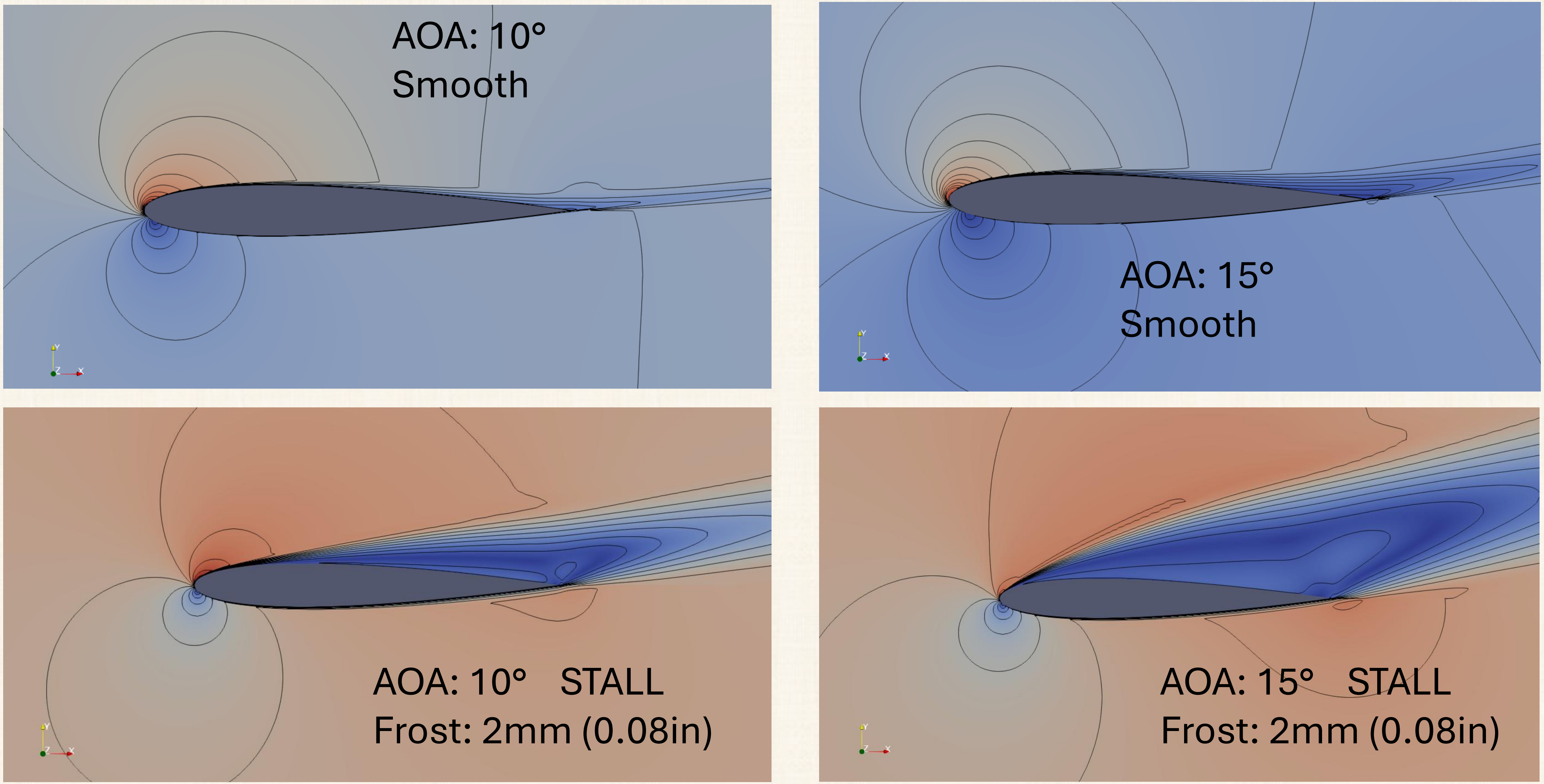


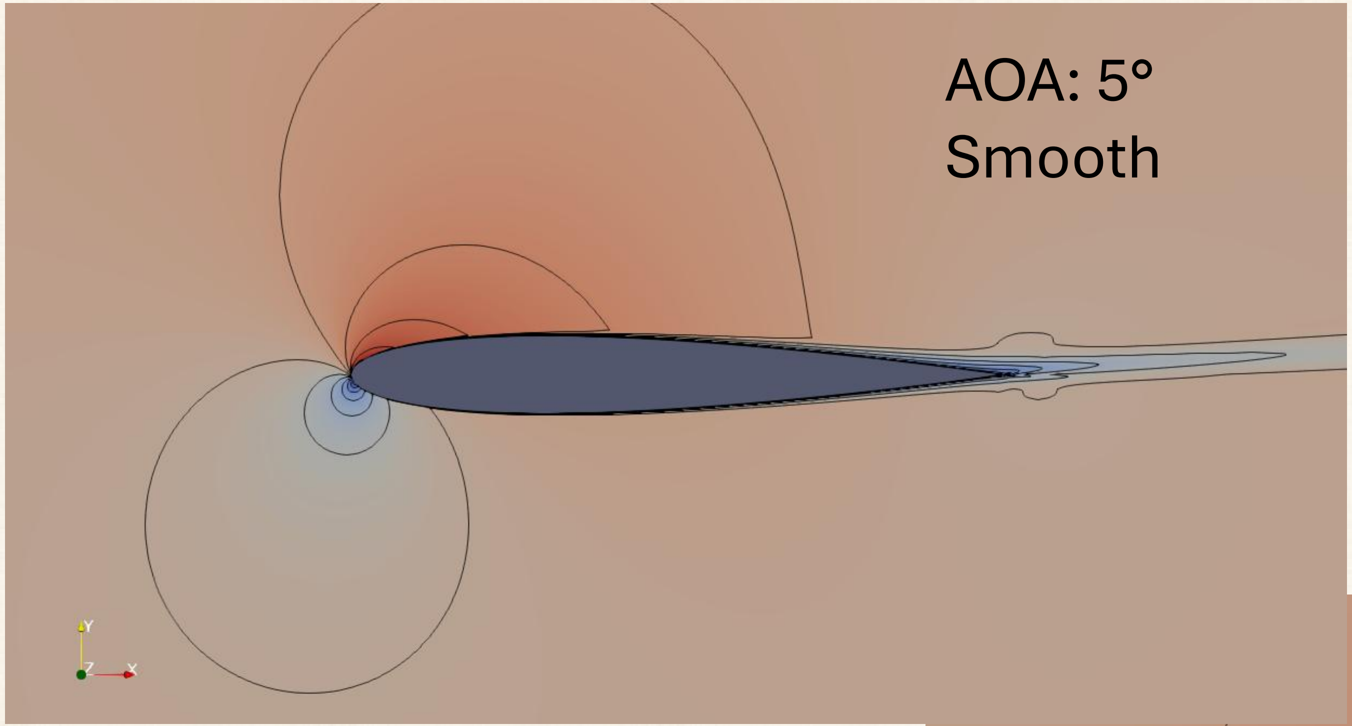
NACA 2412 Wing Section



NACA 2412 Wing Section (*Continued*)

Actual Airfoil Lift Generation: Viscosity & Rough Surfaces

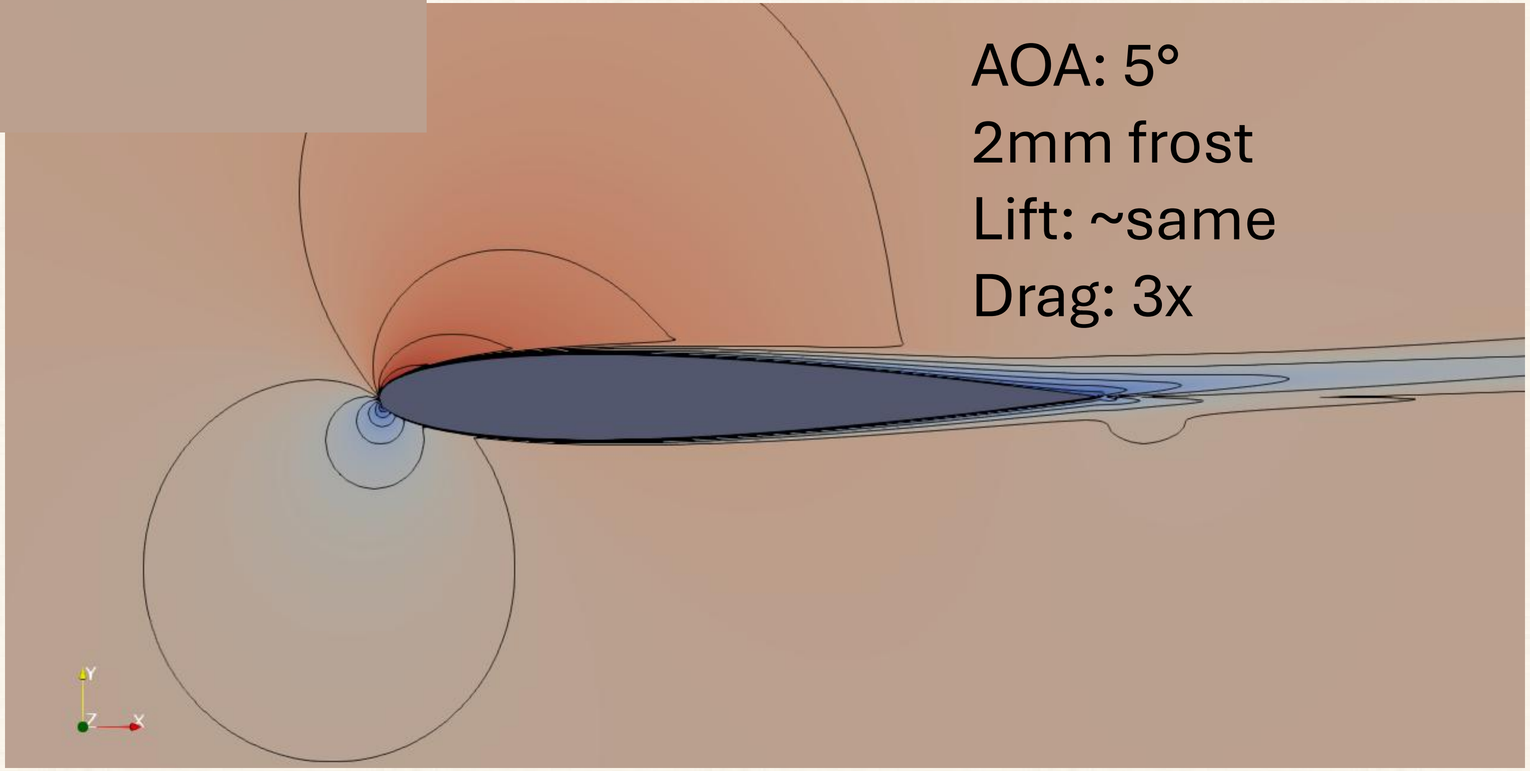




Summary:

- Cruise speed reduced by 30%!
- Stall speed increased by at least 40% to 50%

Cessna 172 is now a 75 kt airplane with a stall speed of 70 kts.



I will explore this in more depth later. Updates will be posted at my website:

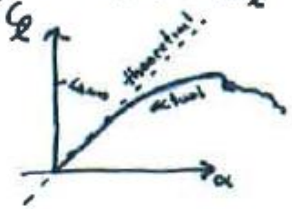
CharlesOneill.com

or

Charles-oneill.com

Stall Characteristics

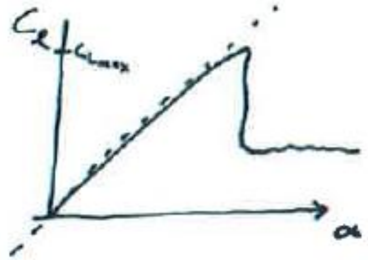
When studying the BL topics, we briefly saw how a thickening BL affects C_ℓ



viscous decambering

We can call the point when viscous decambering leads to reduced C_ℓ from the max C_ℓ as trailing edge stall

Stall also has another dominant mode, the leading edge stall where the separation begins at the LE. This mode is typically sharper and of more magnitude. (and more unsteady).



Why would we choose an airfoil with this abrupt stall behavior? Performance

The Piper PA38 Tomahawk was designed for spin training and uses the sharper GAW 1 airfoil. tiny.cc/PA38Stall

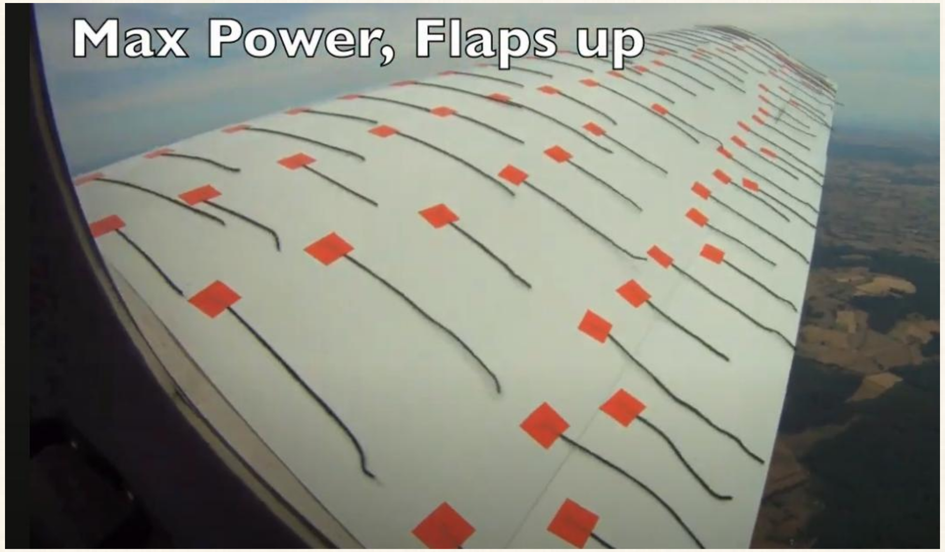
Both TE and LE stall can occur,

Stall Characteristics

Not all surface imperfections degrade stall characteristics. Vortex generators can significantly improve flow separation by energizing the boundary layer, which delays separation. The tradeoff is usually increased drag.

Stall 60kts: No VGs

Stall 45kts: VGs



https://www.youtube.com/watch?v=SXwVyxorvno

VGs improved CLmax by 78%!

Frost

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

NACA TN 2962

TECHNICAL NOTE 2962

EFFECT OF ICE AND FROST FORMATIONS ON DRAG OF NACA 65_1-212 AIRFOIL FOR VARIOUS MODES OF THERMAL ICE PROTECTION

By Vernon H. Gray and Uwe H. von Glahn

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NACA

Washington
June 1953

General comments on effect of frost on airfoil drag. - In general, frost formations over the entire airfoil (sublimation frost) or over the surfaces aft of the heatable areas cause a severe drag increase and at high angles of attack are accompanied by shifts in the position of the momentum wake which indicate a loss in lift and possible stall. Conventional heating systems (continuous or cyclic de-icing) do not remove a sufficient amount of frost to permit safe operation of the airfoil at high angles of attack where loss in lift is critical.

A brief study was made in the icing research tunnel of the effect of a sublimation frost on the drag of an airfoil. This study indicated that the drag may increase as much as 300 percent over the bare airfoil drag value. This increase in drag was obtained at an 8° angle of attack, an airspeed of 100 miles per hour, and a datum air temperature in the range of -25° to -8° F. A photograph of the frost formations causing this increase in drag is shown in figure 38. This drag increase must be considered conservative, because only the upper half-span of the airfoil model was covered with frost. Hence the momentum loss in the wake

Drag increase of 300% (+) = 4x

Prop power output is constant:

$$Power = \frac{1}{2}\rho V^3 C_d S$$

The new velocity at 4x drag with **same** power is:

$$\frac{V_{frost}}{V_{clean}} = \sqrt[3]{\frac{C_{d\,clean}}{C_{d\,frost}}} = \sqrt[3]{\frac{1}{4}} = 63\%$$

A C172 cruising at 100 kts now becomes a 60 kt airplane. At best.

Q: Wing frost is dangerous but what about damaged & flaking paint?

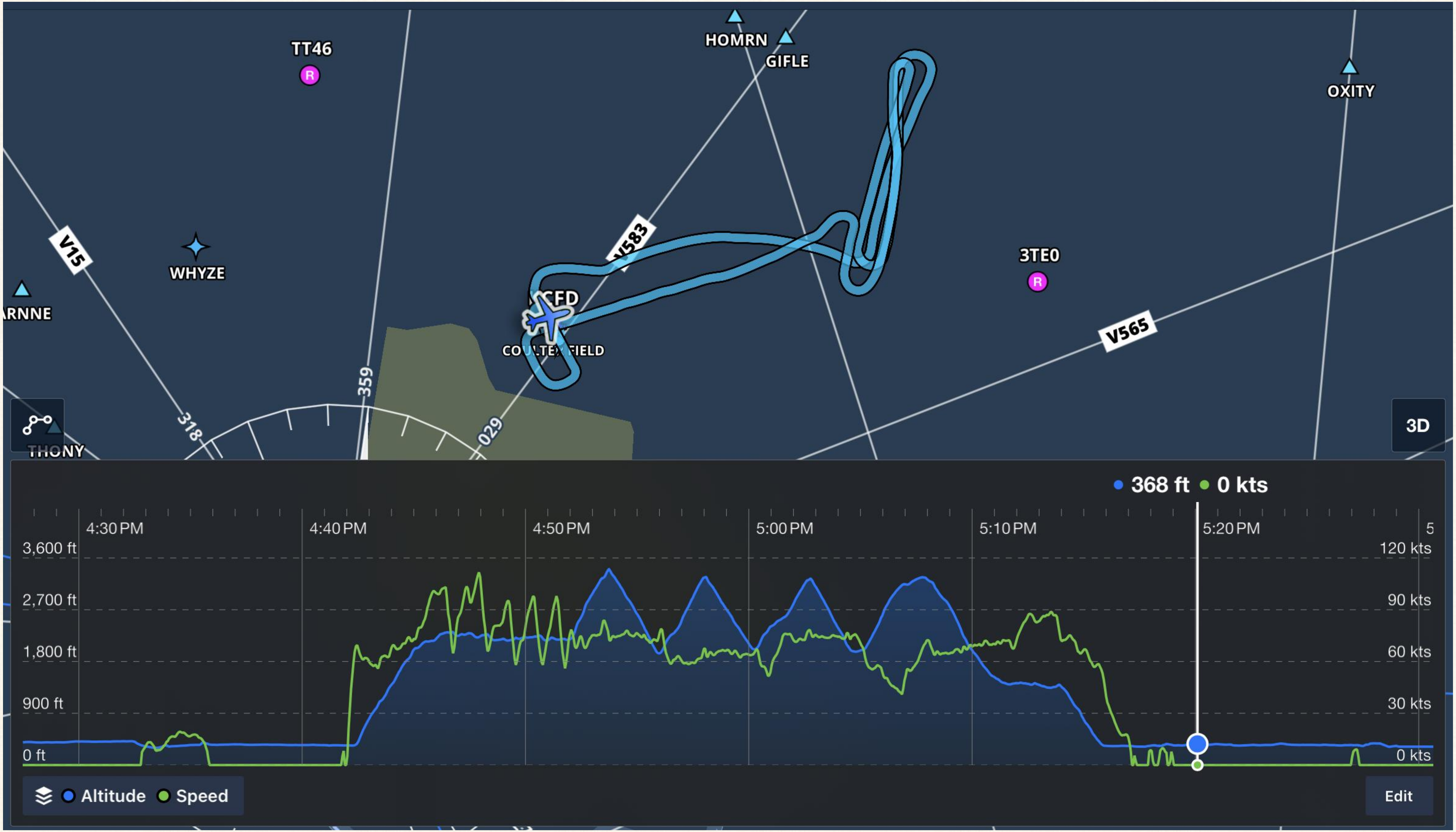
Paint characteristics :

- Paint thickness: ~0.005” – 0.010”
- Edge gap vs. Edge curling
- Location of damage & flaking. LE?
- Differentials? Top/Bottom is ok.
  Left/Right is not ok.

Mild damaged and flaking paint is unlikely to be dangerous.
Moderate to severe flaking paint could begin to affect safety.

Paint Characterization

This paint is primarily adding drag. Exceptions.


TT46
HOMRN
GIFLE
OXITY
V15
WHYZE
RNNE
V583
3TE0
CFD
COULTER FIELD
V565
359
318
029
THONY
3D
368 ft
0 kts
4:30 PM
4:40 PM
4:50 PM
5:00 PM
5:10 PM
5:20 PM
3,600 ft
2,700 ft
1,800 ft
900 ft
0 ft
120 kts
90 kts
60 kts
30 kts
0 kts
Altitude
Speed
Edit

Flight Test Results

Drag Coefficient:

- N60HF: $C_D \approx 0.0310$
- N7385T: $C_D \approx 0.0420$

This is about 35% more drag (!!). I can feel it when doing PO-180s.

Could this also explain the stall flap squawk?

Surface Roughness Takeaways:

Posted at: https://charles-oneill.com
Email at: oneill@aerofluids.com

1. If you can feel imperfections on the leading edge, remove the contamination.

2. No flights with any frost.

3. Aircraft performance is significantly affected by widespread surface roughness. Stall speed and cruise speed merge!

4. Stalls are flow separation, which can slowly form from the TE or quickly form from the LE. Surface roughness degrades both.