Topological Aspects of the FAITH Experiment

(Fundamental Aerodynamic Investigation of flow over The Hill)

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Experimental Aero-Physics Branch

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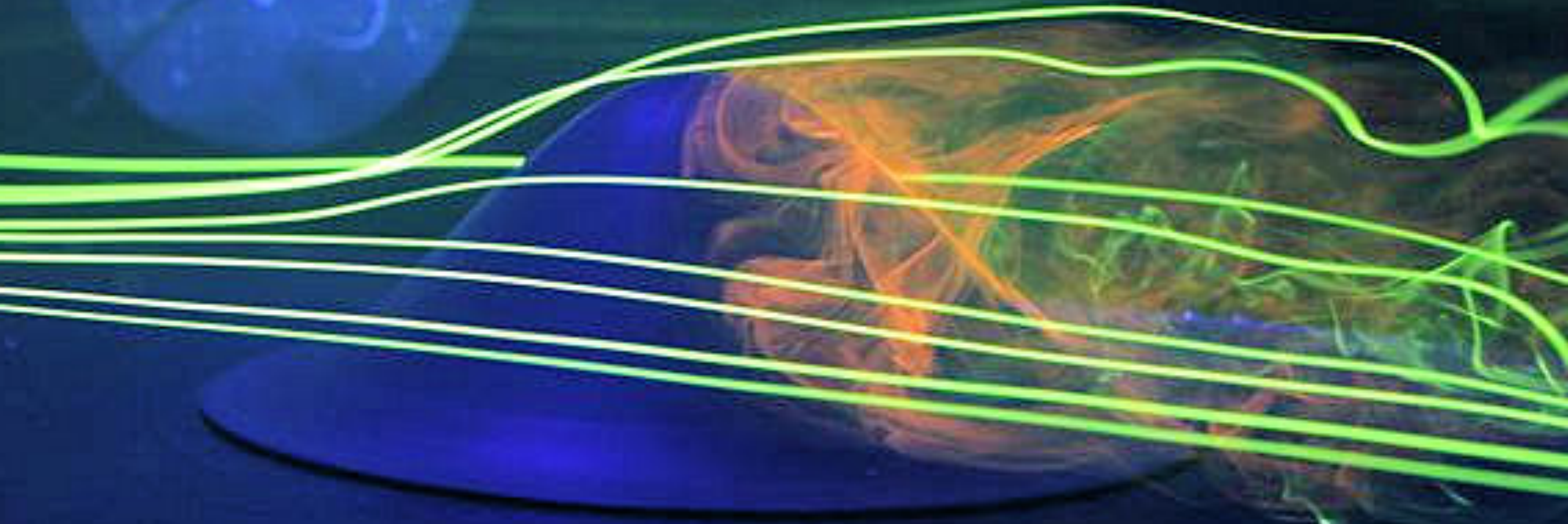


Invited Talk

AIAA Joint Working Group on Fluid Dynamics Challenges in Flight Dynamics

January 7, 2010

Background

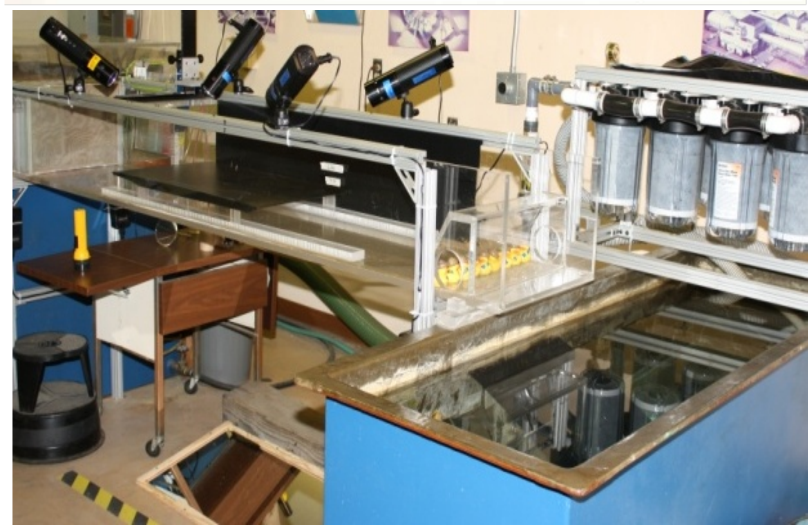
- Subsonic Flow Topology (Attached and Separated Flows)
  - What is relationship between surface pressure extrema and singular points?
    - Does every singular point in a pattern of skin friction lines occur at a surface pressure extremum? (and/or vice versa?)
  - Can this relationship be generalized to all geometries?
  - Previous Work
    - Legendre, Werlé, Coon, Tobak, et al
- FAITH Project
  - Ongoing effort at NASA Ames Experimental Aero Physics Branch
  - Multi-parameter wind tunnel investigation of separated flow around obstacle
    - PIV, FISF, PSP, Kulites, Oil Flow, Cobra Probe
  - Acquire data for CFD validation, optimization
- Relationship between FAITH and topology projects
  - Resulted in work described in this brief
  - This brief represents a status report of ongoing work

Effort Scope

- **Water Channel Experiments**
  - FML Test Cell #3 (17” x 11”); 1 ips
  - 2” (height) hemisphere and FAITH models
    - Re $\#_{height}$ = 1250
    - $\delta/h \sim 0.2$
- **Wind Tunnel Experiments**
  - FML Test Cell #2 (48” x 32” indraft); 160 fps
  - 6” FAITH and 8” hemisphere (height) models
    - Re $\#_{height}$ = 500,000-750,000
    - $\delta/h \sim 0.2$
- **Analytic Efforts**
  - Make use of prior work
    - Legendre, Werlé, Coon, Tobak, et al

Experimental Facilities

- **FML Test Cell #2 Wind Tunnel**
  - Oil/Smoke Flow, Cobra Probe, FISF, PSP, PIV
  - Indraft facility w/sonic throat
  - Test Section:
    - 48" X 32", 120" long
    - Polycarbonate sides, roof
    - Speed Range: 40 - 170 fps, 0.1% TI
  - Instrumentation plenum above ceiling



- **FML Test Cell #3 Water Channel**
  - Dye Flow
  - Test Section:
    - 17" X 11", 96" long
    - Acrylic sides, floor
    - Speed Range: 1 – 4 in/s
  - UV lamps and fluorescent dye

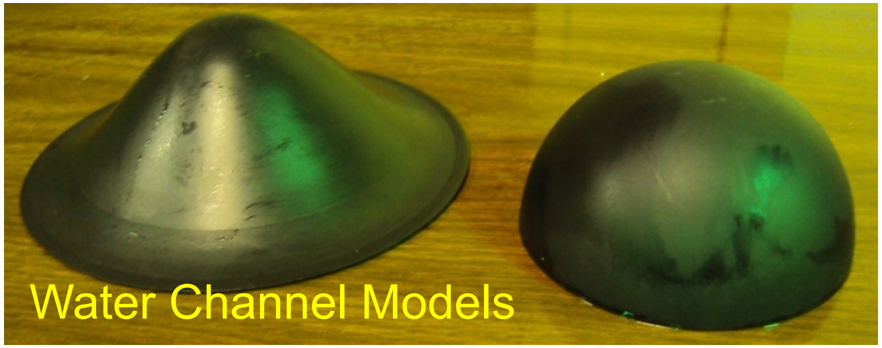
Models

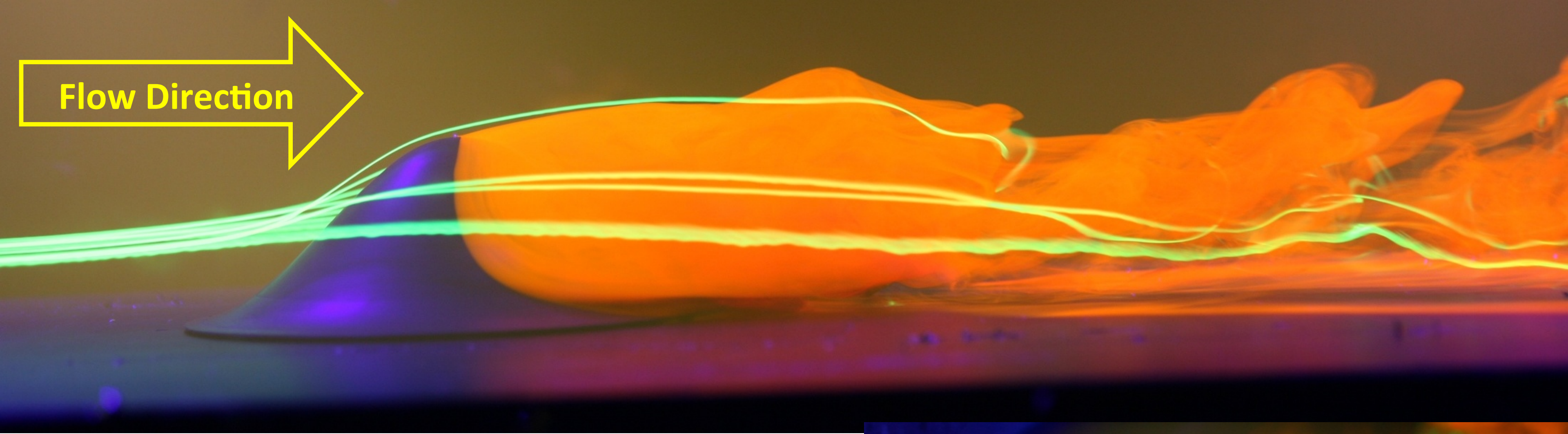
- **FAITH**
  - **Water Channel Experiments**
    - » SLS Sintered Nylon
    - » Max height = 2”
    - » Base diameter: 6”
  - **Wind Tunnel Experiments**
    - » Machined Aluminum
    - » Max height = 6”
    - » Base diameter: 17.95” (18”, sanded to eliminate razor edge)

$$h = 3 \cdot \cos\left(\frac{\pi}{9} r\right) + 3$$

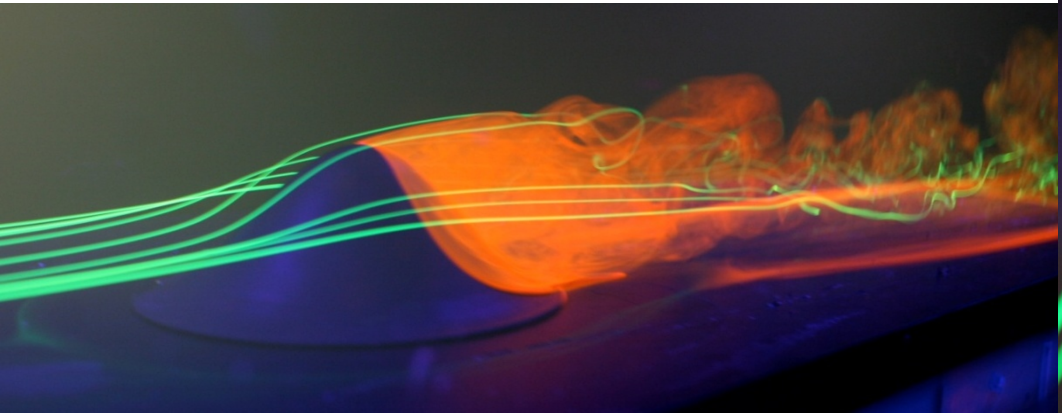
h = height above ground, in
r = radial distance from center, in

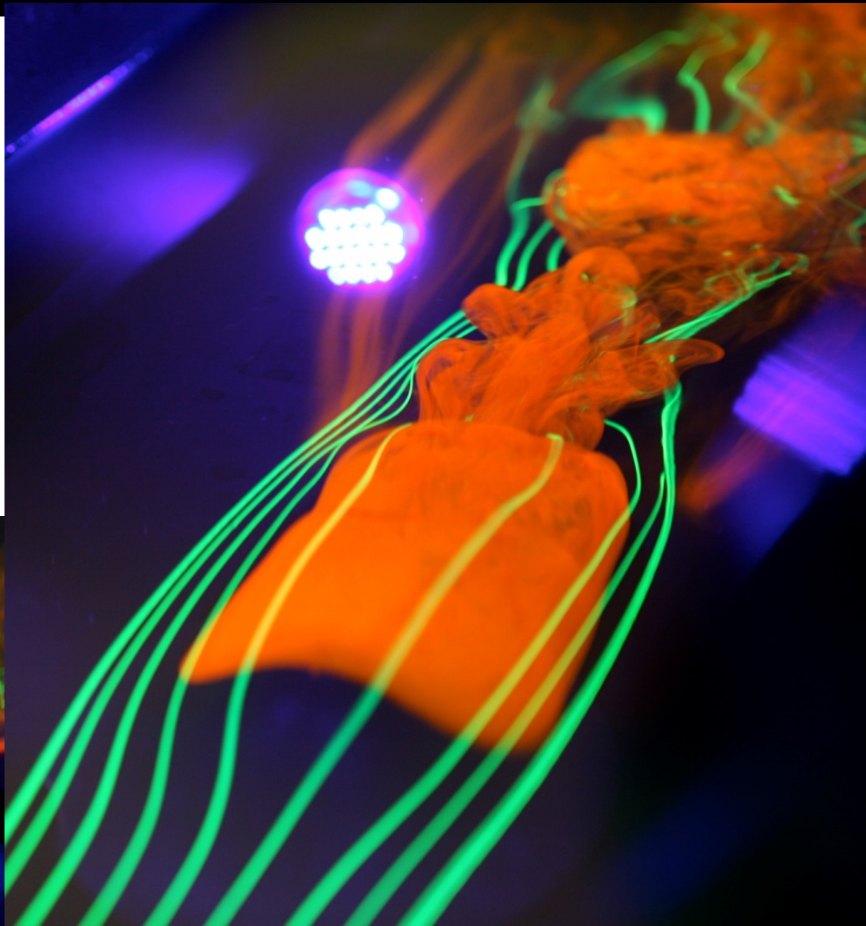
- **Hemisphere**
  - **Water Channel Experiments**
    - » SLS Sintered Nylon
    - » Max height = 2”
    - » Base diameter: 4”
  - **Wind Tunnel Experiments**
    - » Blown Acrylic
    - » Max height = 8”
    - » Base diameter: 18”



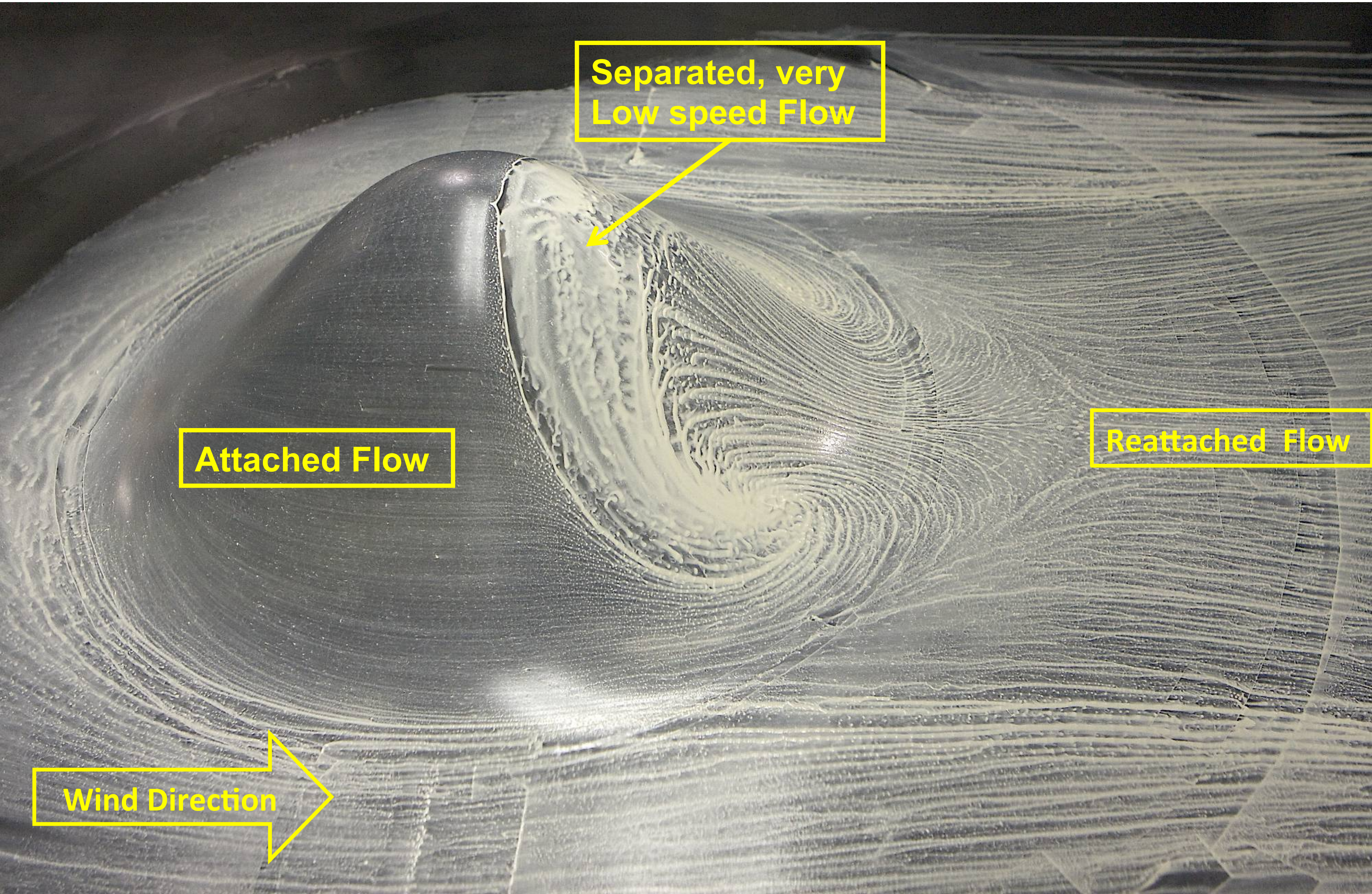


FAITH Water Channel Flow Visualization Experiments

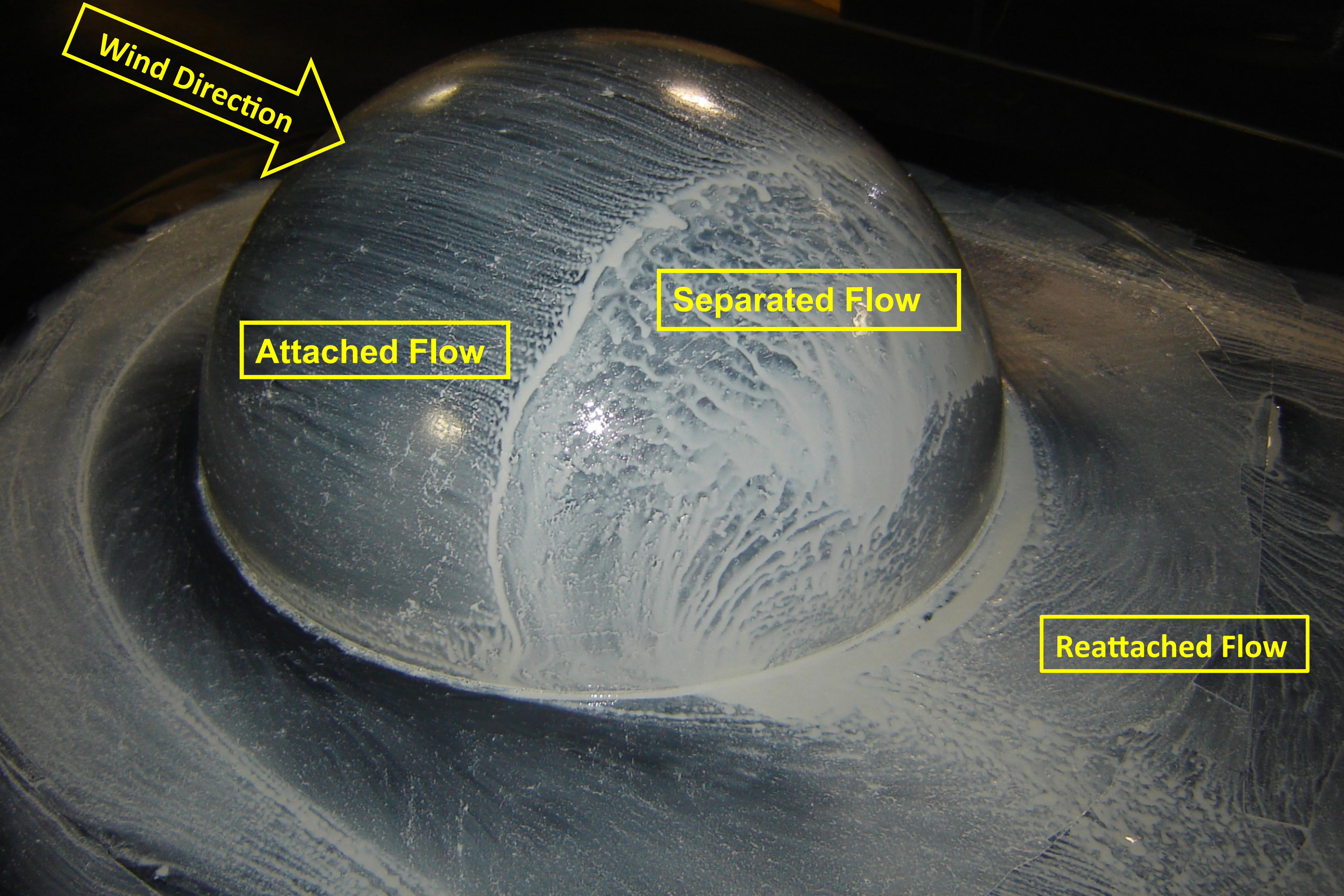




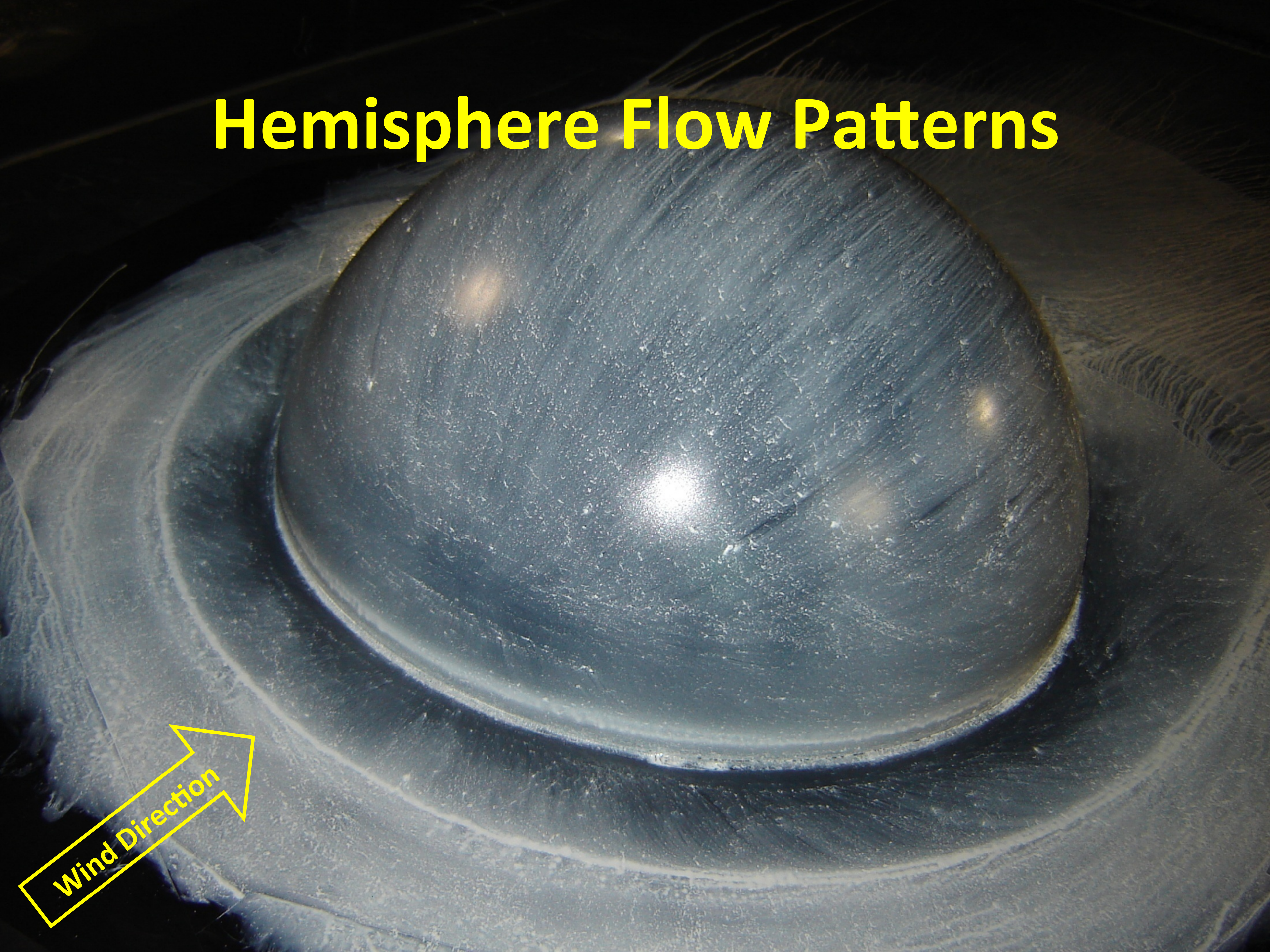
Oil Flow Visualization Experiments



Hemisphere Oil Flow Patterns



Hemisphere Flow Patterns



Surface Flow Topology

- **Flow Topology**
  - **Flow field generalizations**
  - **Flow commonality**
- **Critical Point Definitions**
  - **Saddle Point**
  - **Node**
  - **Focus**
- **General Topological Rule:**

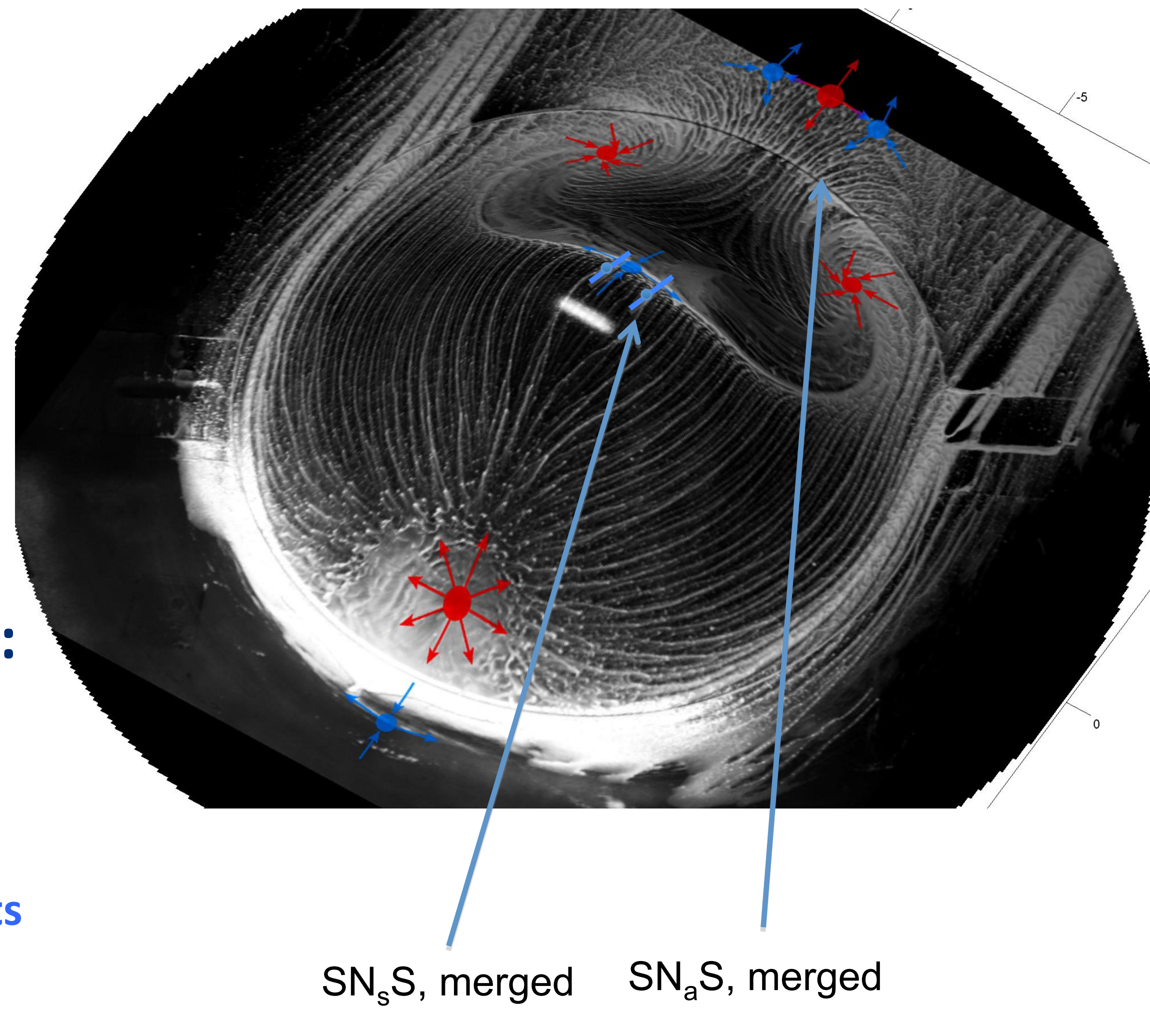
$$\Sigma N - \Sigma S = 0$$

where

N =number of nodes

S = number of saddle points

Critical Points on FAITH Model

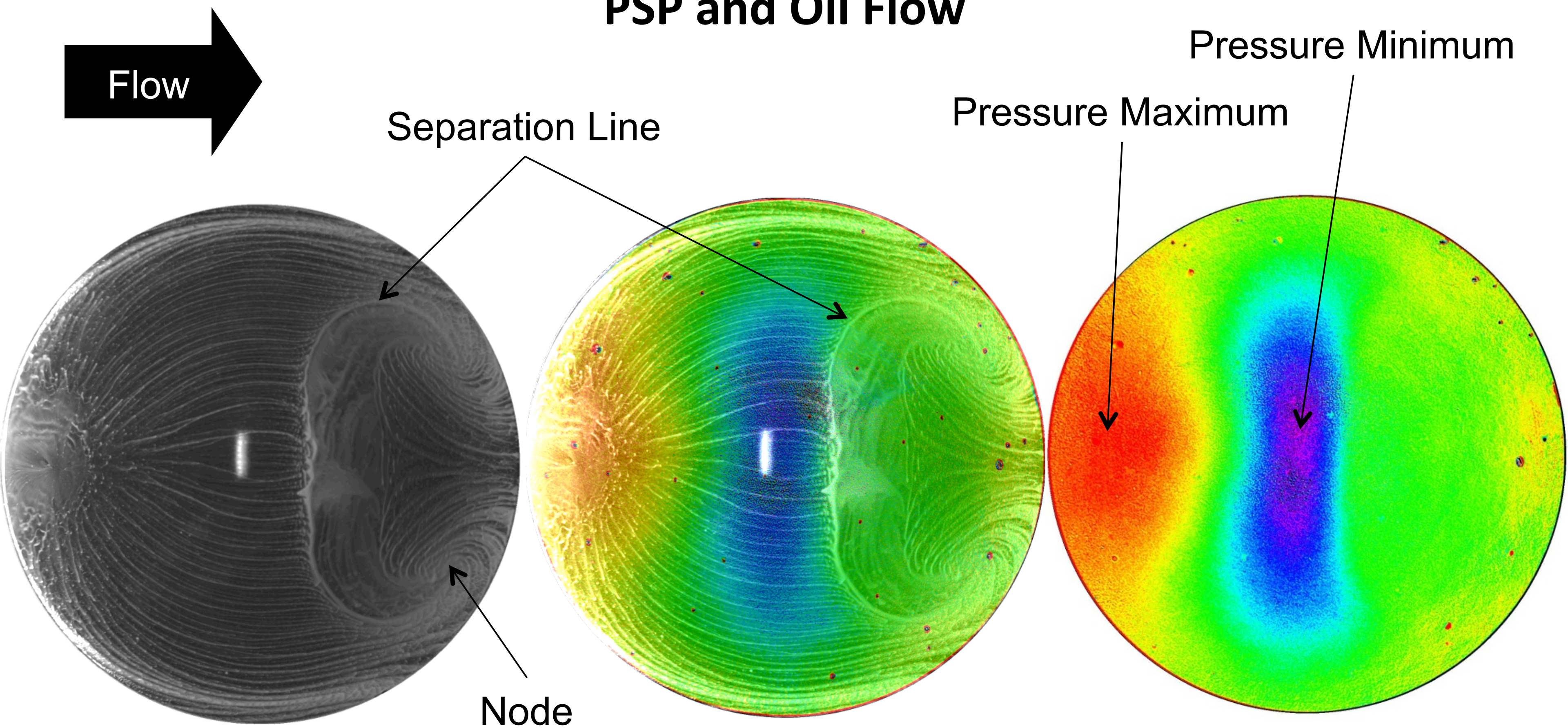


(Note new feature: Saddle-node-saddle merged)

Comparing Pressure and Oil Flow Patterns

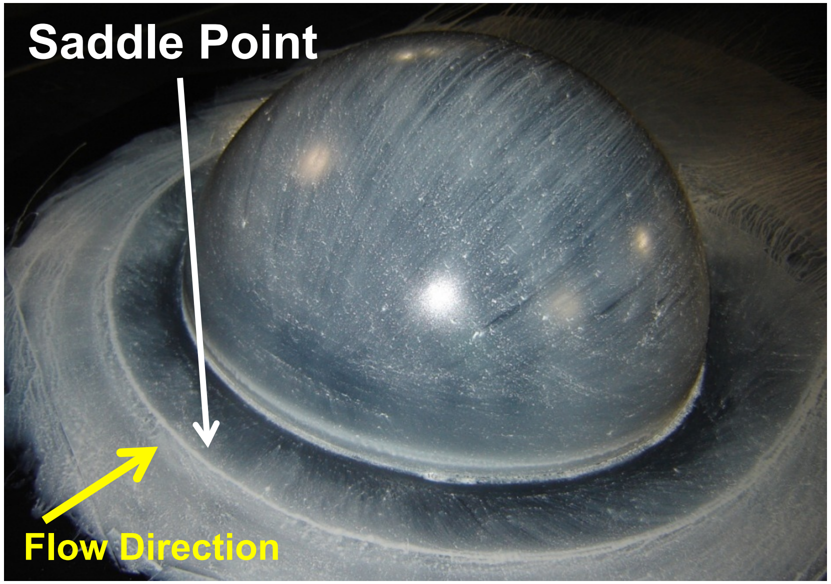
FAITH Model, 150 fps

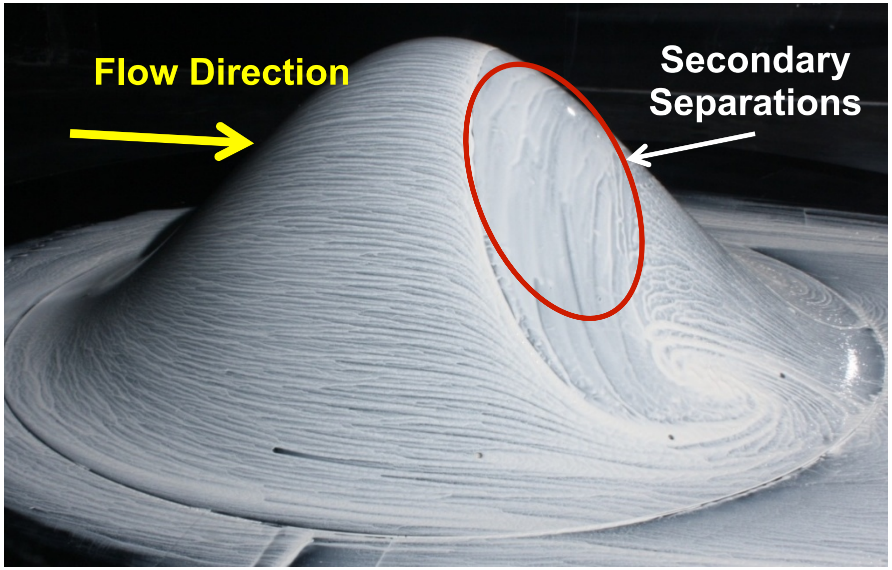
PSP and Oil Flow

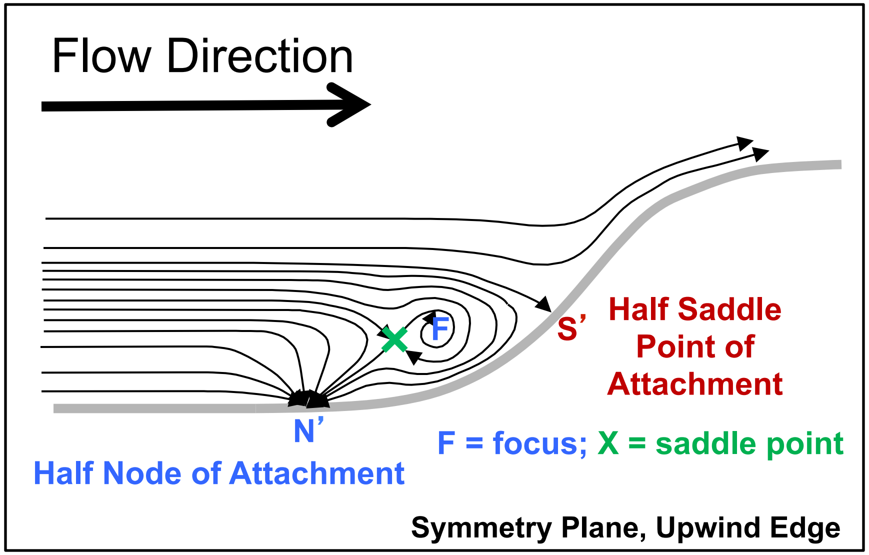


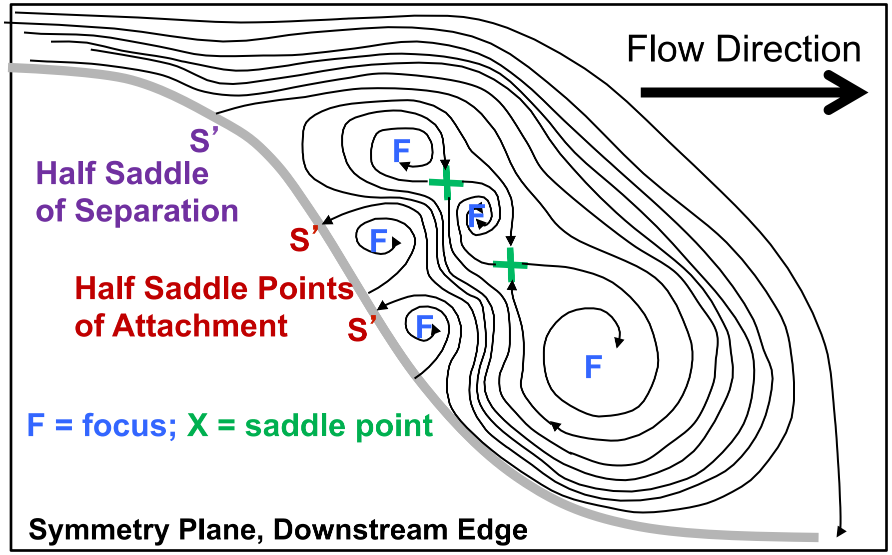
Oil Flow **Overlay of Oil Flow on top of PSP** **PSP**

Saddle Points of Attachment and Separation





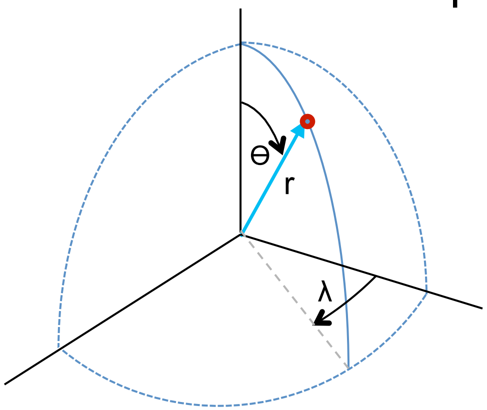




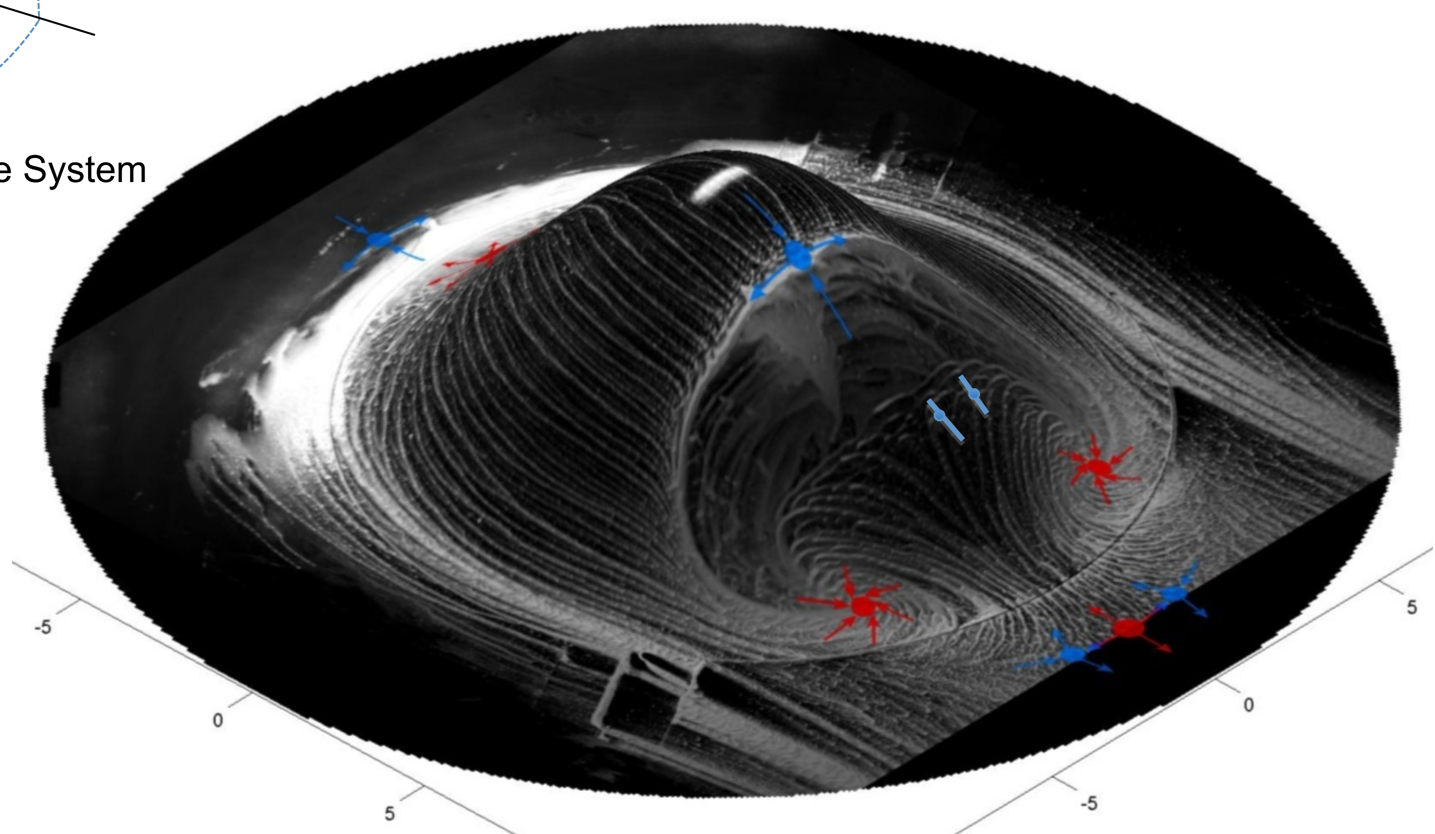
Similar to flow patterns noted in Coon and Tobak, "Experimental Study of Saddle Point of Attachment in Laminar Juncture Flow" AIAA J., Vol. 33, No. 12, pp 2288 – 2292, Dec 1995

Analysis of Surface Flow Topology

Need to employ spherical polar coordinate system (r, ϴ, λ)



Spherical Polar Coordinate System

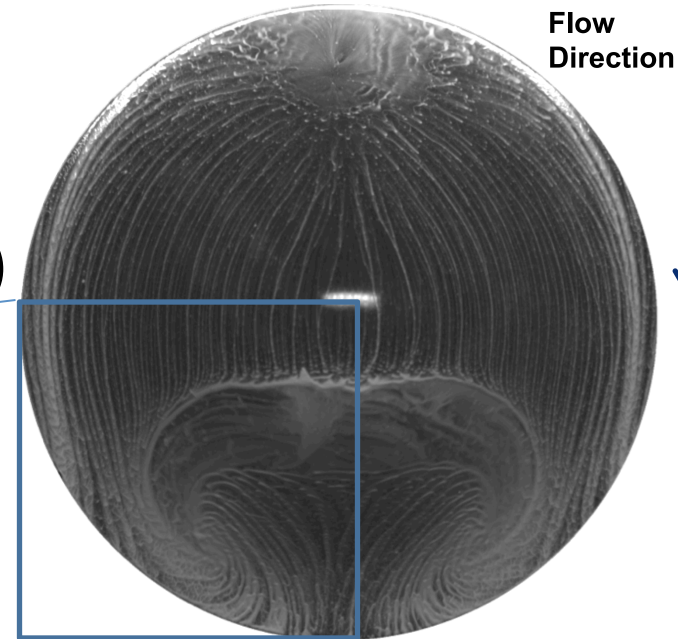


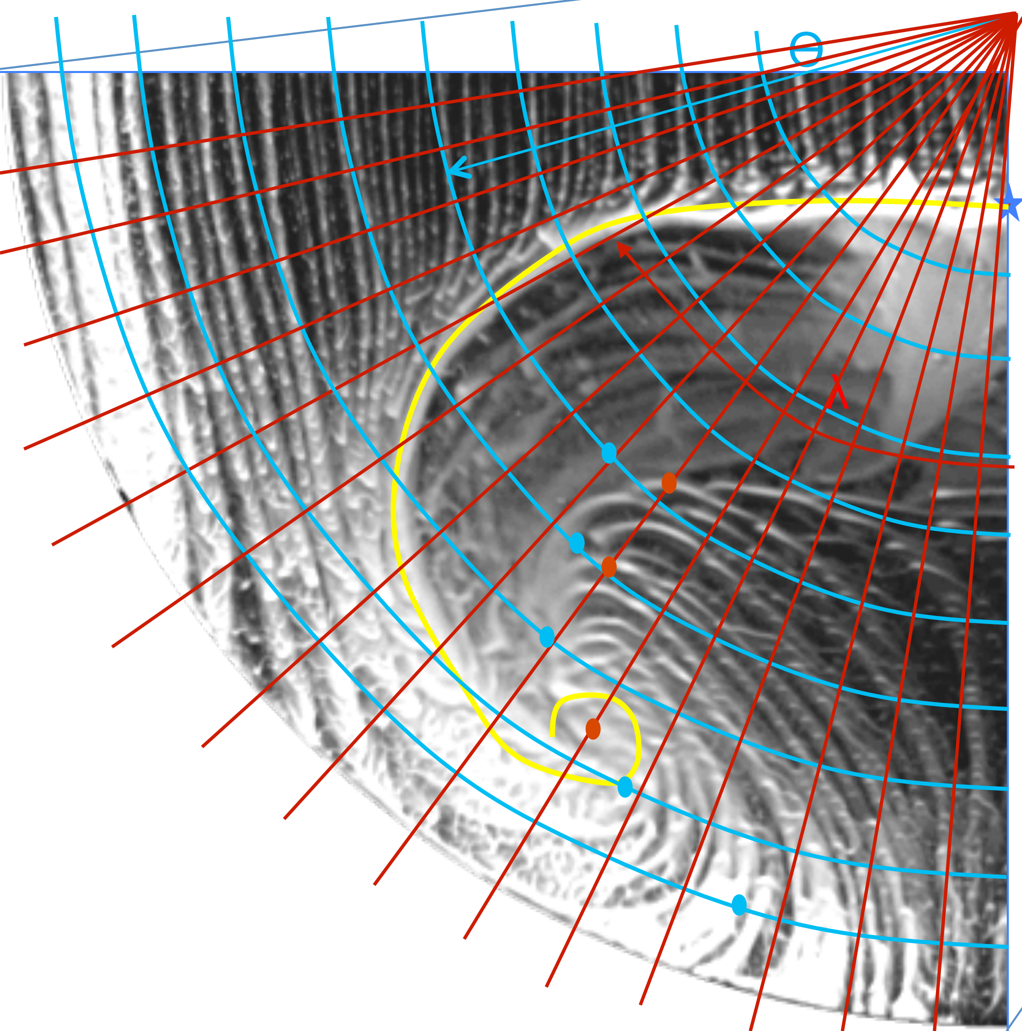
Skin Friction Line Analysis

Vorticity: vector, perp to SF lines everywhere

Momentum equations at wall:

$$\frac{1}{r}P_{\theta} = \frac{\mu}{r\sin\theta}\frac{\partial}{\partial r}\left(\omega_{\lambda} r\sin\theta\right) \qquad \frac{1}{r\sin\theta}P_{\lambda} = \frac{\mu}{r}\frac{\partial}{\partial r}\left(r\omega_{\theta}\right)$$





Graphical Determination of Pressure Extrema

1) Superimpose coordinate system (λ, ϴ, r) over skin friction line pattern

2) Determine locations of zero vorticity components:

a) Find the points where skin-friction lines cross coordinate curves θ = const orthogonally. ($\omega_\Theta = 0$)

b) Find the points where skin-friction lines cross coordinate curves λ = const orthogonally. ($\omega_\lambda = 0$)

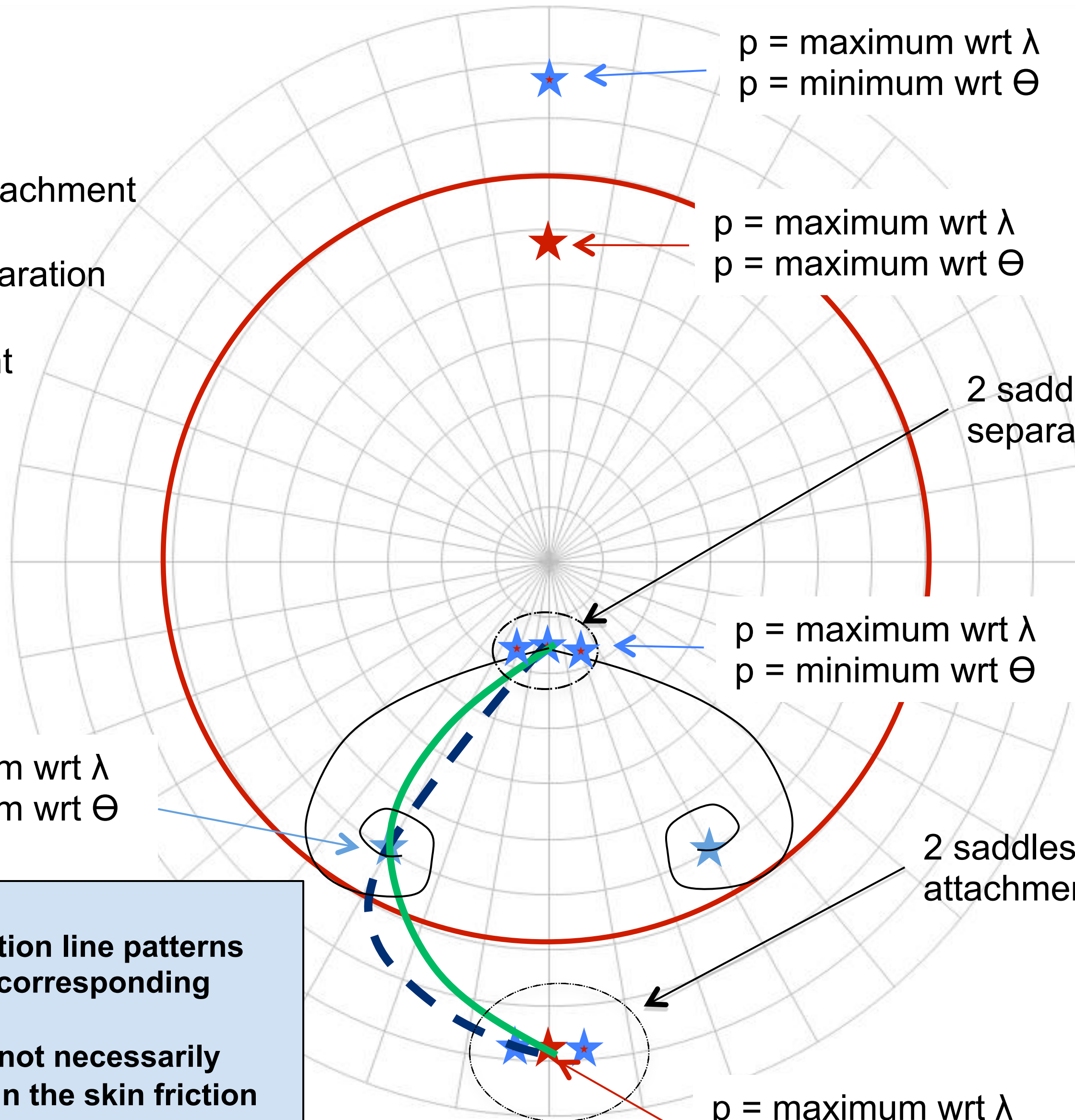
3) From momentum equation at wall, when $(\omega_\theta)_r = 0$, p_λ must also = 0. (surface-pressure extrema)

Connection between surface pressure extrema and skin-friction-line singular points

p = max/max => node of attachment

p = min/min => node of separation

p = min/max => saddle point



Main Results:
A) Singular points in the skin friction line patterns are necessarily accompanied by corresponding surface pressure extrema
B) Surface pressure extrema are not necessarily accompanied by singular points in the skin friction line patterns!

Summary and Ongoing Work

- **External Flow Mapping**
  - **FAITH and Hemisphere have identical topological structures**
  - **Can one external flow be mapped into the other?**
- **Critical Point - Extremum Similarity**
  - **Each singular point accompanied by surface-pressure extremum of the same type:**
    - **Node of attachment => surface pressure maximum**
    - **Node of separation => surface pressure minimum**
    - **Saddle point => surface pressure min/max**
- **Saddle Point Attachment or Separation**
  - **Not possible to identify the SP types without additional info. Experimentally:**
    - **If sufficient flow is diverted outward from SP >> saddle point of attachment.**
    - **If sufficient flow is diverted inward towards SP >> saddle point of separation.**
- **Grammar analog**
  - **A sentence can be grammatically correct but have no meaning**
  - **It is possible to mis-identify flow structures that are not physically realizable. Only realizable flow structures will contribute to topological understanding.**
  - **Can topological rules be extended to describe the evolution of topological structures, as governing parameters change? (Reynolds number, angle of attack, etc.)**

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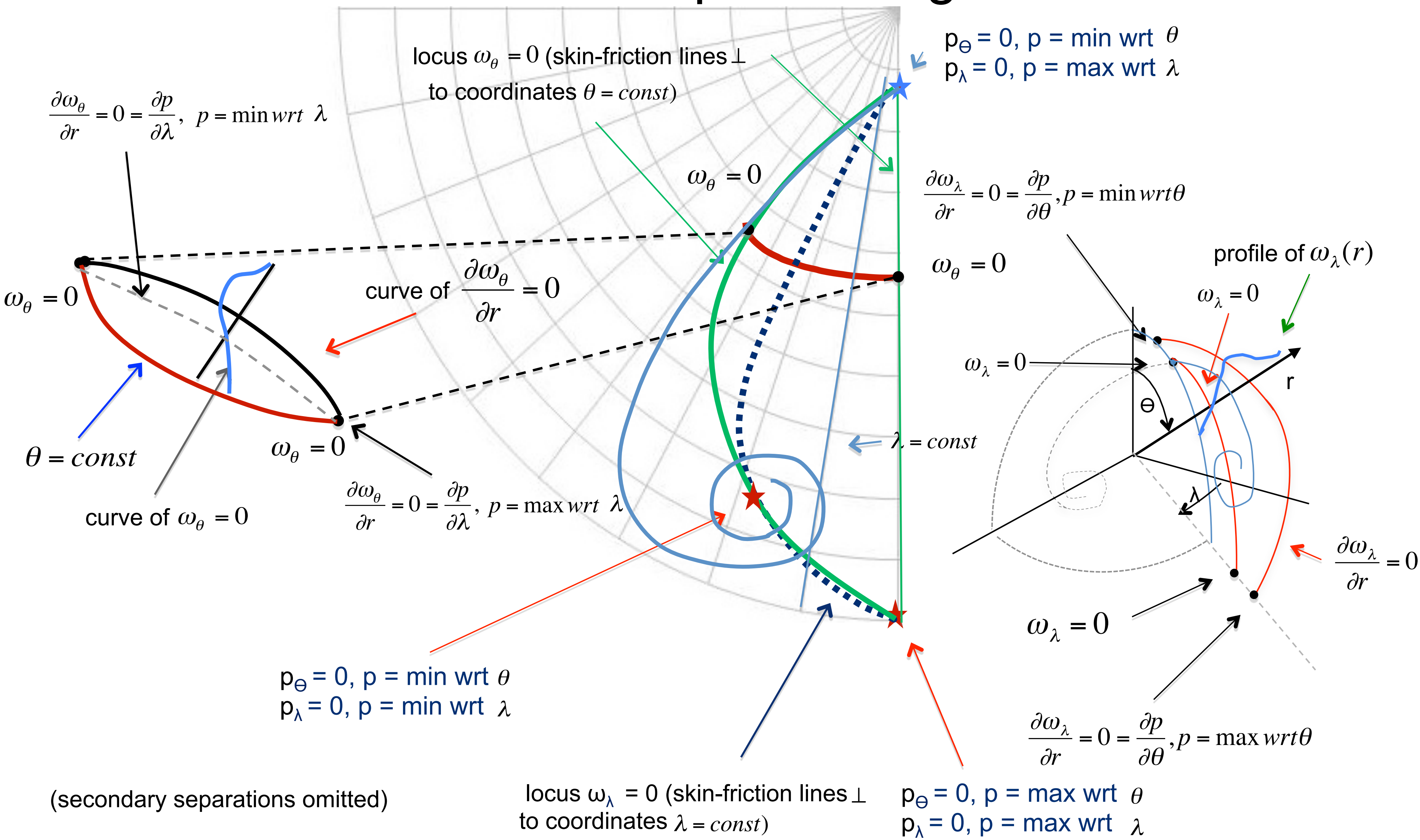
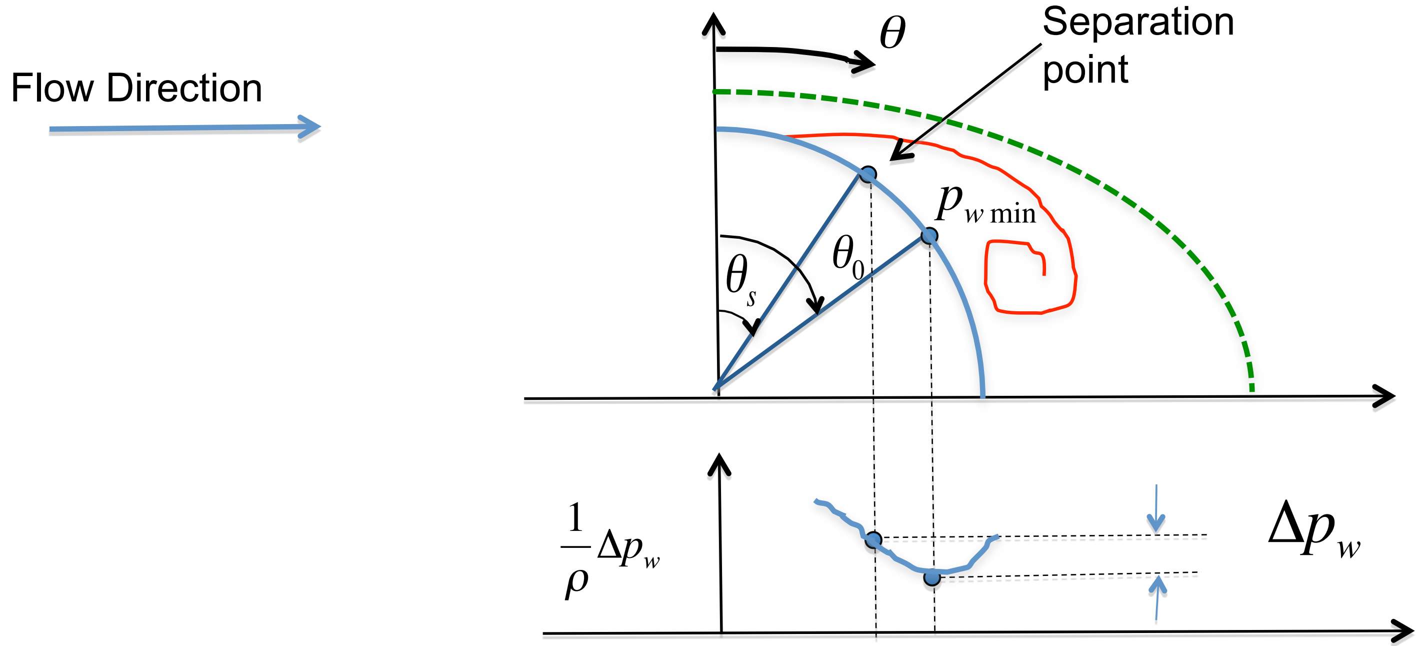
Loci of points on the surface where $\omega_\theta = 0, \omega_\lambda = 0$ and connection with wall pressure-gradient extrema



(secondary separations omitted)

Onset of Secondary Separation



$$\frac{1}{\rho}\Delta p_w\left(\frac{\partial}{\partial\theta}\left(\frac{p_w(\theta_s)}{\rho}\right)\right)^2 = C = \frac{1}{9}\left(\frac{\mu}{\rho}\right)^2(\omega_w(\theta_0))^4$$

(Topological derivation in cylindrical coordinates of counterpart of Stratford criterion)