AAE 538: Air-Breathing Propulsion

Lecture 17: Turbine Heat Transfer

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Turbine Heat Transfer

- In our discussion of engine cycles, we learned about two mechanisms to achieve increased engine performance:
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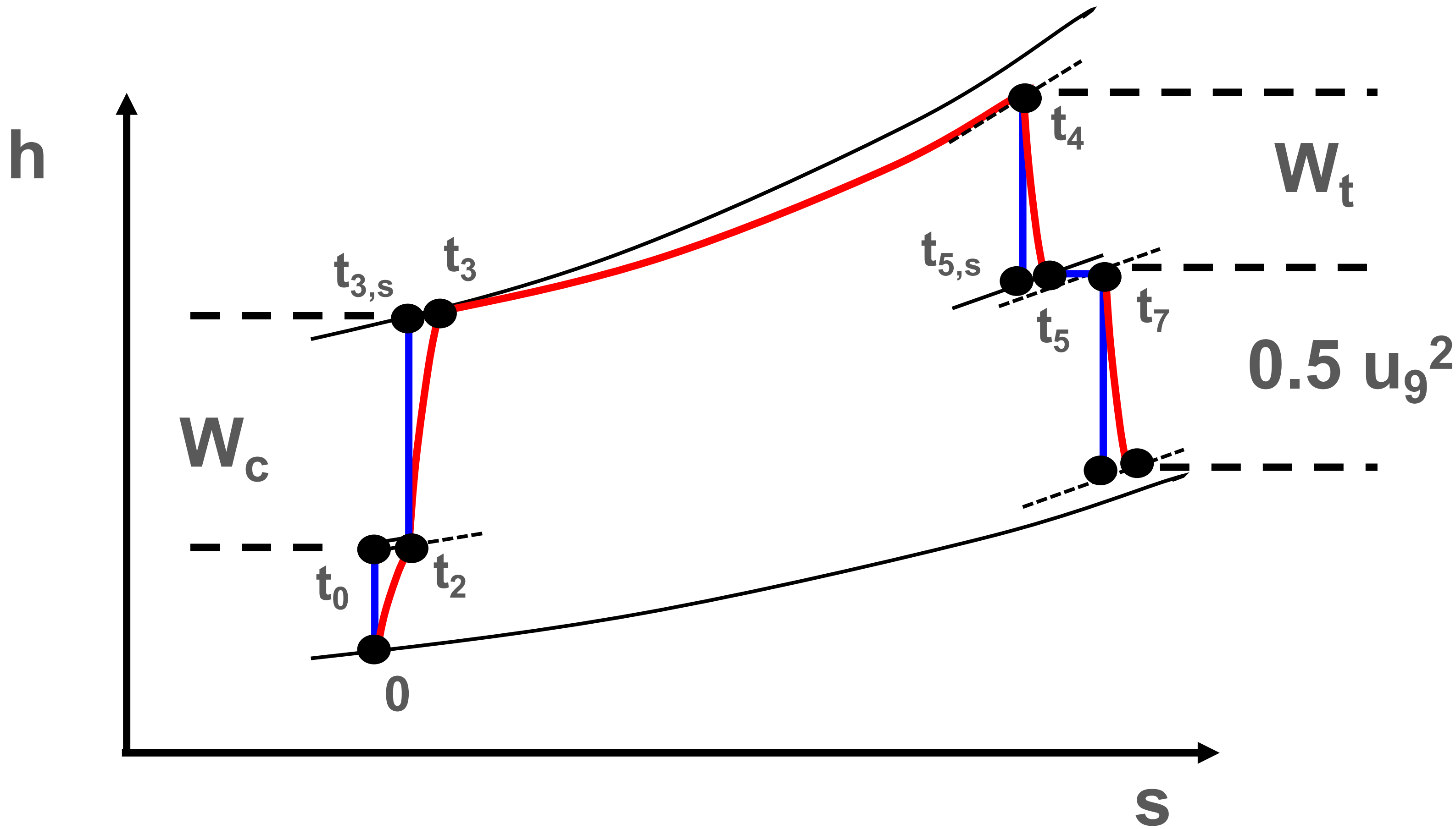
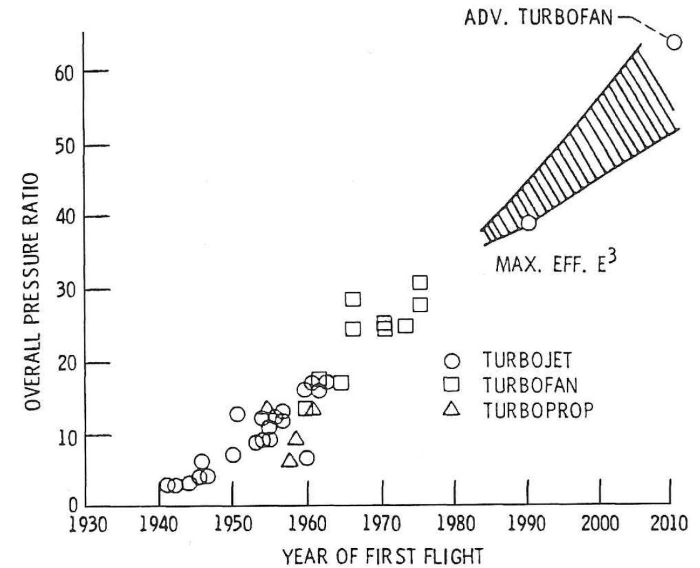
  -

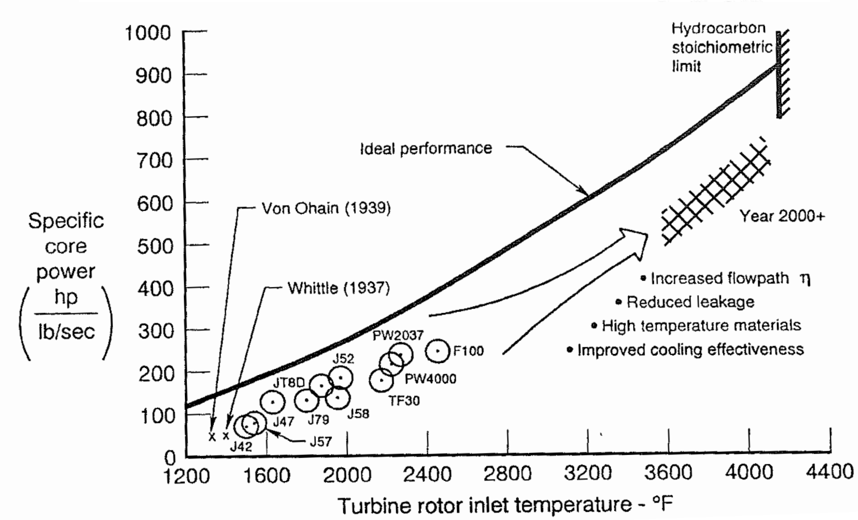


Turbine Heat Transfer

- If we can withstand high turbine inlet temperatures, we stand to gain
  - Increased Specific Thrust
  - Decreased Specific Fuel Consumption

- For this reason, turbine blade cooling has become standard in nearly all of the advanced engines in use today.
  - Increased $T_{o,4}$
  -

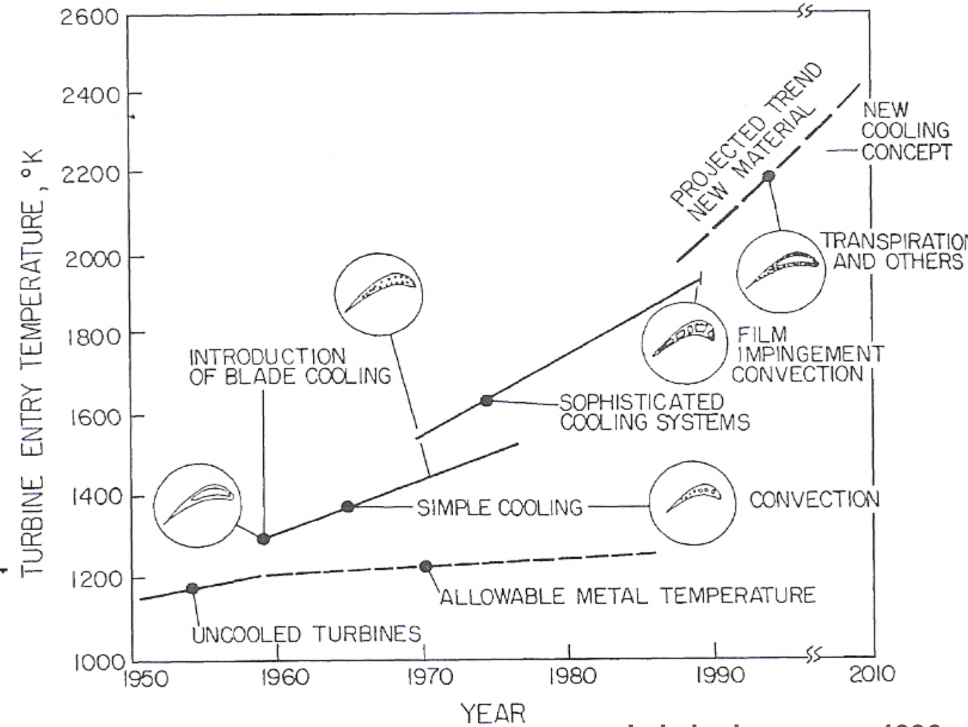




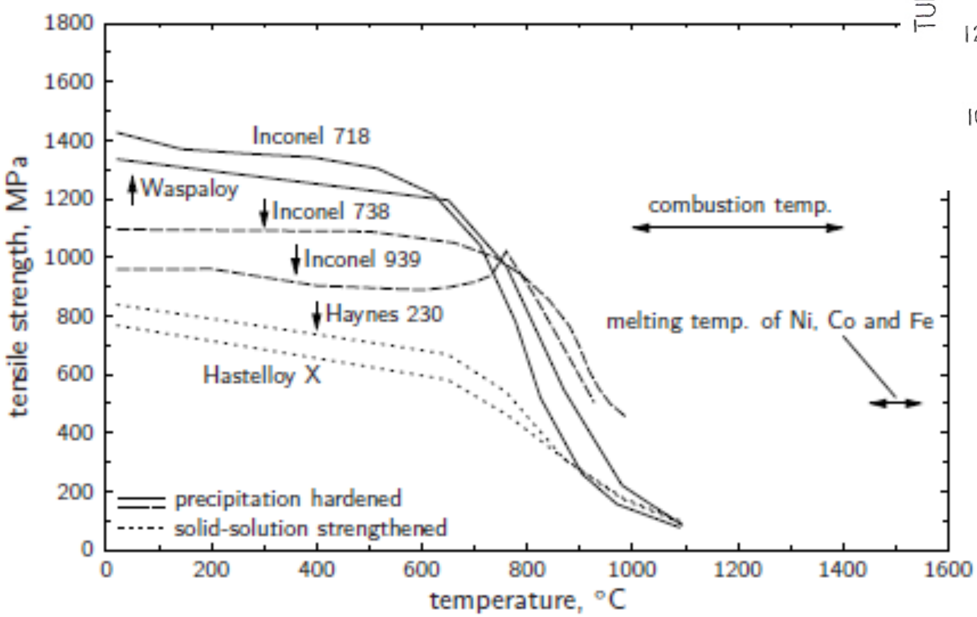
Courtesy of Pratt and Whitney and Sautner et al. (1992)

Turbine Heat Transfer

- Key parameters of cutting-edge engines
    - 1700°C Turbine Inlet Temperatures
    - 1000°C Hot Component Temperatures
    - 10^5 Hours of Component Life
    - 1.5– 2.0% Secondary Bleed



Lakshminarayana, 1996



The amount of heat to be removed … is enough to power 14 average American homes <u>per blade.</u>
Moustapha, et al. (2003)

Turbine Heat Transfer

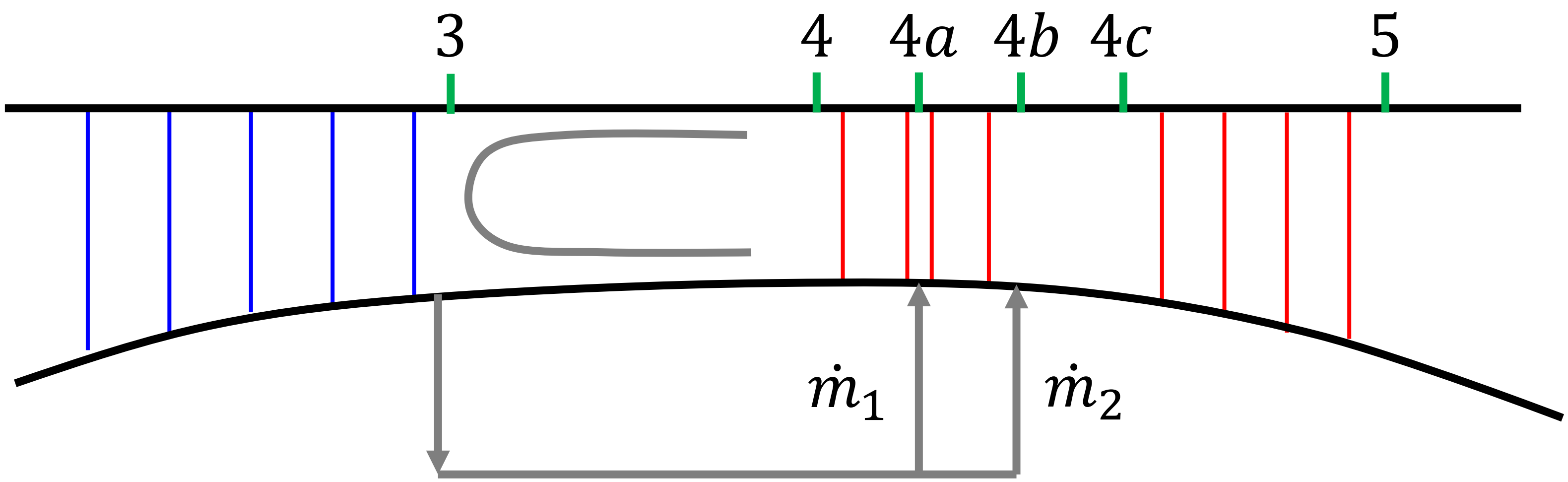
Modification to Cycle Analysis

- Another balance of tradeoffs in the design space;
  - With our present materials, higher turbine inlet temperatures can only be achieved with cooling.
  - The resulting penalties to machine efficiency can be substantial.
  - Component life and reliability are the actual variables in this trade-space

- We will consider a simple example to lay the framework for this extended analysis.

Turbine Heat Transfer

Modification to Cycle Analysis



- We now need define (or re-define) some new terms to account for the mass-flow rate split through these secondary flow systems:

Turbine Heat Transfer

Modification to Cycle Analysis

- We also now define the ratios representing the stagnation condition changes for each process, where we continue to assume that the gas downstream of the combustor is calorically-perfect with constant properties: γ_t, $c_{p,t}$, etc.

- From here, routine (but tedious) application of the power balance between the compressor, fan, and turbine (now in two stages) still holds. However, there is now a modification to the mass-flow ratios and the stagnation temperature change across the burner-turbine, such that:

Turbine Heat Transfer

Modification to Cycle Analysis

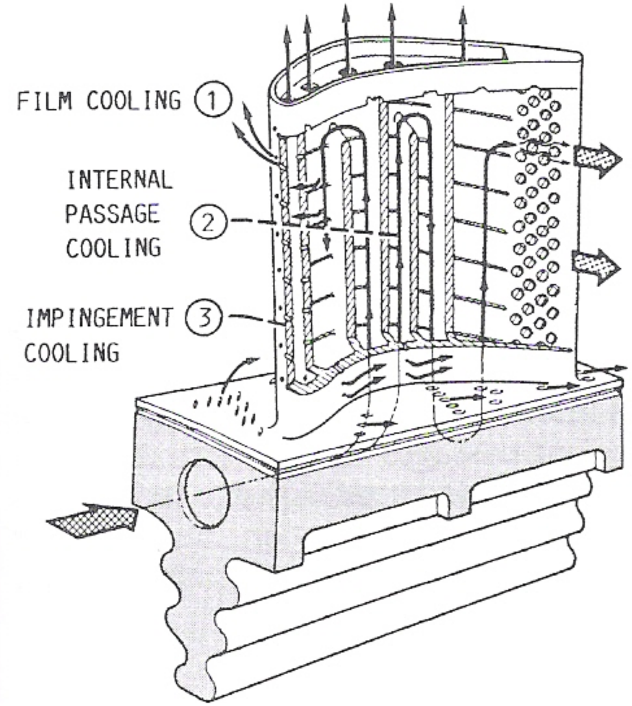
- As you will see in your homework, engine performance is very sensitive to the required amount of cooling air
  - Mixing Losses (entropy generation)
  -

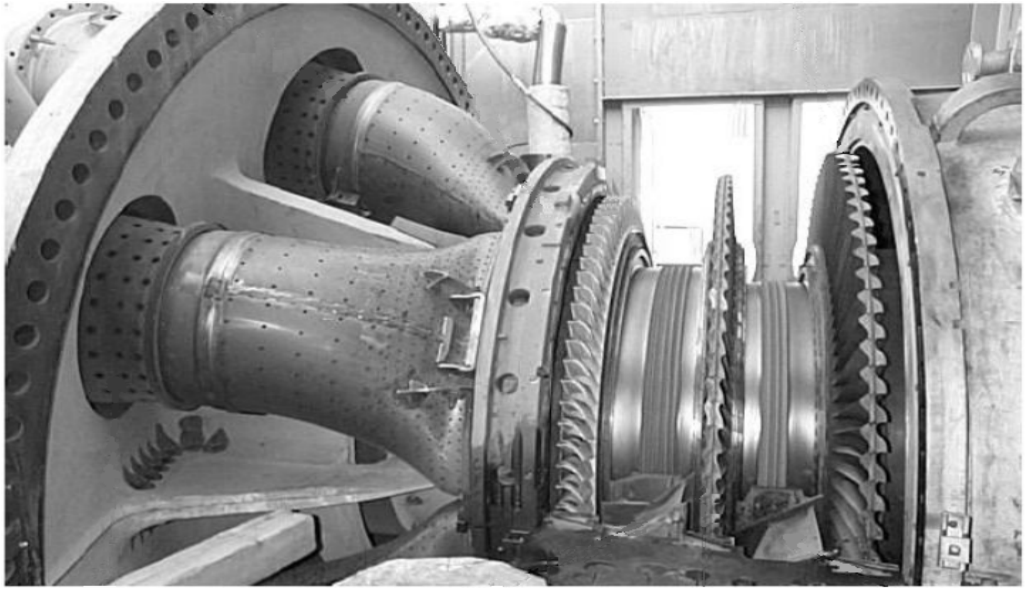
- Remains a big area of research, with two primary modes of cooling as the focus
  - Internal (channel) cooling
  - External (film) cooling

Turbine Heat Transfer

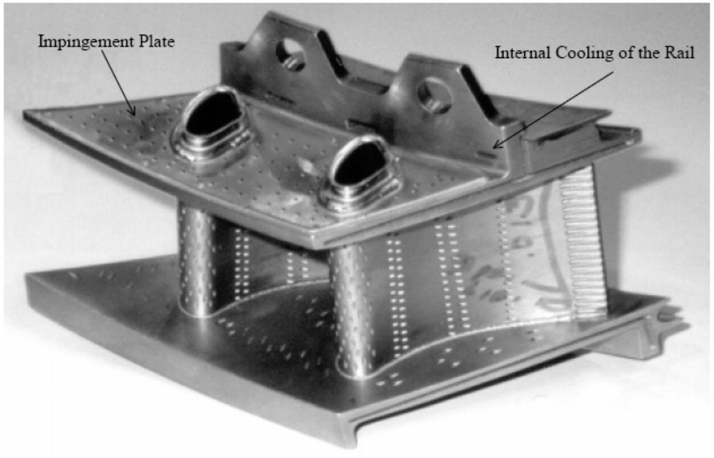
Hot Section Component Cooling

- Optimization of cooling system performance promotes gains and minimizes loss.
    - Component life (+)
    - Performance (+)
    - Efficiency (-)





Sultanian, 2009

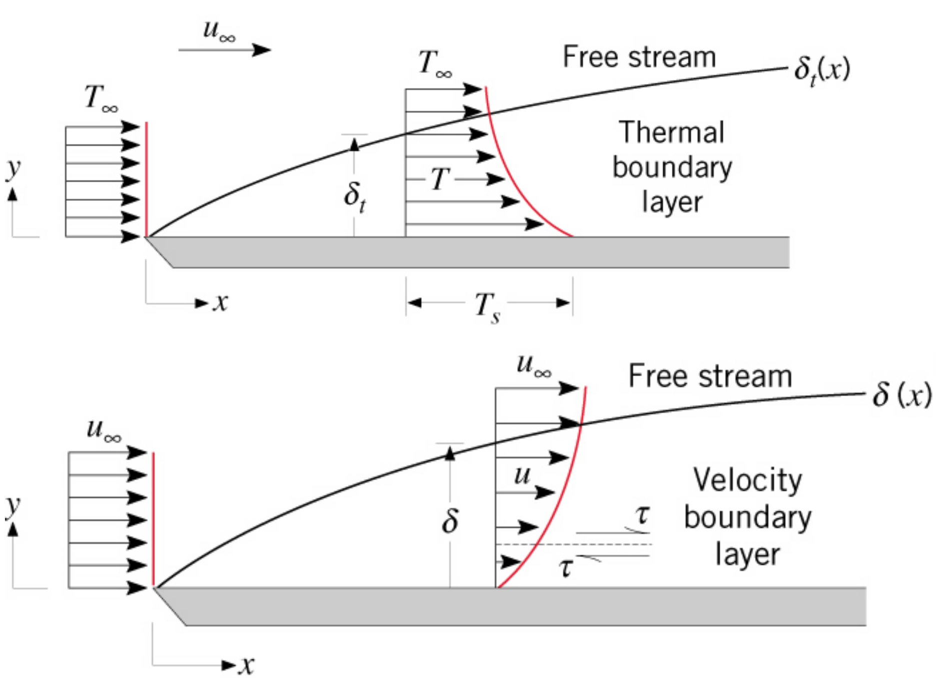


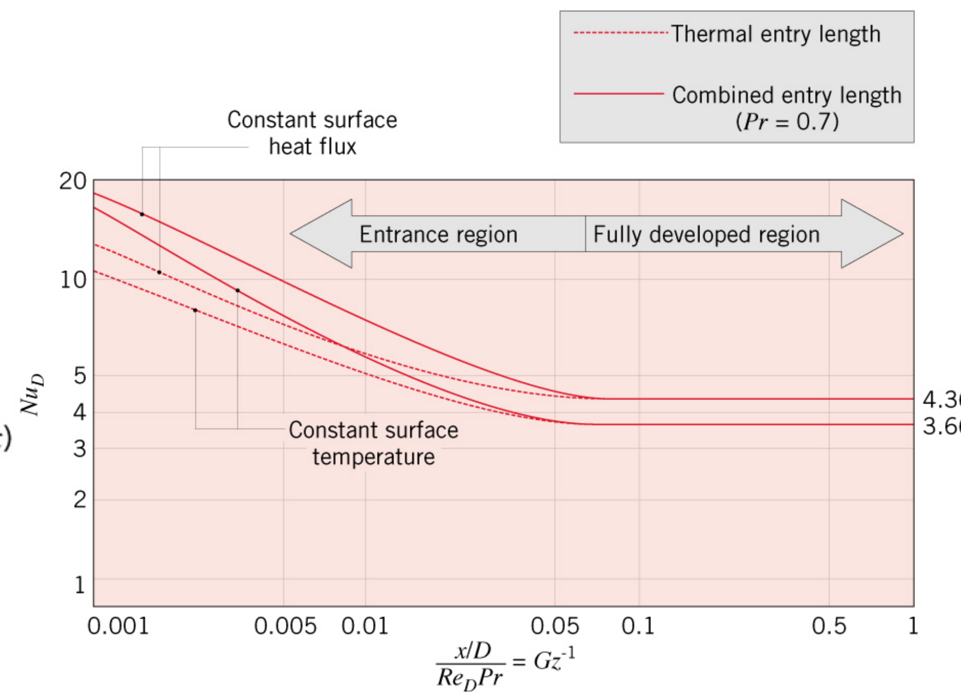
Internal Cooling

Heat Transfer Augmentation

- Boundary layer development inhibits transport (exchange) of energy between the fluid and the wall
- Once fully-developed the heat transfer coefficient ____________________ for the length of the duct.

- The ____________________ characterizes the enhancement of heat transfer as a result of advection, where

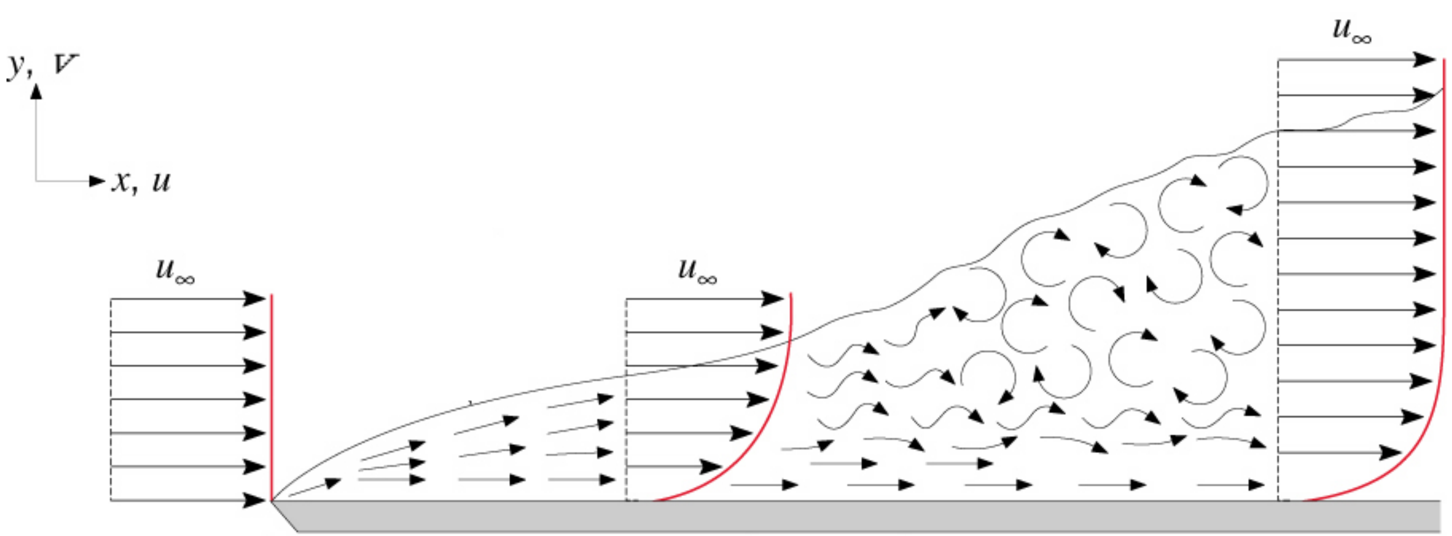




Internal Cooling

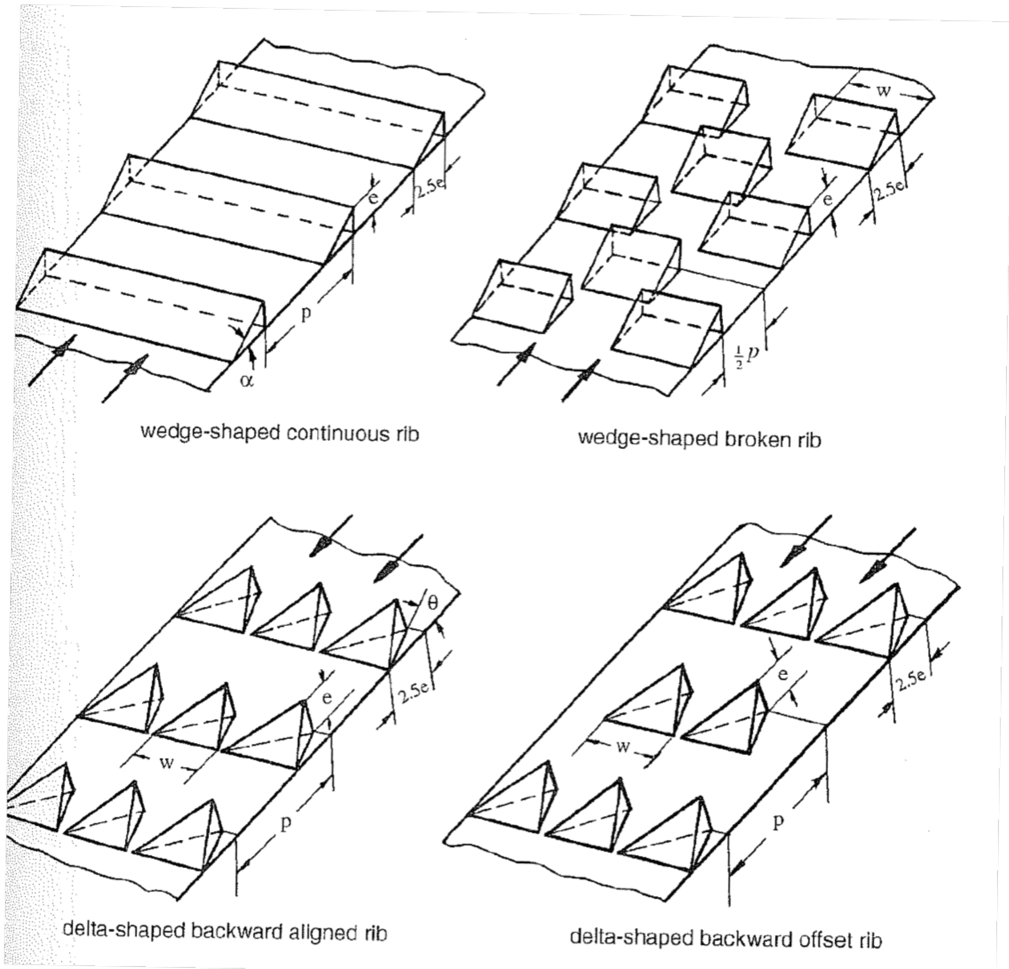
Heat Transfer Augmentation

- Disruption of the boundary layer, specifically the viscous (laminar) sub-layer provides enhancement of heat transport from the surface to the fluid by carrying the warm fluid to the channel core and ____.
- The price paid is in _______________, which is characterized by a friction factor.



Internal Cooling

Heat Transfer Augmentation



wedge-shaped continuous rib

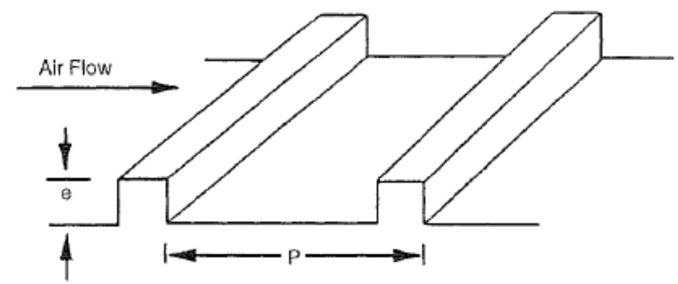
wedge-shaped broken rib

delta-shaped backward aligned rib

delta-shaped backward offset rib

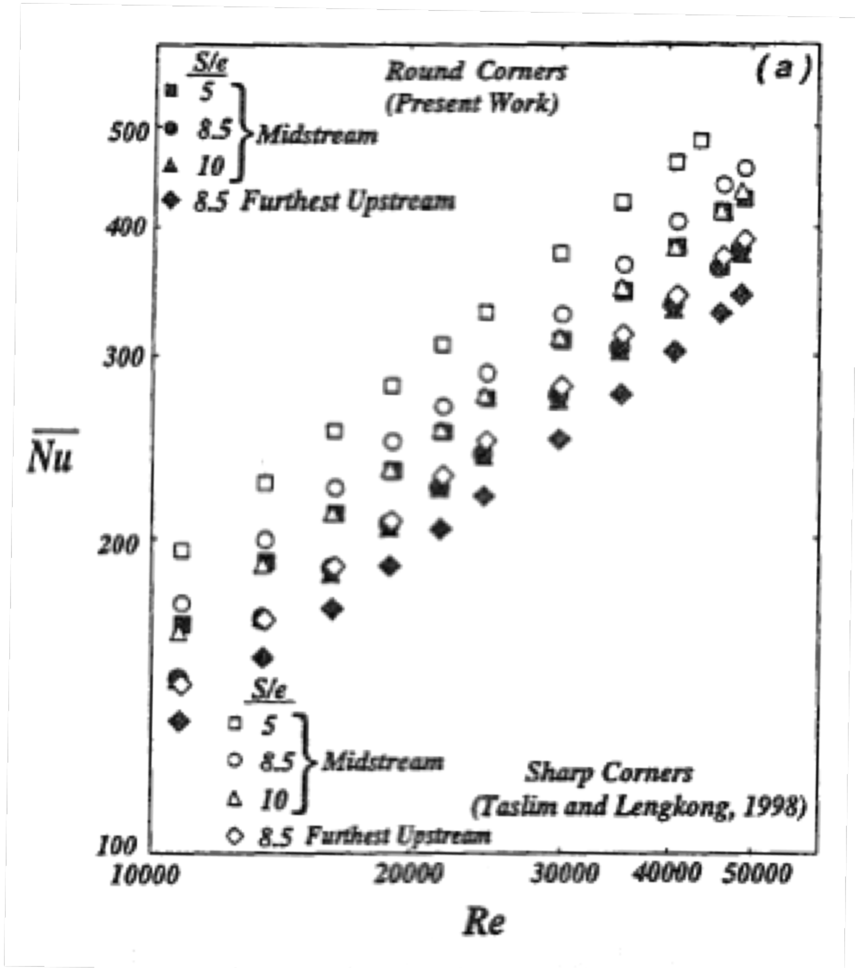
Han et al. (1993)

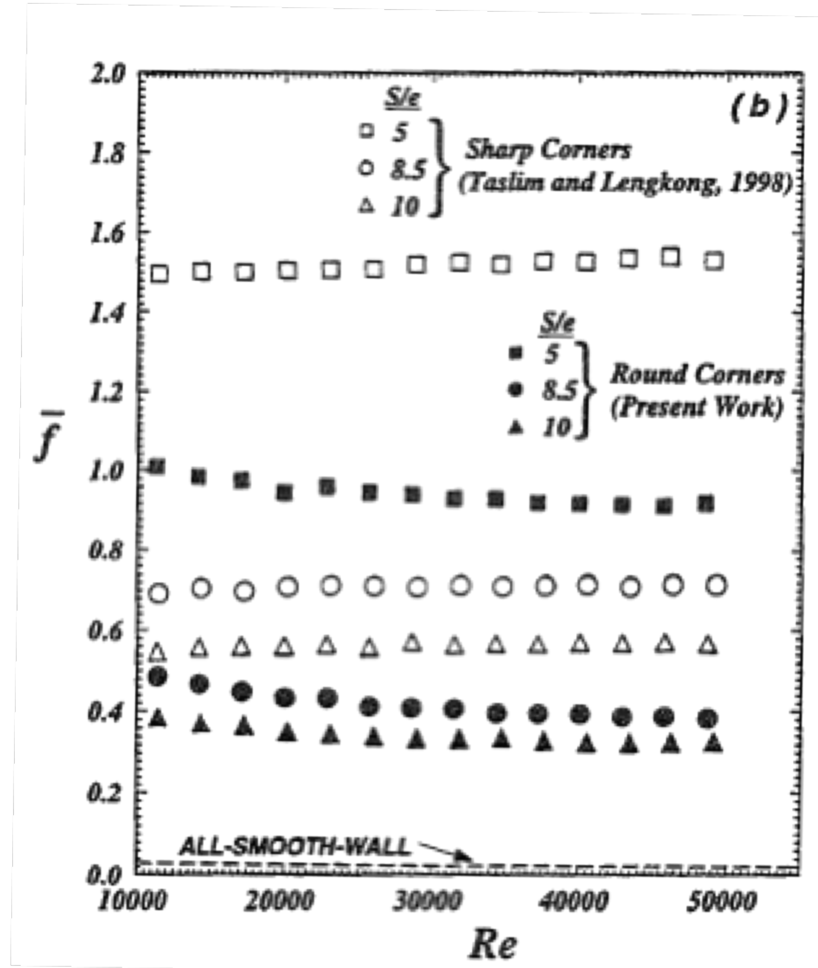
- The addition of turbulence generating features serves to enhance turbulent mixing within the channel and forces the boundary layer to restart.



Internal Cooling

Heat Transfer Augmentation

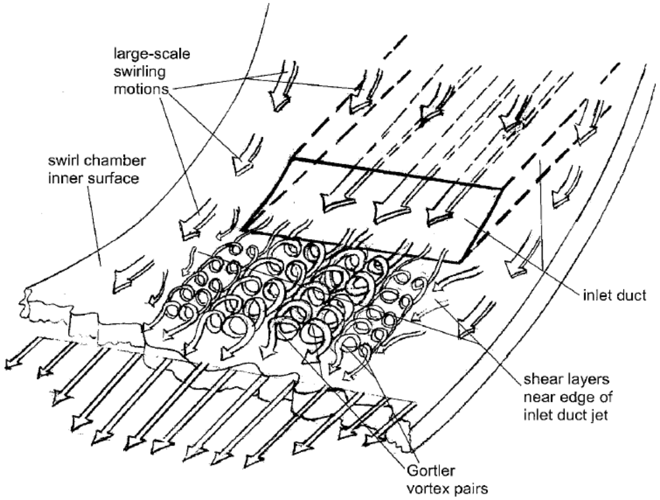




Heat transfer and friction augmentation as a function of rib pitch (Taslim and Lengkong, 1998)

Internal Cooling

Heat Transfer Augmentation



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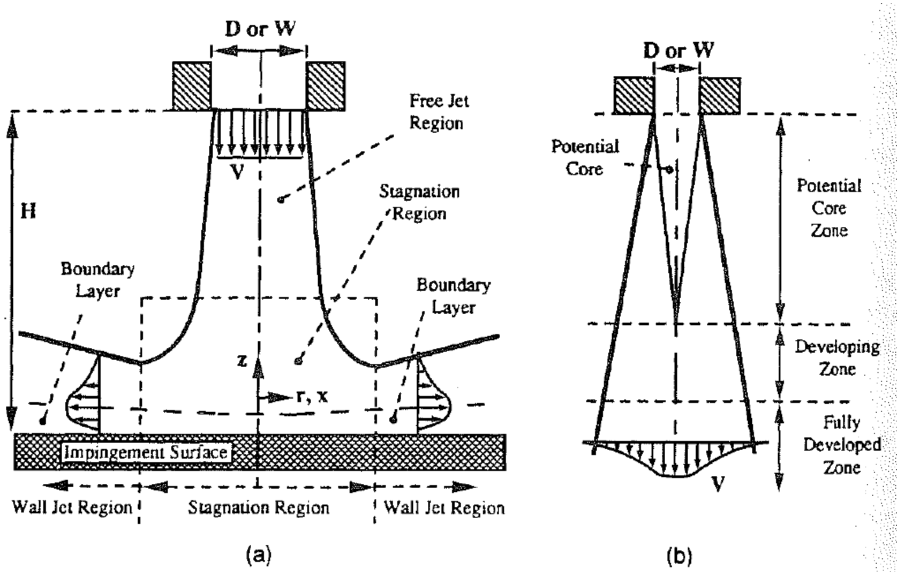
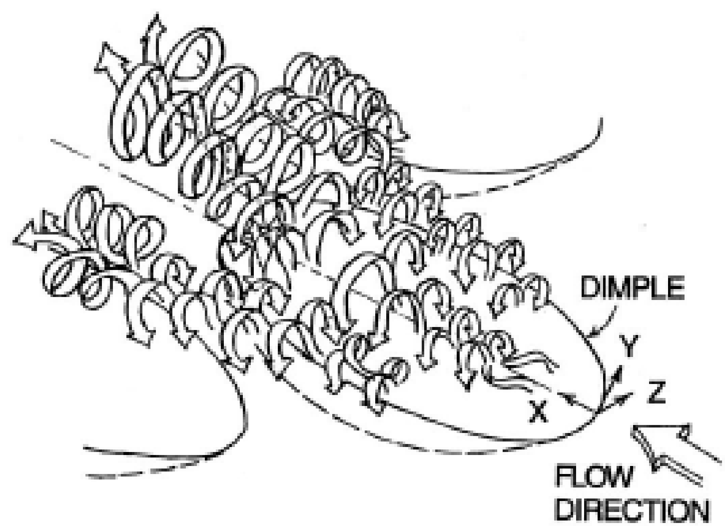
- ______________________________ and ______________________________ have been found to present similar heat transfer augmentation characteristics with low pressure drop penalties.

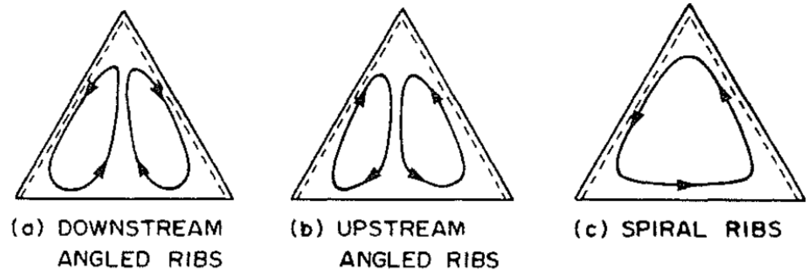


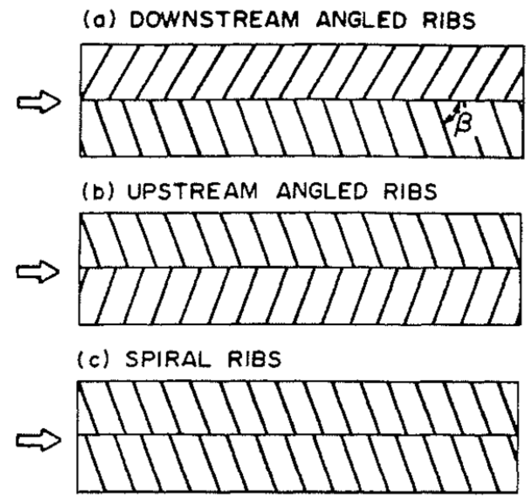


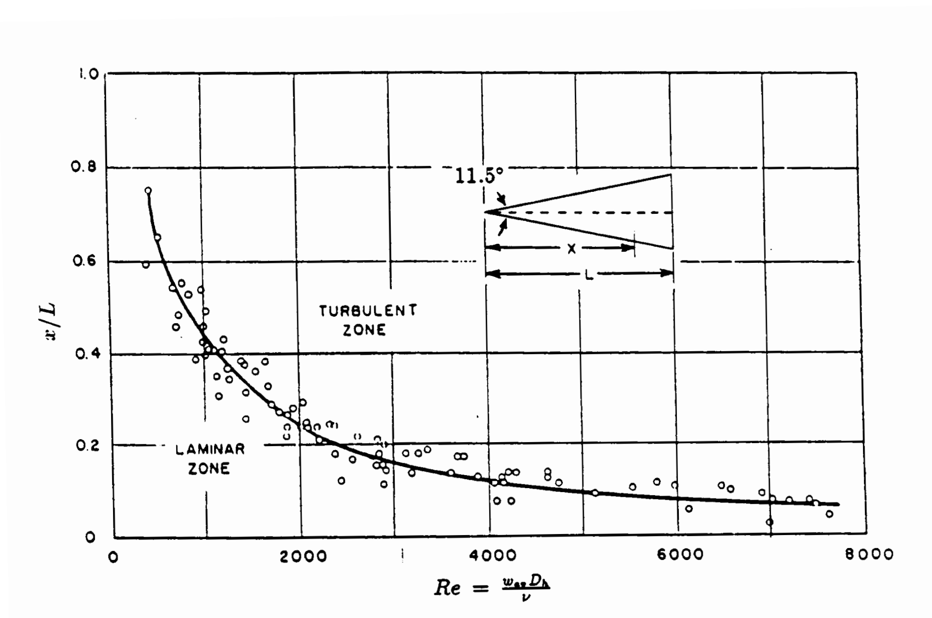
Internal Cooling

Heat Transfer Augmentation

- The trailing edge of the blade/vane presents a challenging region to effectively cool.







Rib angle tuning to induce large-scale secondary flows of different spatial structure (above). Reynolds number vs base-height of triangular duct (left)

Internal Cooling

Heat Transfer Augmentation

- Pin fins provide an ideal solution in the trailing edge.
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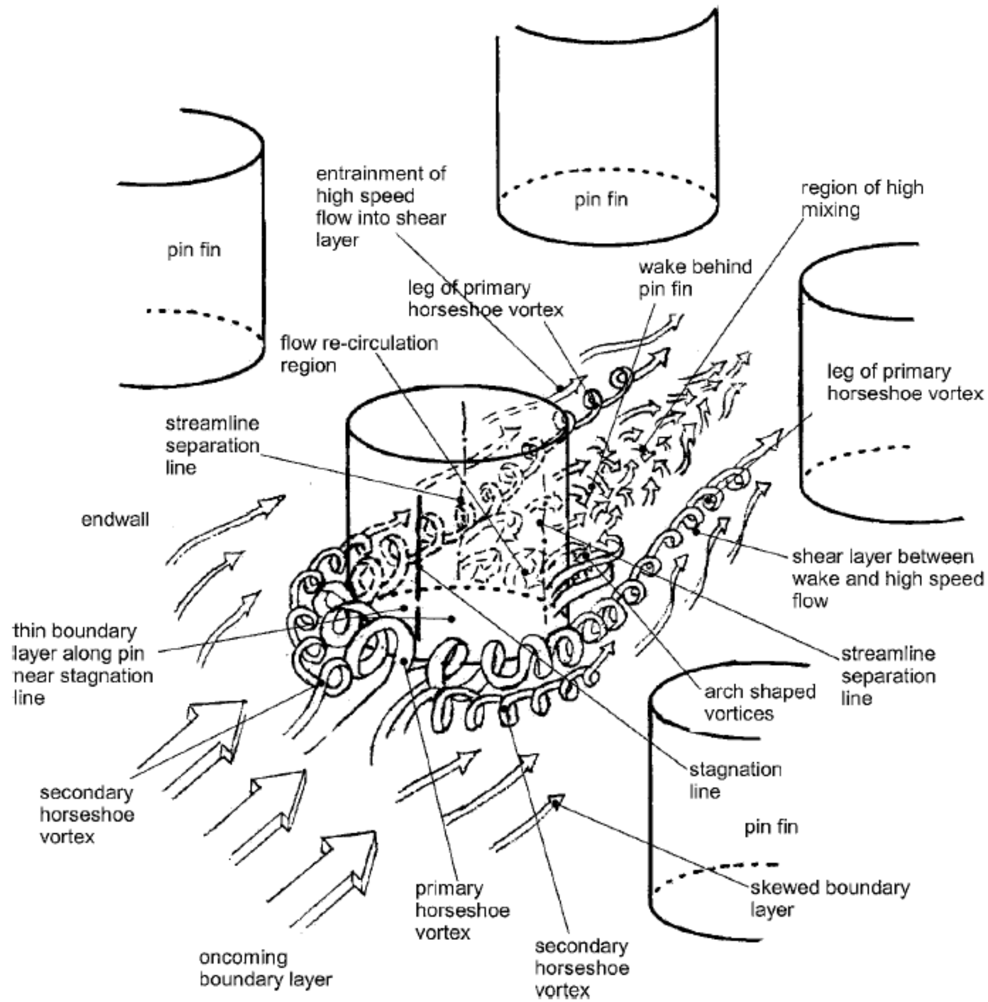
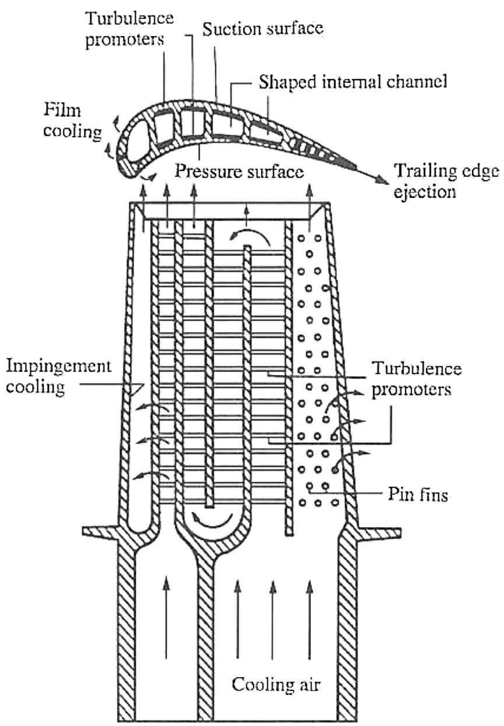
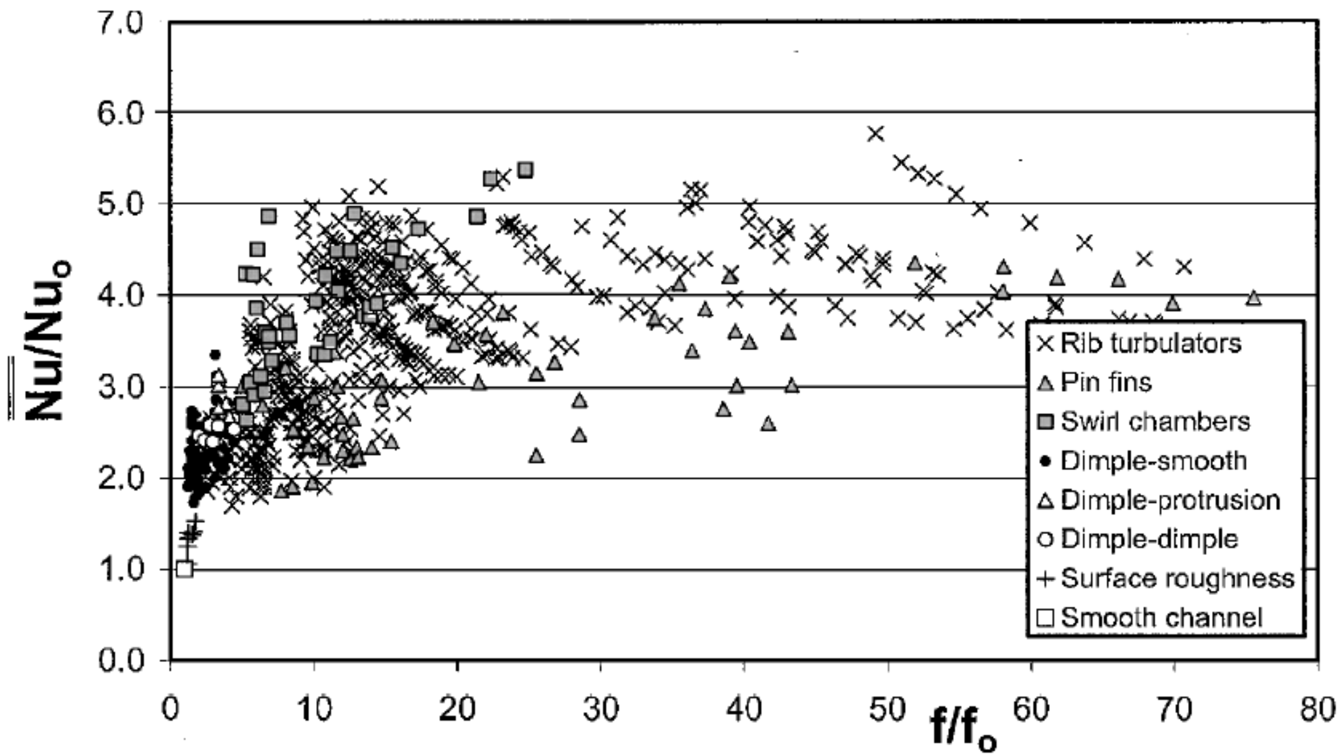
    -
    -
    -
    -



Internal Cooling

Heat Transfer Augmentation

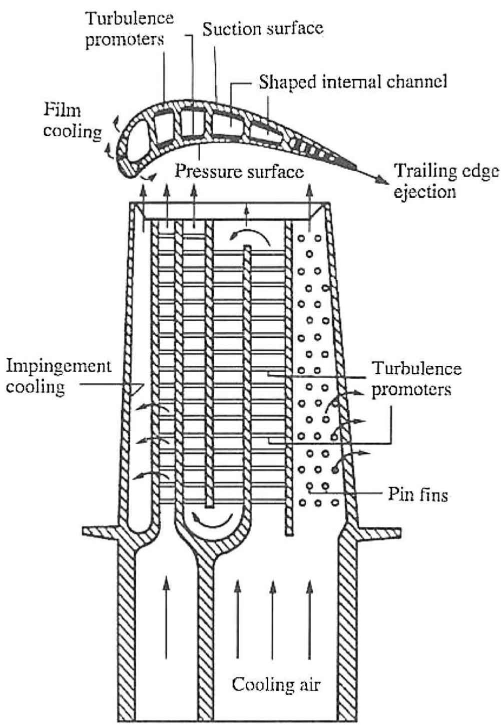


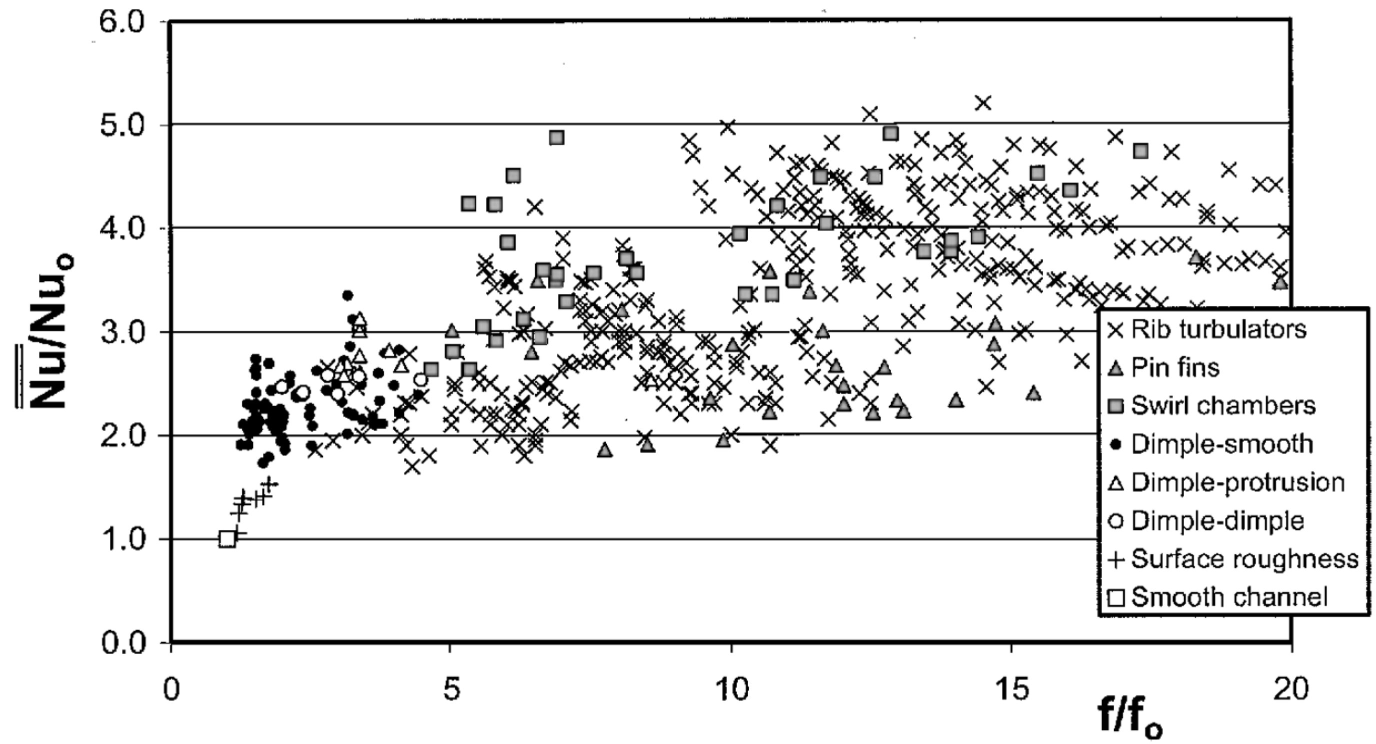


- Friction augmentation computed relative to the predicted value for a turbulent flow in a smooth pipe from the Blasius solution: $f_o = 0.316\, Re^{-0.25}$
- Similarly, the baseline Nusselt number was computed for a smooth pipe flow from the Dittus-Boelter correlation: $Nu_o = 0.023\, Re_D^{0.8} Pr^{0.4}$

Internal Cooling

Heat Transfer Augmentation





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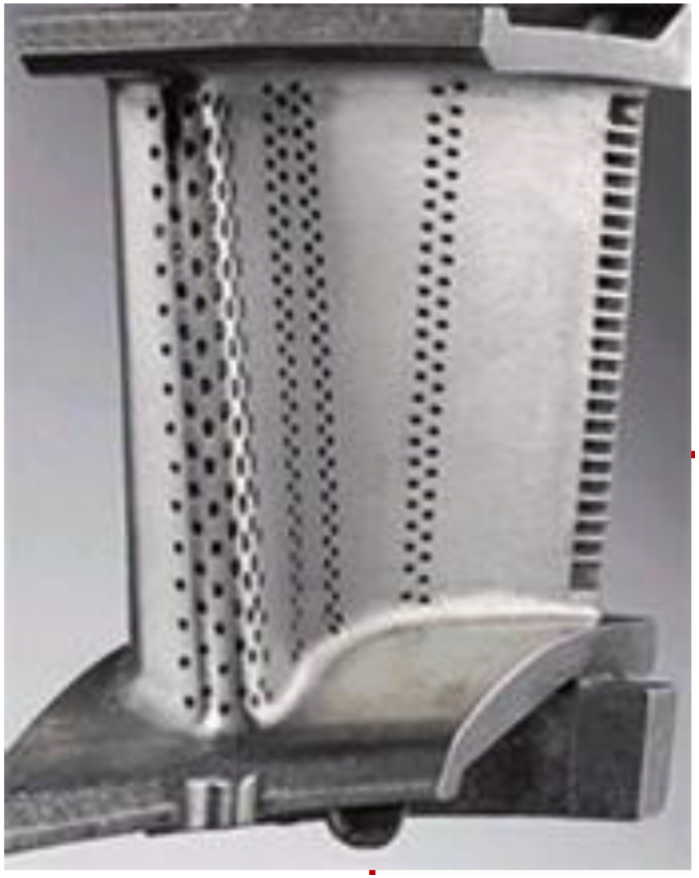
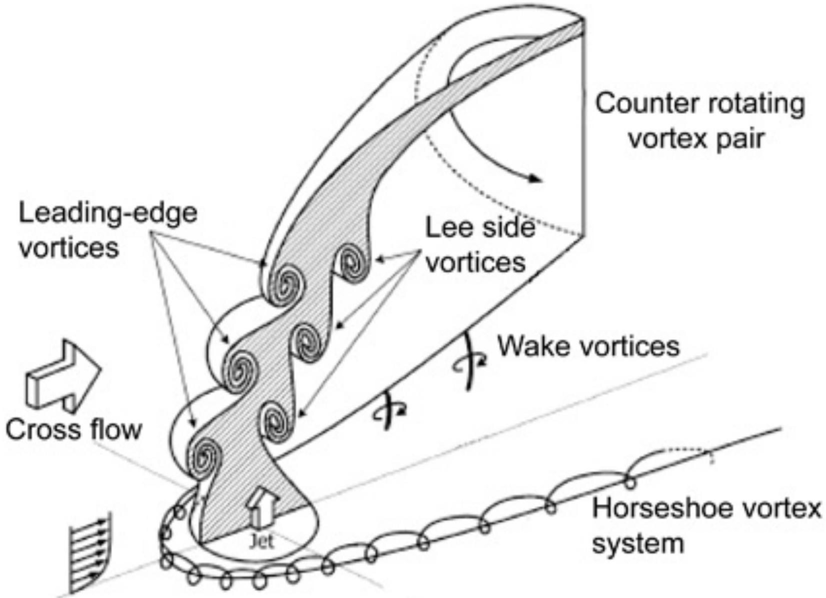
(External) Film Cooling

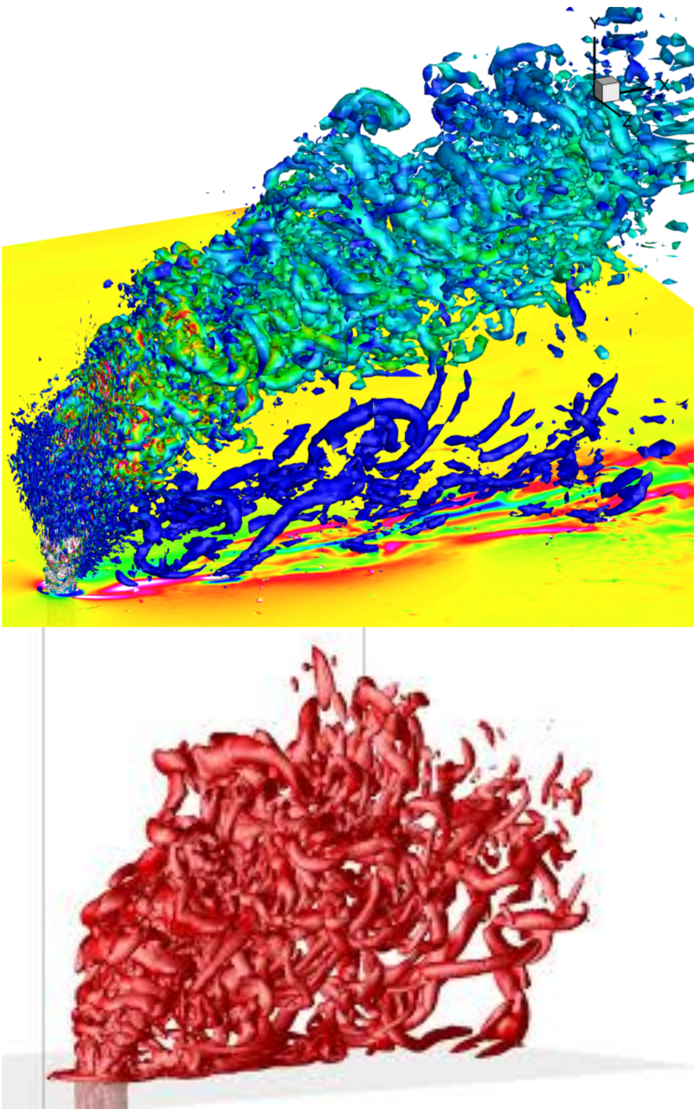
- External protection of the turbine blades is accomplished with an array of holes on the surface through which cooling air is injected from an internal manifold.
  - The coolant flow is supplied from the compressor and, thus, it is 'expensive'
  - Injection leads to a loss in p_o
- The flow structure of the film is a cold jet issuing into a hot cross-flow





Typical film-cooled airfoil design with injection holes on the air-foil surface (above). Schematic illustration of Jet-In-Cross-Flow (JICF) flow structure (left).

Film Cooling



JICF with high J (above) and low J (below)

- The jet in cross-flow is a well-characterized canonical flow, with high-fidelity data and many empirical correlations to predict centerline jet trajectories, entrainment rates, etc. as a function of:
  - Mass flux ratio (blowing ratio):
  - Momentum flux ratio:
- The global impact of the film cooling is characterized by the _______________:

Film Cooling

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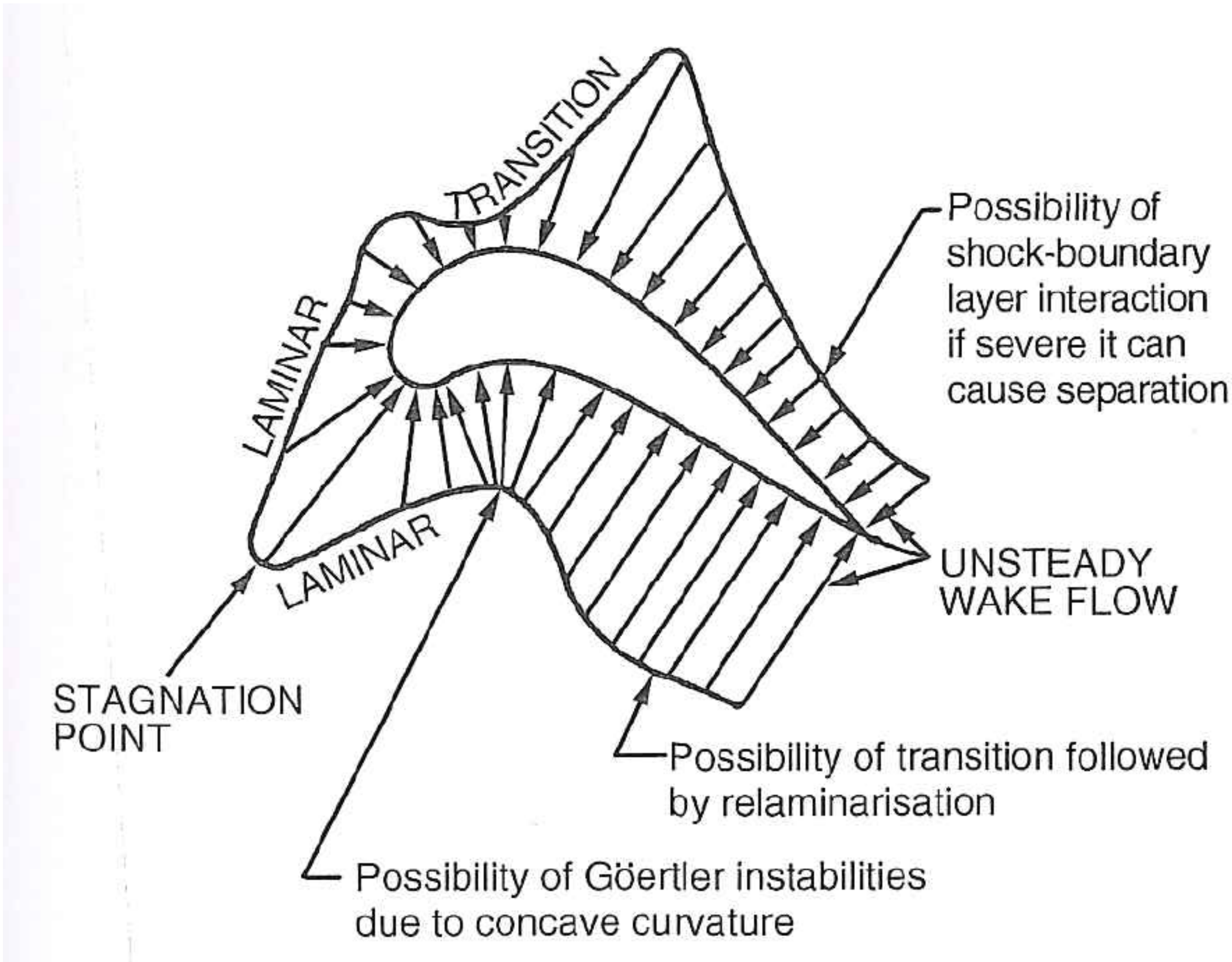

Shih and Sultanian, "Chapter 5: Computations of Internal and Film Cooling," in <u>Heat Transfer in Gas Turbines</u>, 2001.

Film Cooling

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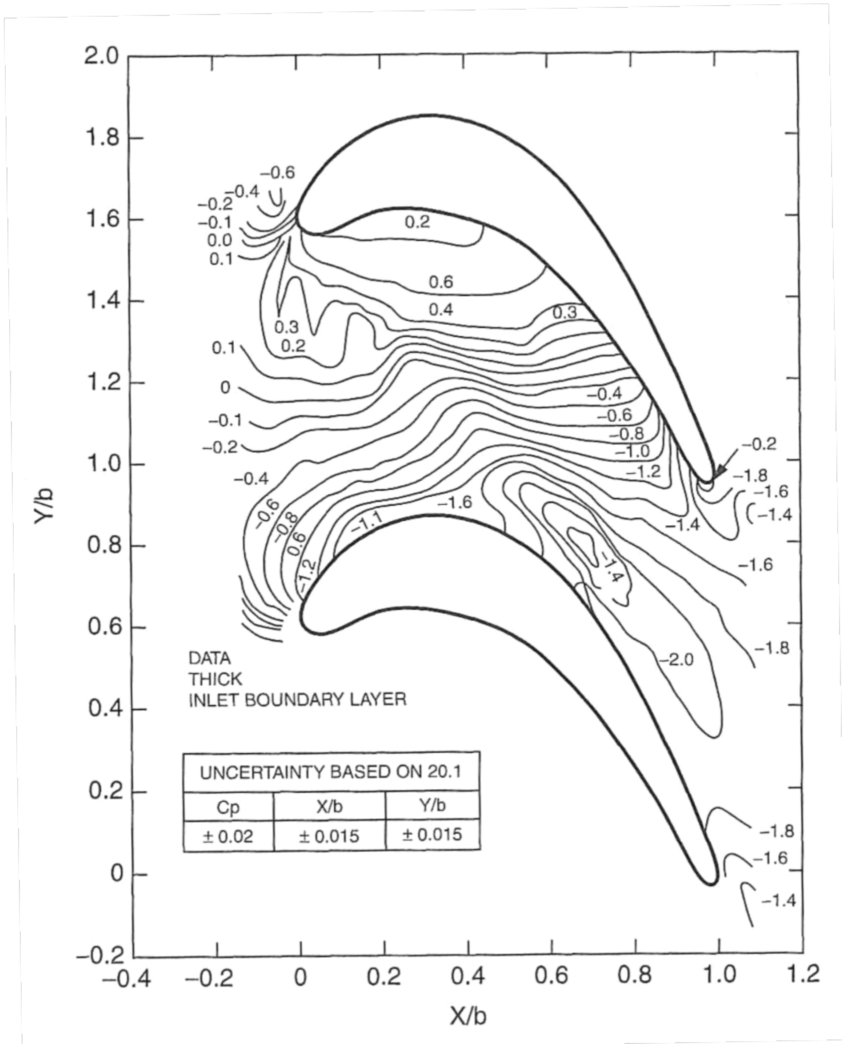
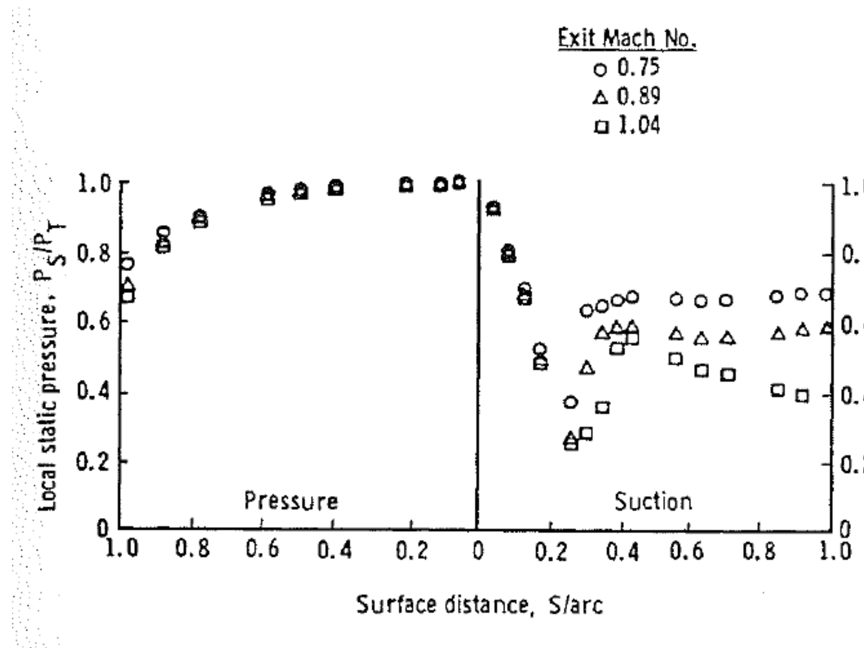


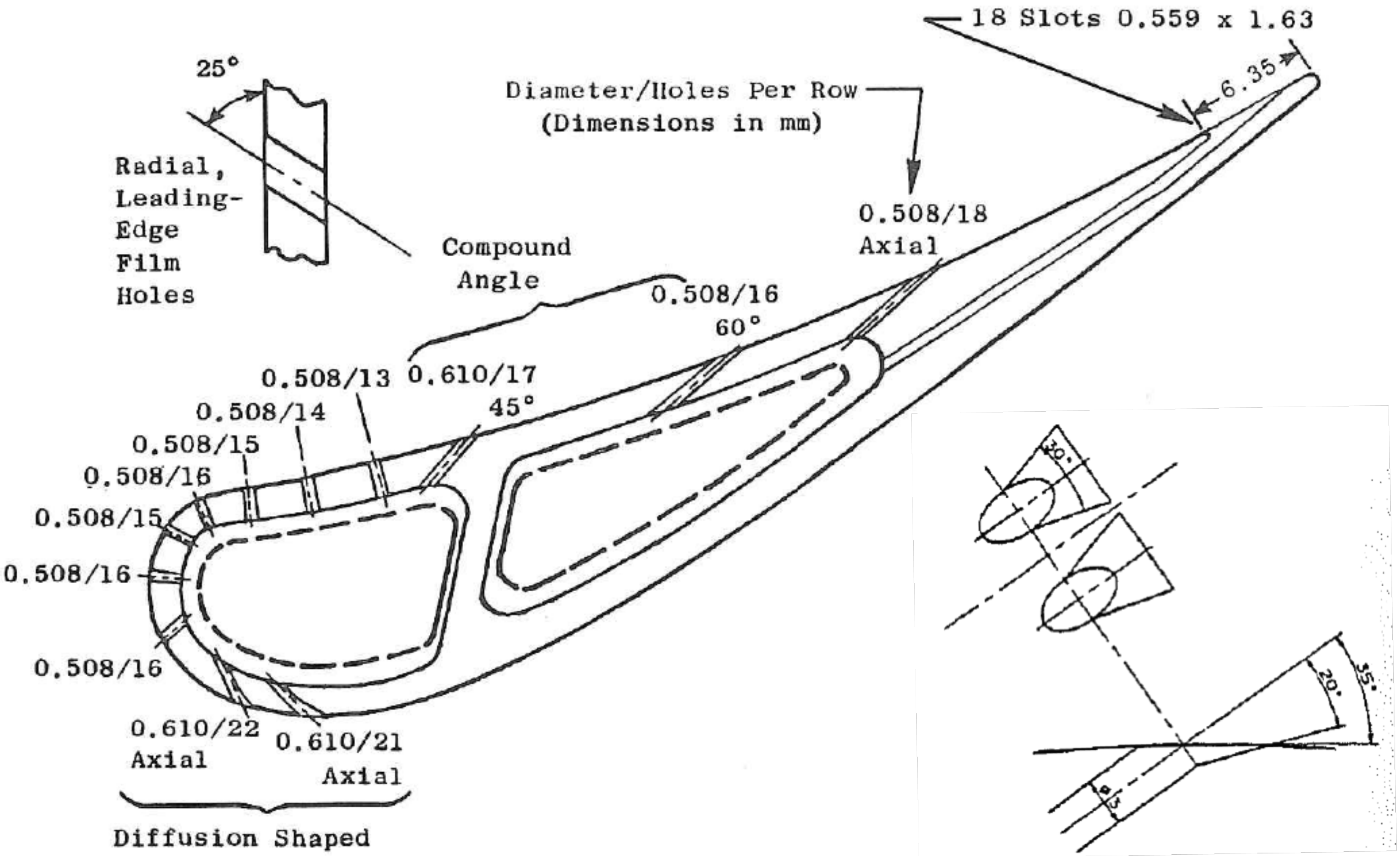
- Variation in wall static pressure throughout the cascade passage leads to large changes in the blowing ratio and momentum flux ratio
    -



End-Wall (Left) and Blade Surface (Right) Static Pressure Contours (Graziani et al., 1990)

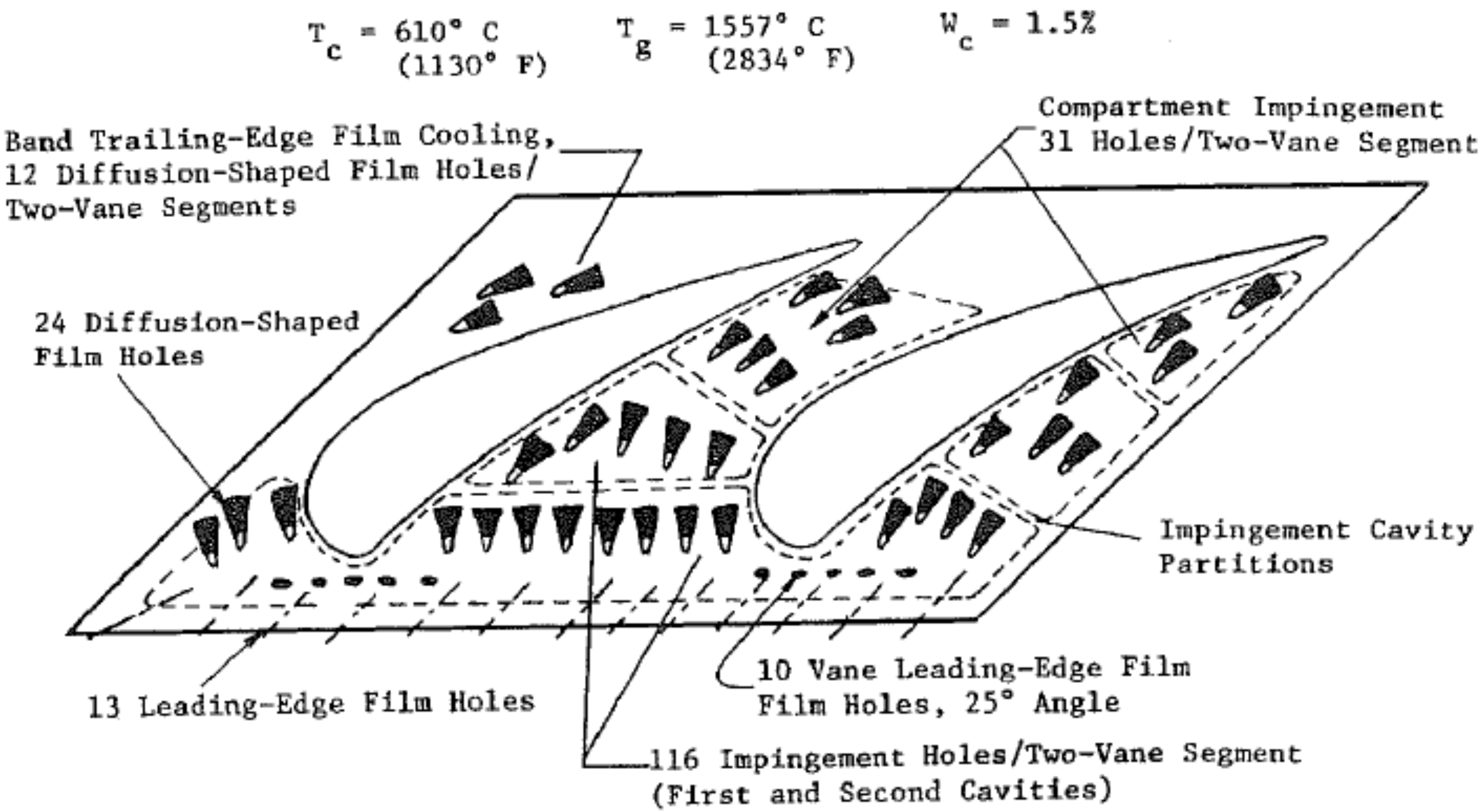
Film Cooling

Detailed Vane Cooling Design



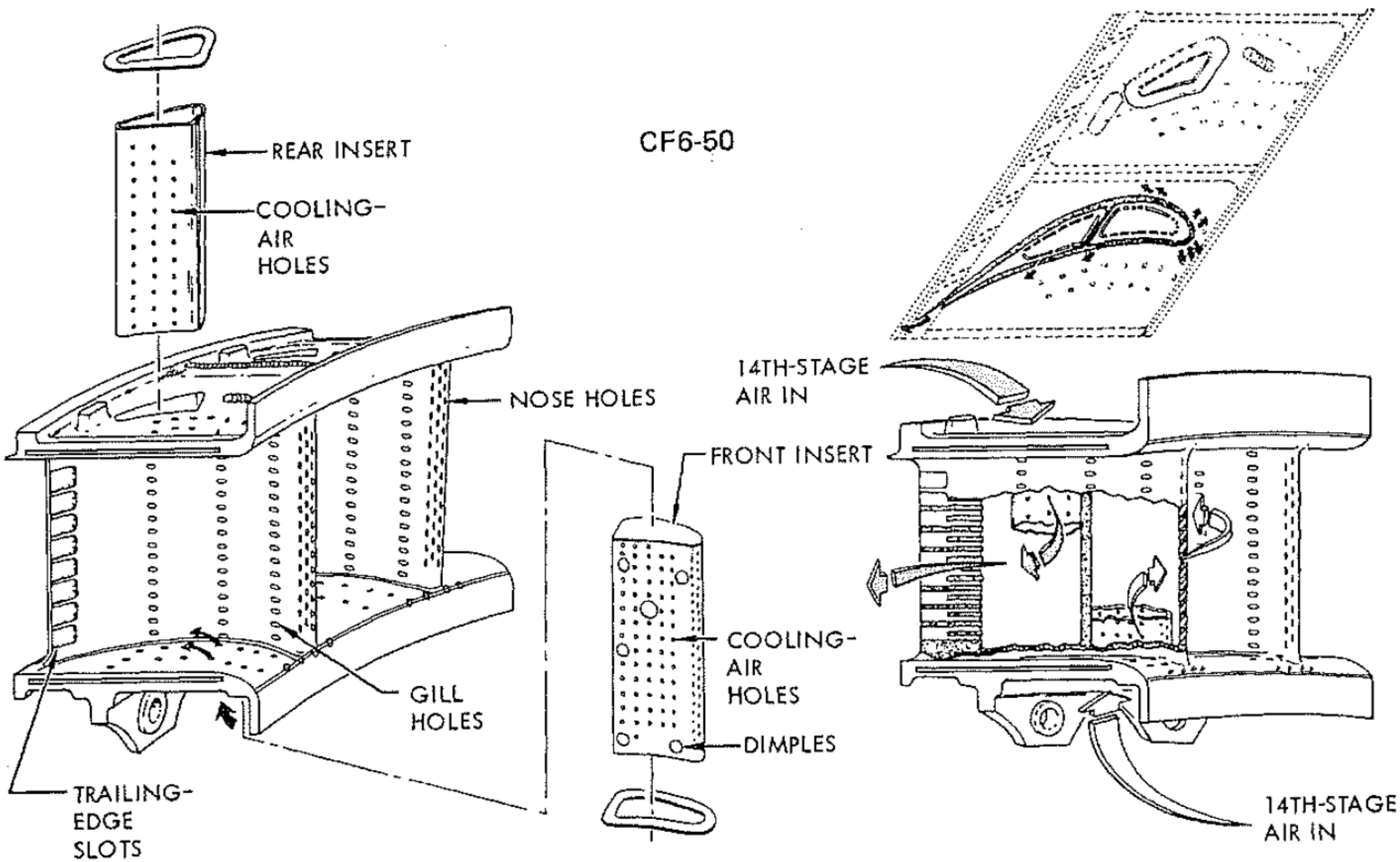
Film Cooling

Detailed End-Wall Cooling Design



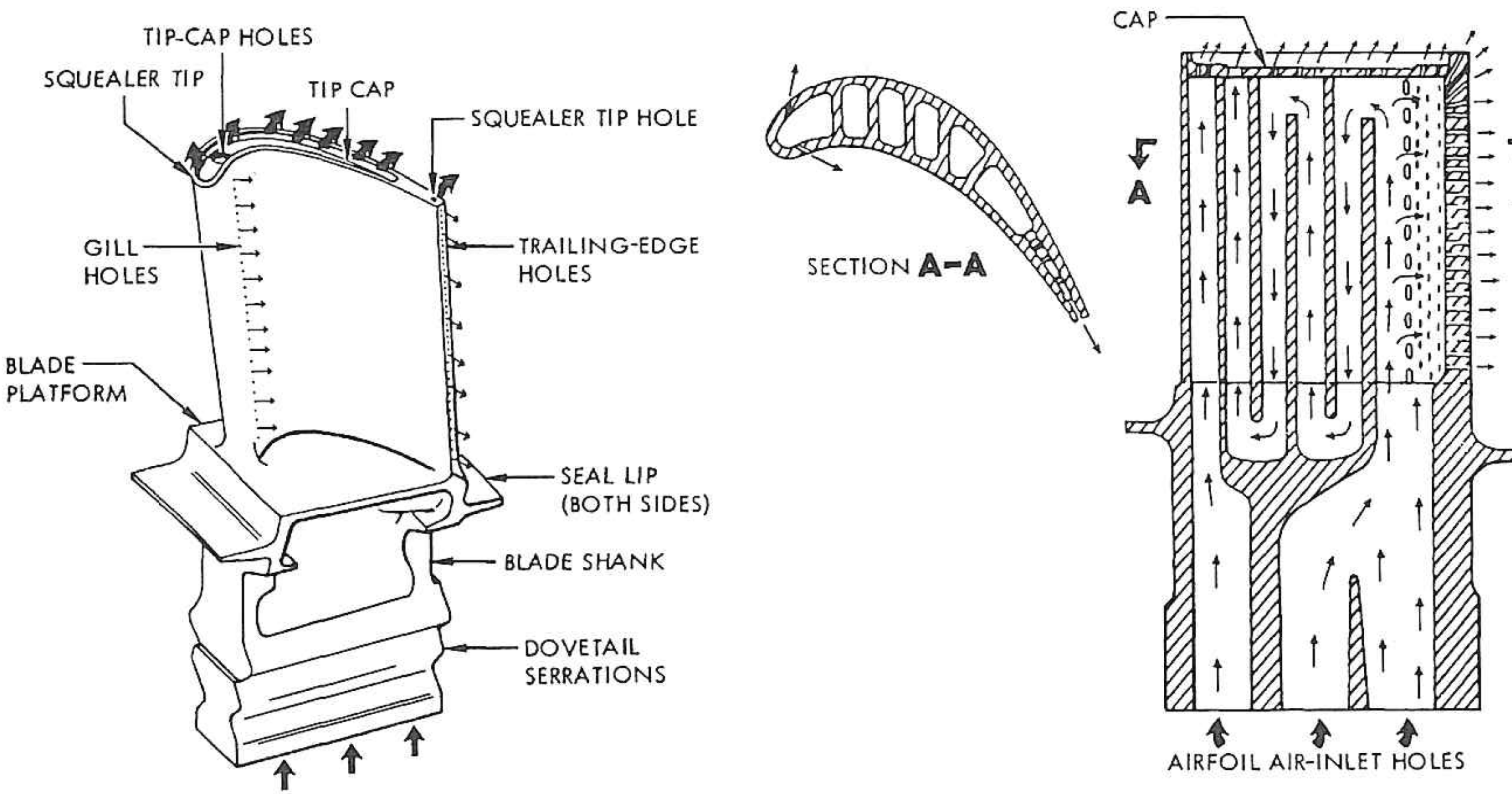
Cooling System Designs

GE CF6: Stage 1, High-Pressure Stator



Cooling System Designs

GE CF6: Stage 1, High-Pressure Turbine Rotor



Cooling System Designs

NASA E3 Engine (NASA CR-167955)