Overset Grids for Multi-Disciplinary Simulations in Gas-Turbine Engines

Roger L. Davis

davisrl@ucdavis.edu

University of California, Davis, CA, 95616

John F. Dannenhoffer, III

jfdannen@syr.edu

Syracuse University, Syracuse, NY, 13244

John P. Clark

john.clark3@wpafb.af.mil

Air Force Research Laboratory, Wright-Patterson, OH, 45433

Overset Grid Symposium

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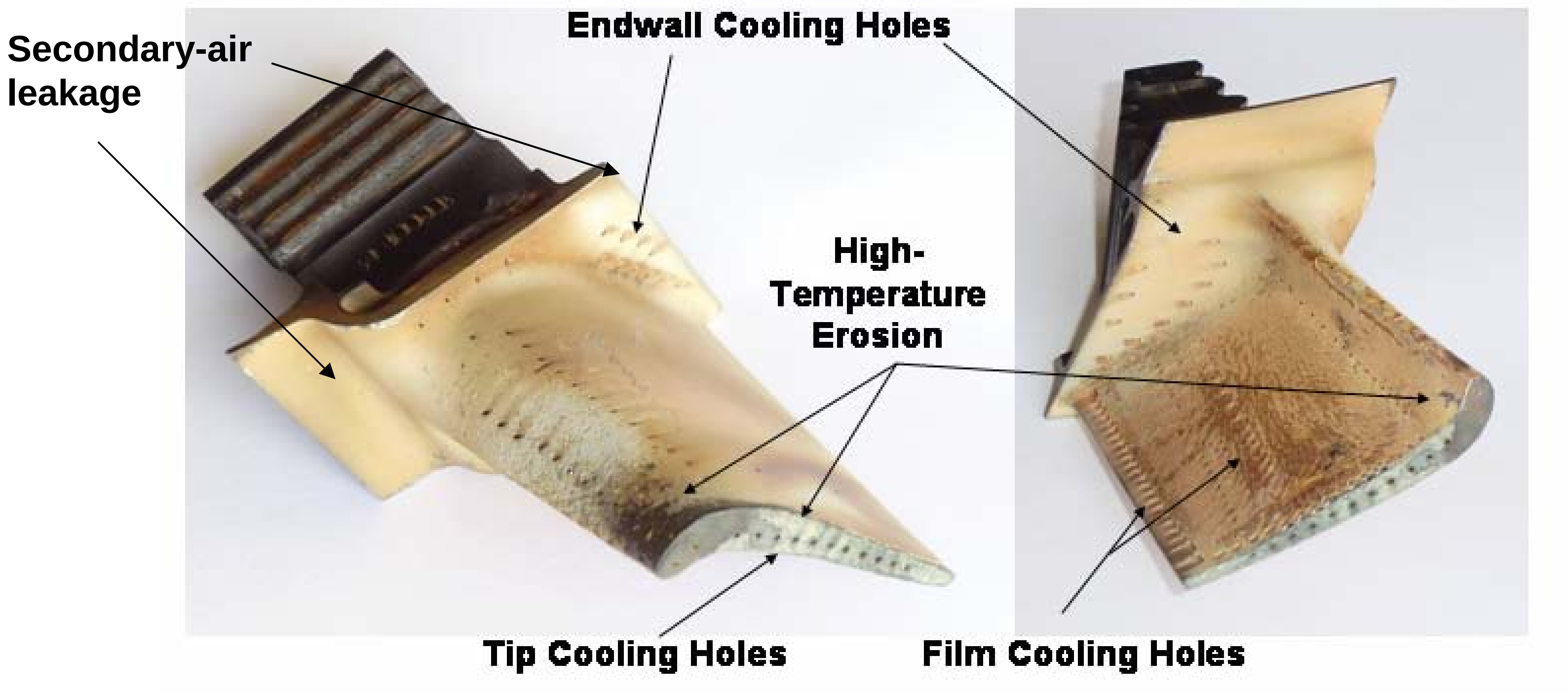
Overview

- **Background**
- **Objectives**
- **Approach – Model and Grid Creation**
  - Use of overset grids in various jet-engine applications
- **Solution Procedure**
- **Results**
- **Summary**
- **Acknowledgements**

Background



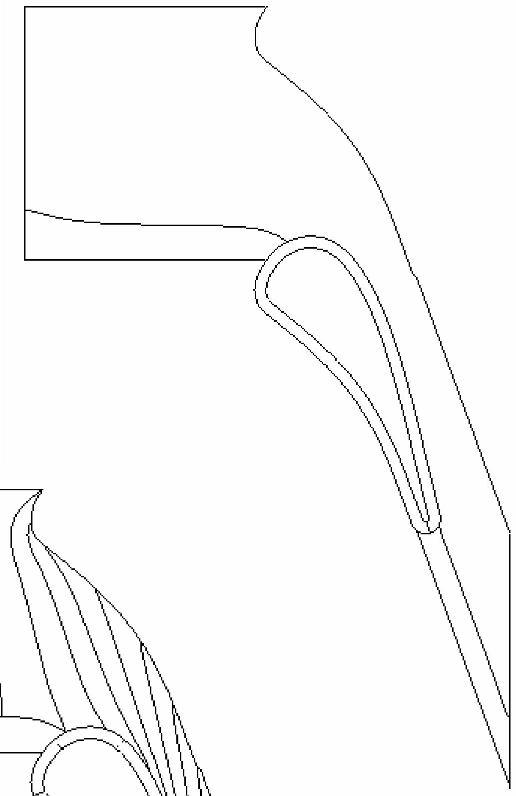
- **High aerothermal loads in the first stages of jet-engine turbines can lead to erosion and fatigue**
- **Film-cooling and secondary-air is an integral part of design to mitigate these effects**
- **A 2D design/analysis tool is needed for aerothermal optimization early in the design cycle**

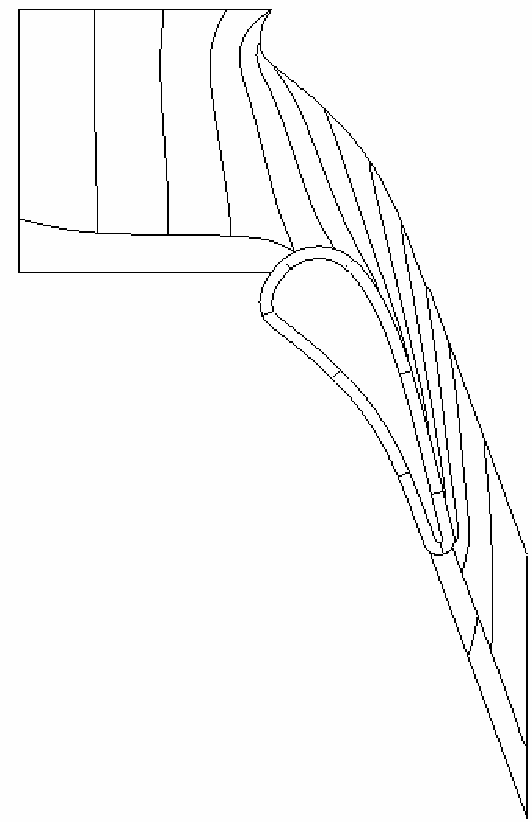
Objectives

- **Develop a fast design/analysis tool that incorporates**
  - Conjugate heat transfer between all solids and fluids
  - Thermal barrier coating
  - Flows internal as well as external to airfoil
  - Film-cooling and secondary-air system flows
  - 2D procedure for use early in design cycle with concepts easily extendible to 3D
  - Time-averaged, detached-eddy flow simulation for improved accuracy of unsteady/mixing effects
- **Demonstrate procedure on realistic turbine geometry and flow conditions**
- **Produce a benchmark test case that can be used for comparison with other similar approaches**

Model and Grid Creation

- **Start with 4-block OHHH grid generated by CASCADE procedure for main flow-path external to airfoil**
  - Inputs: airfoil coordinates, cascade pitch, cascade flow conditions



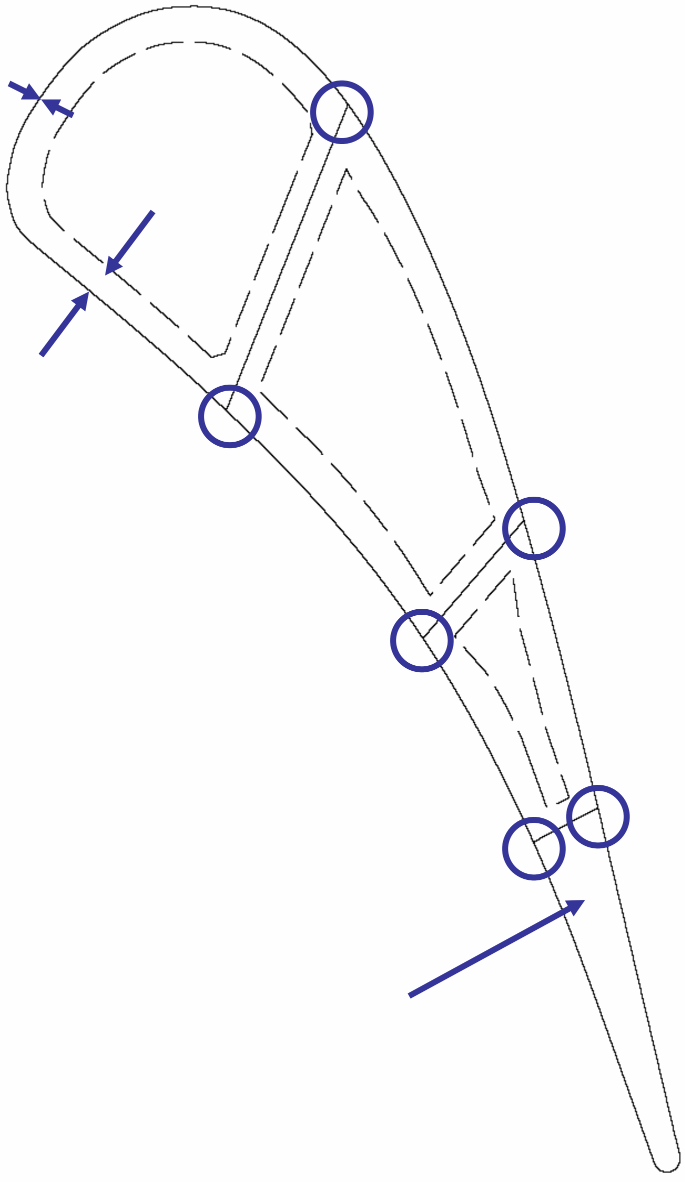


- **Decompose the 4-block main flow-path grid into multiple blocks for parallel computing**

Model and Grid Creation

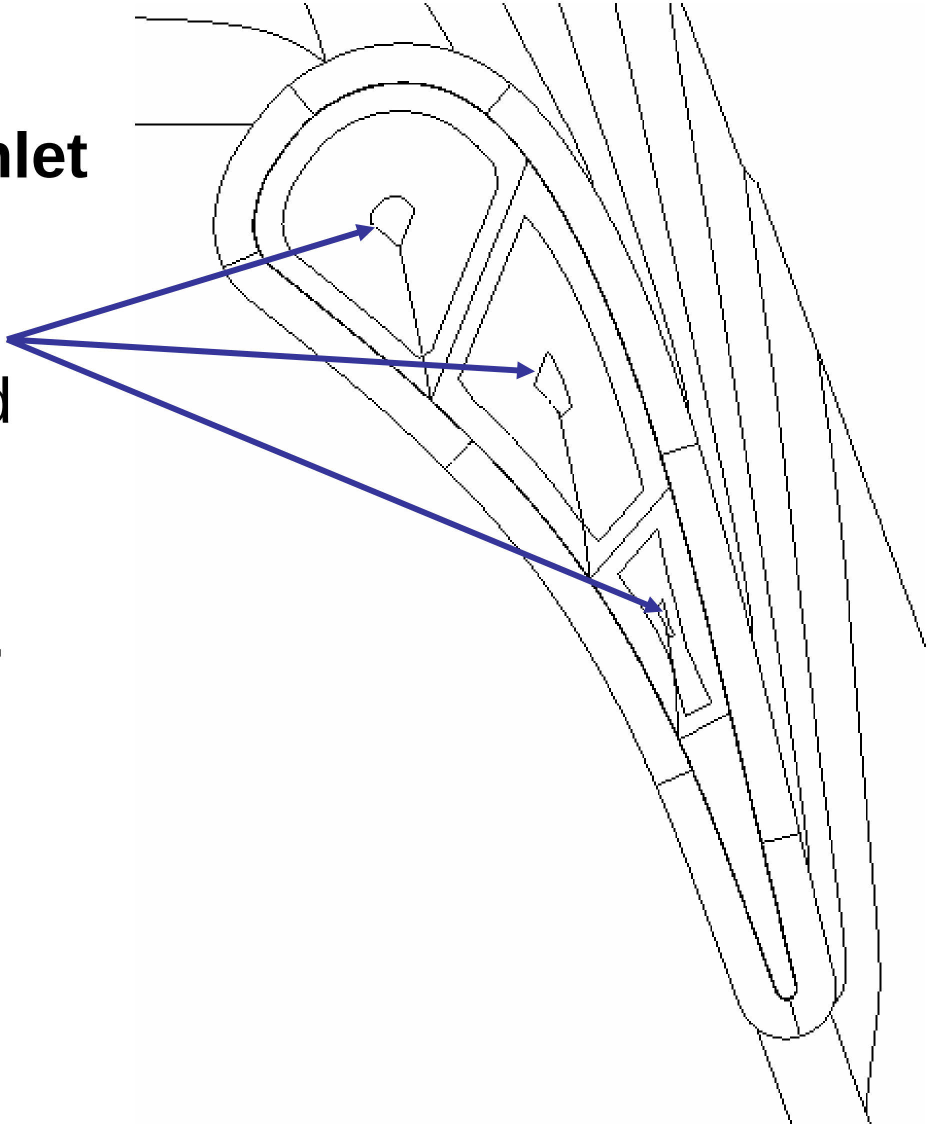
- **Using additional specified inputs:**
  - x-location of where inter-plenum wall intersects suction and pressure surfaces
  - thermal barrier coating thickness
  - wall thickness
  - trailing-edge design strategy
    - solid (shown) or plenum

generate outer wall of thermal barrier coating and internal plenums



Model and Grid Creation

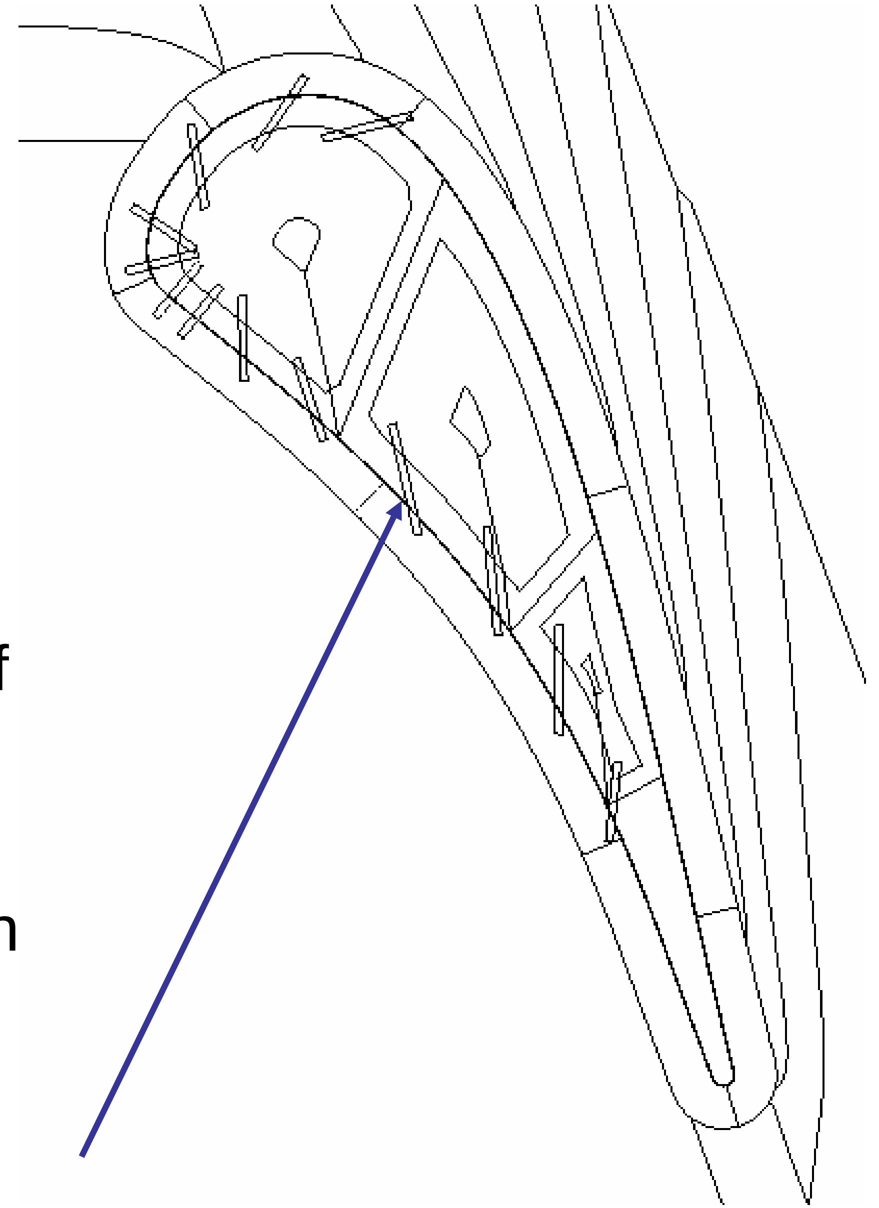
- **Create plenum inner boundary that serves as inlet to plenum flow**
  - total pressure, total temperature are specified
  - flow enters normal to boundary
- **Create O-grid topology for**
  - thermal barrier coating
  - wall
  - plenum



Model and Grid Creation

- **Create generic film-cooling tube with 1x1 unit lengths and 65x65 stretched grids**
- **Using specified film-cooling tube inputs:**
  - number of tubes
  - tube effective diameter
  - x-location and airfoil side of tube exit
  - angle (relative or absolute)
  - calculate appropriate length to connect internal plenum with main flow-path

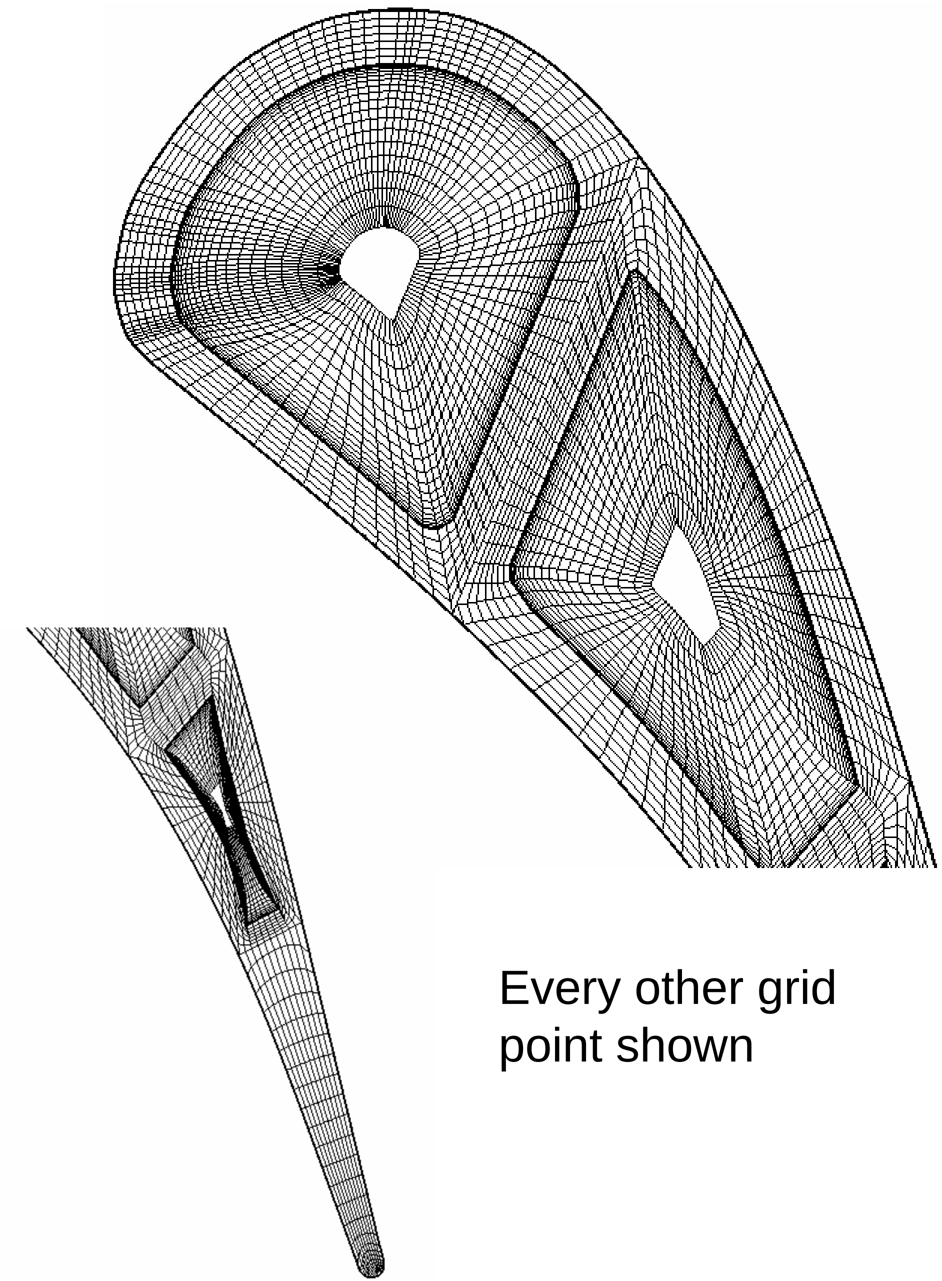
generate film-cooling tubes and overlay onto domain



Model and Grid Creation

- **Generate O-grids in plenum and walls**
  - Uniform normal spacing in thermal barrier coating and walls
  - Clustered grids at walls for plenum and main flow-path

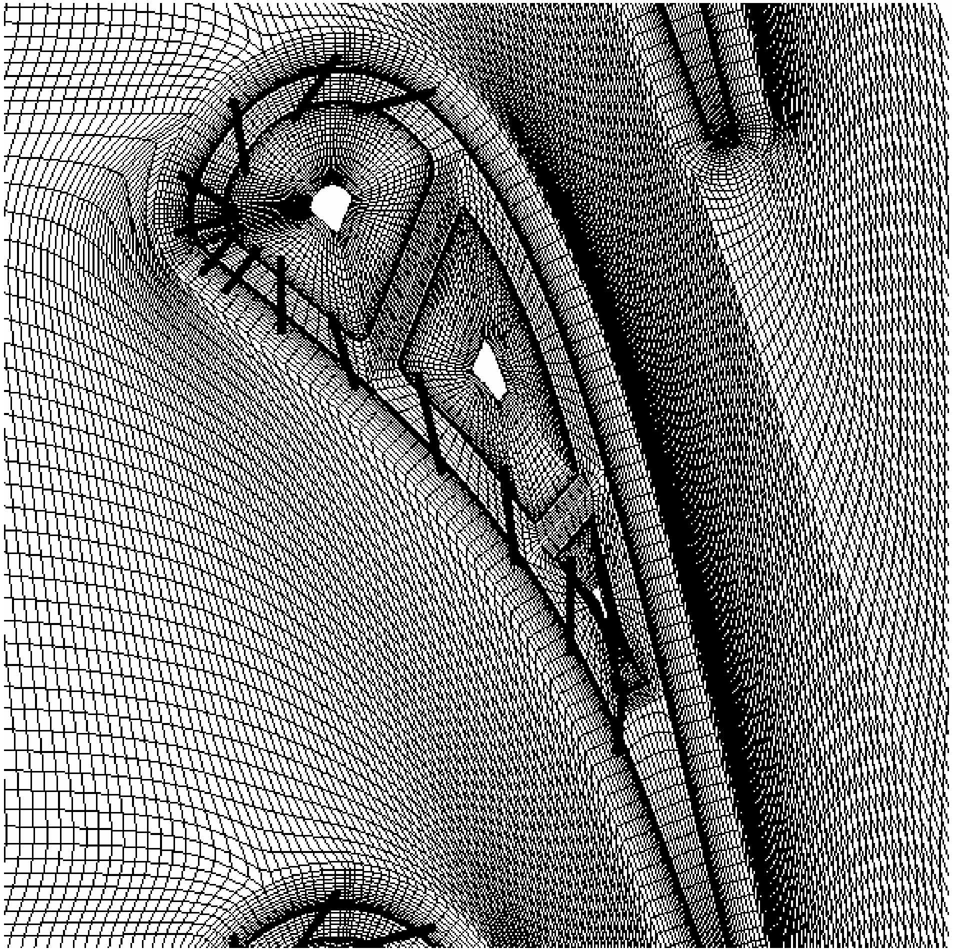
- **Generate optional H-grid in trailing edge if plenum is not desired**

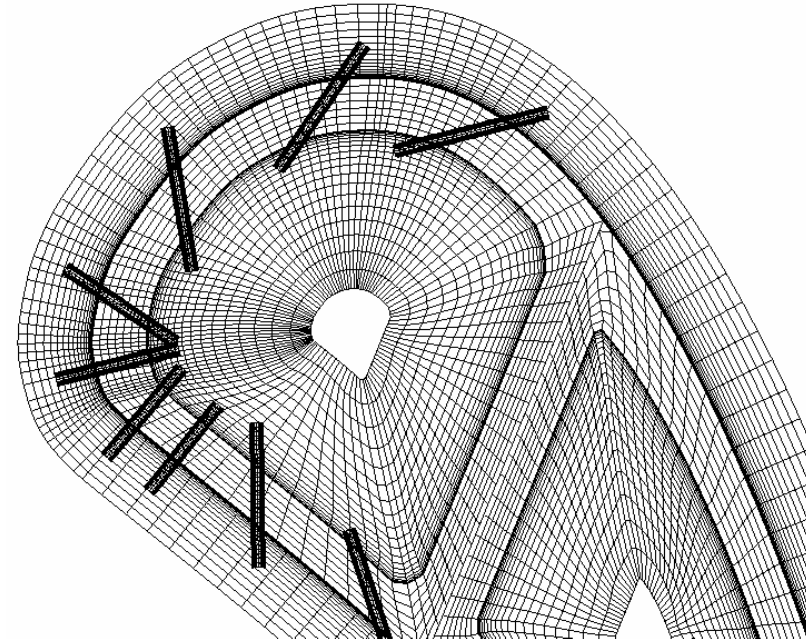


Every other grid point shown

Model and Grid Creation

- **Generate cooling tube embedded, overset grids**
- **Resulting overall grid:**

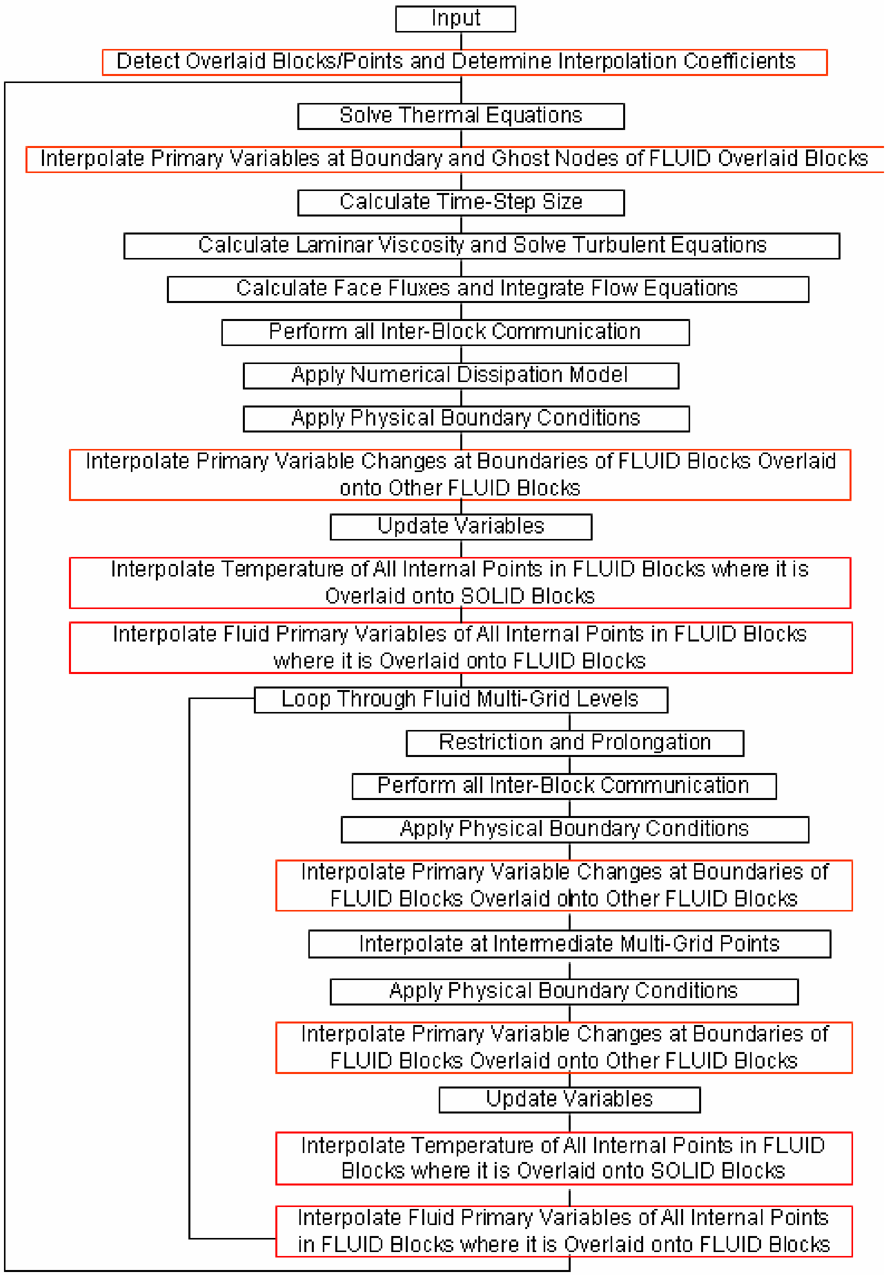




- **Advantages of approach:**
  - Totally automated and generated in seconds
  - Can add/subtract film cooling tubes without re-gridding
  - Technique lends itself very well to automated optimization schemes

MBFLO2 Solution Procedure

- **Time-averaged Detached-Eddy Simulations are the Norm !**
  - Enables effects of unsteadiness and mixing on aerothermal performance to be more accurately predicted
  - Parallelization and dual time-step point-implicit allows for fast turn-around
    - Time-averaged DES solution turn-around time with 13 cooling tubes and ~123K points:
      - ~6 hrs on 32 cpu cluster
      - ~90 mins (est) 32 core/gpu cluster
- **Solution procedure extended to handle embedded, overset blocks for film-cooling**
  - Additional kernels shown in red

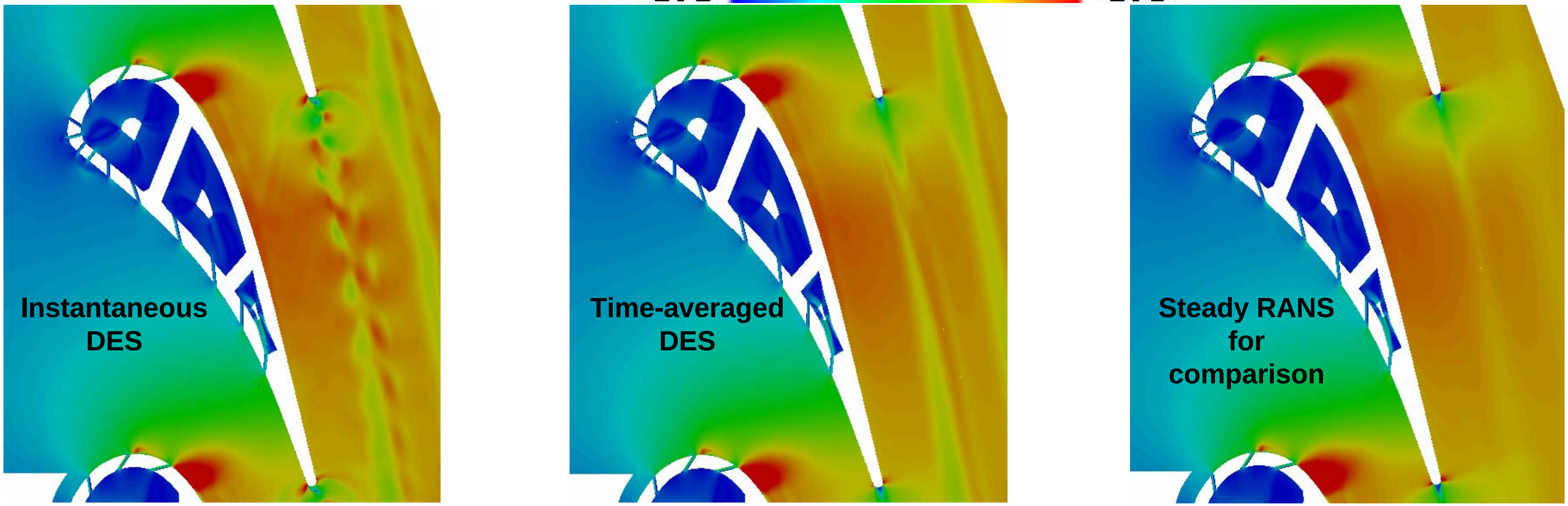


VKI Vane Test Case

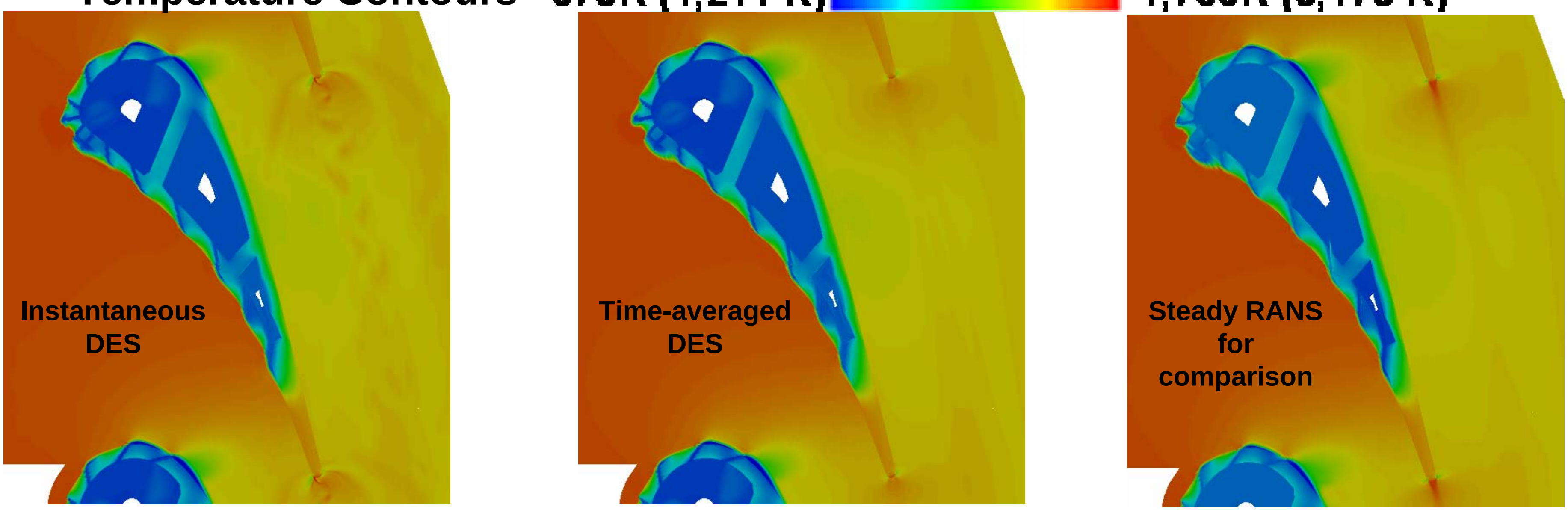
- **Little or no experimental data available**
  - Due to proprietary nature of problem
  - Need a realistic test case so that others may compare
- **Created a benchmark test case from publicly available information:**
  - VKI transonic turbine vane (Arts, et al, MUR46)
  - Engine conditions for F100 (Mattingly)
    - Main flow-path at Pt4, Tt4 conditions
    - Cooling flows at ~Pt3, Tt3 conditions
    - M_1=0.15, M_2=0.875, Re_{bx}= 337,711
  - TBC with realistic properties
  - Stainless steel for metal walls
  - Realistic cooling tube numbers, locations, angles, diameters, etc. (details given in paper)

Single Blade-Row Results

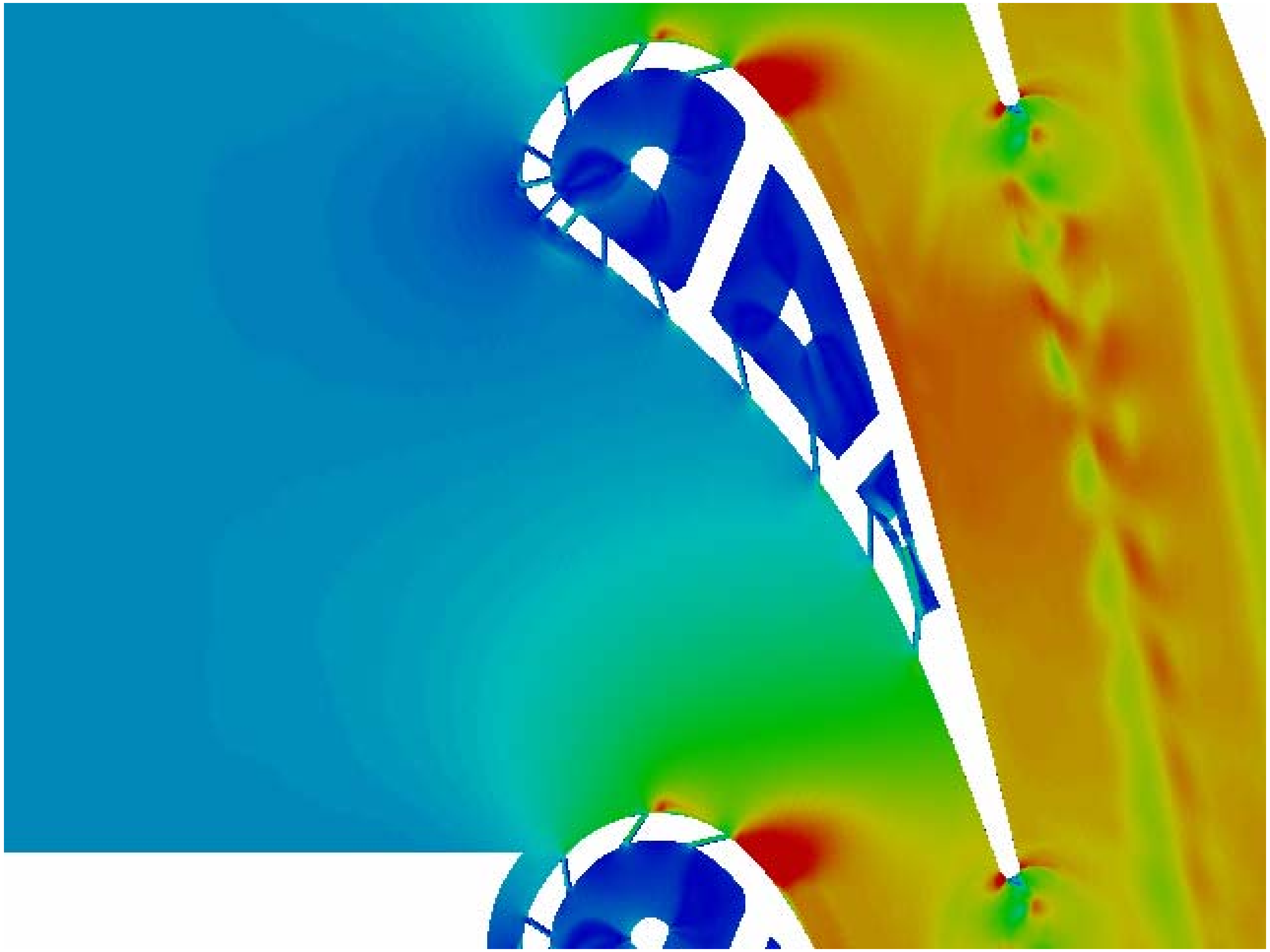
Mach Contours 0.0 – 0.9



Temperature Contours 673K (1,211 R) – 1,766K (3,178 R)

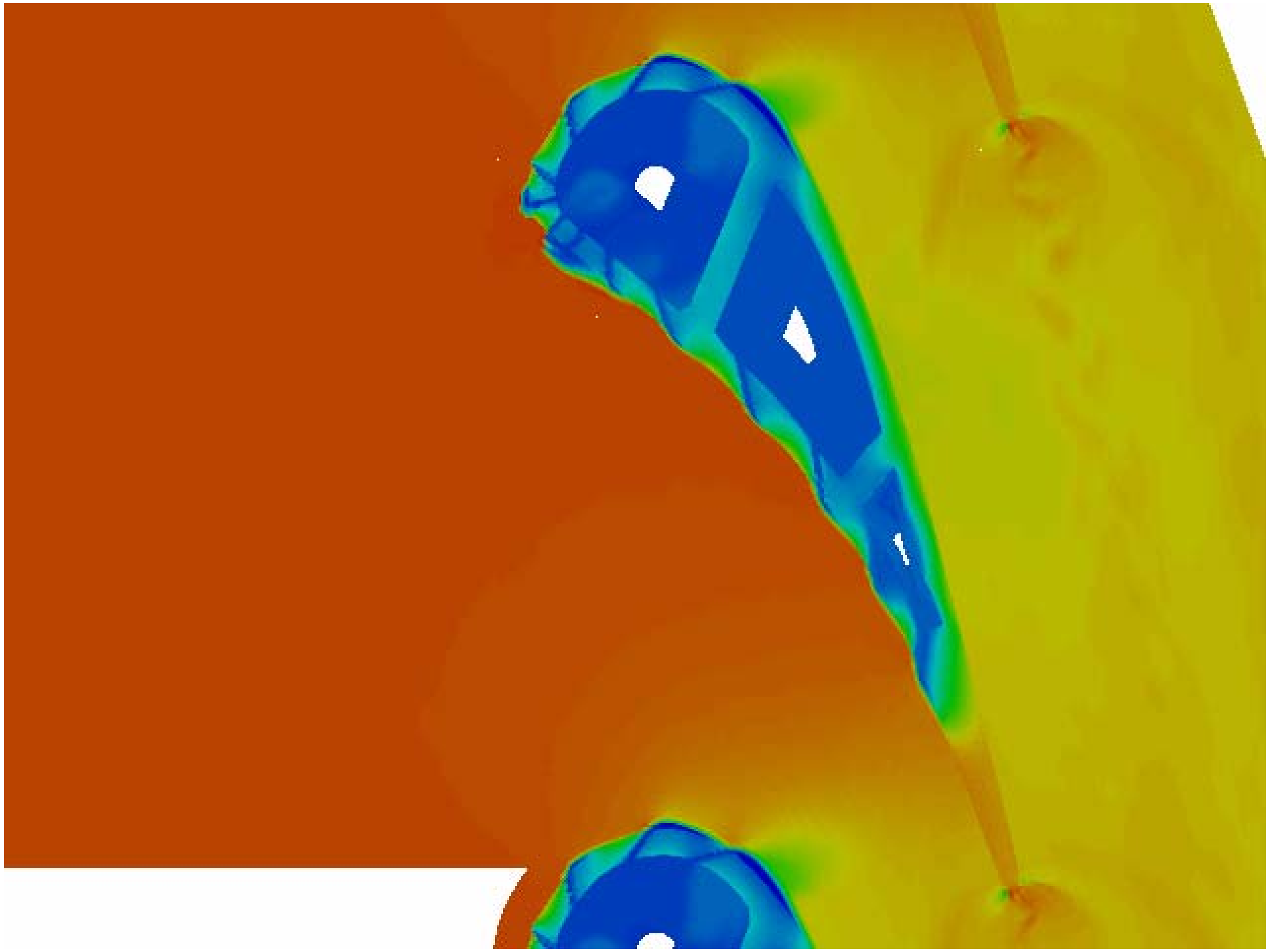


Aero Unsteadiness – DES



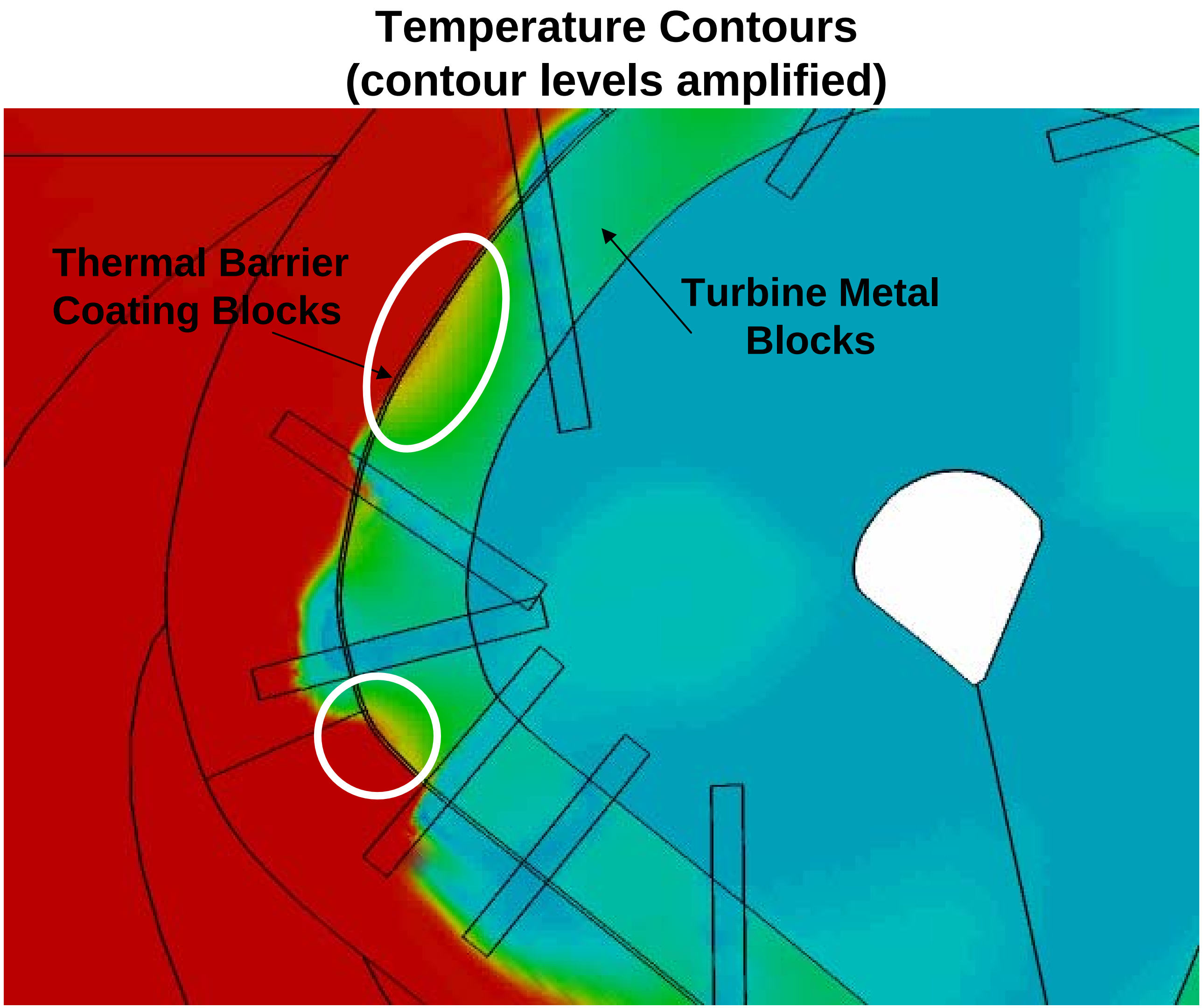
Mach Contours 0.0 0.9

Thermal Unsteadiness – DES



Temperature Contours 673K (1,211 R) 1,766K (3,178 R)

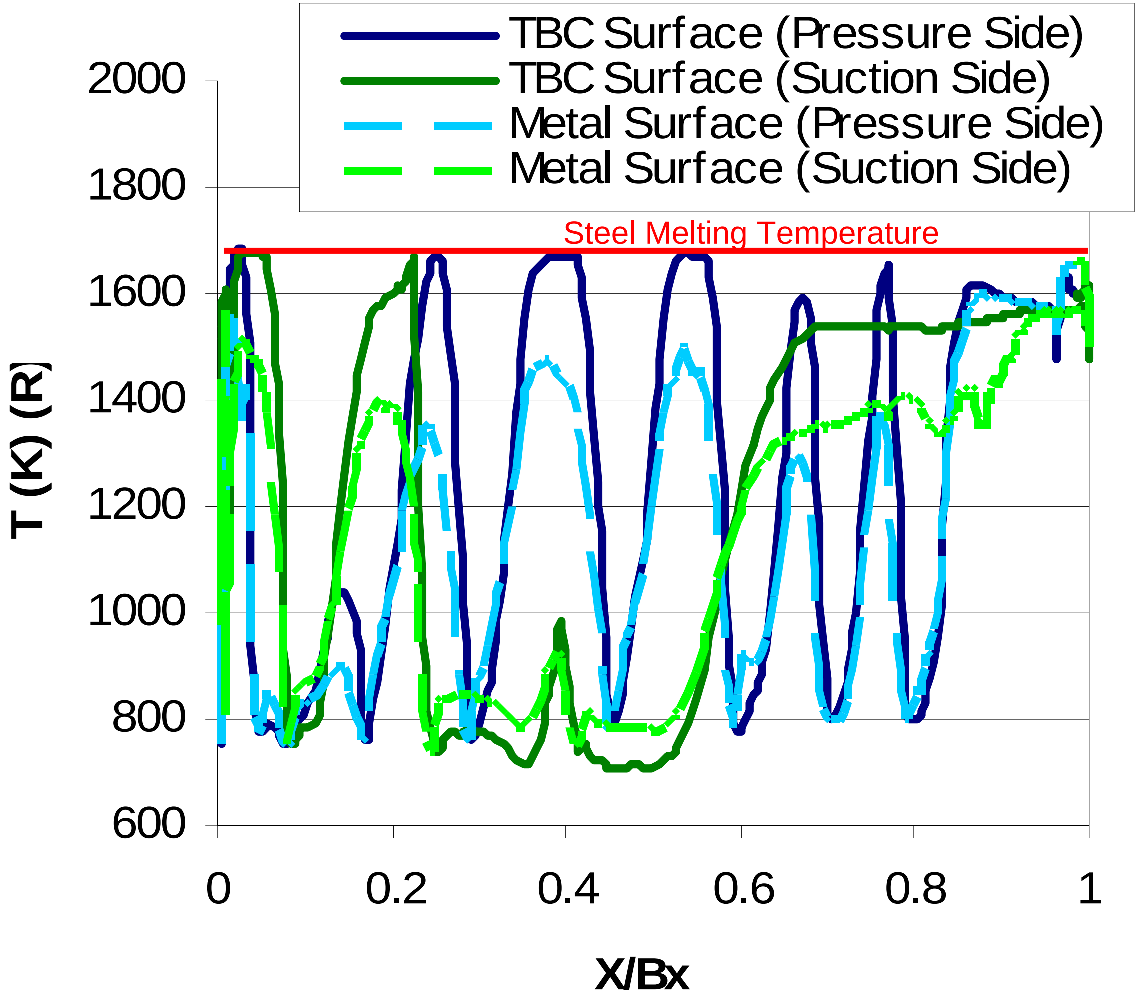
Easy to Detect Hot-Spots – DES



Block boundaries are shown to help identify various regions

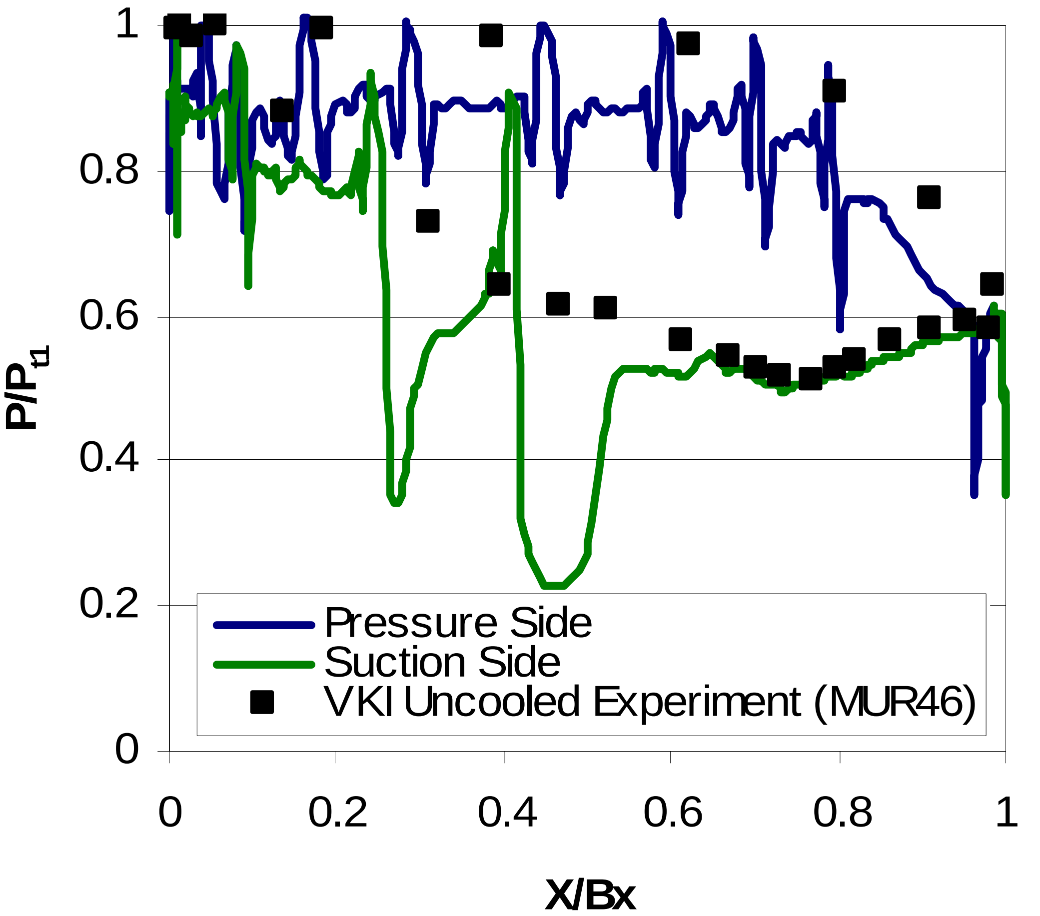
Thermal Barrier and Metal Surface TA'd-DES Temperature Distributions

- **Thermal barrier coating does a good job at isolating the metal from the combustor hot gases**
- **Cooling effectiveness readily shown for each cooling tube**



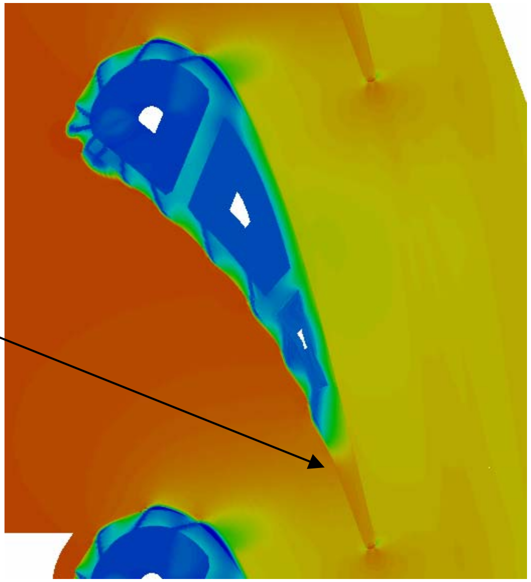
TA'd DES Airfoil Pressure Distributions

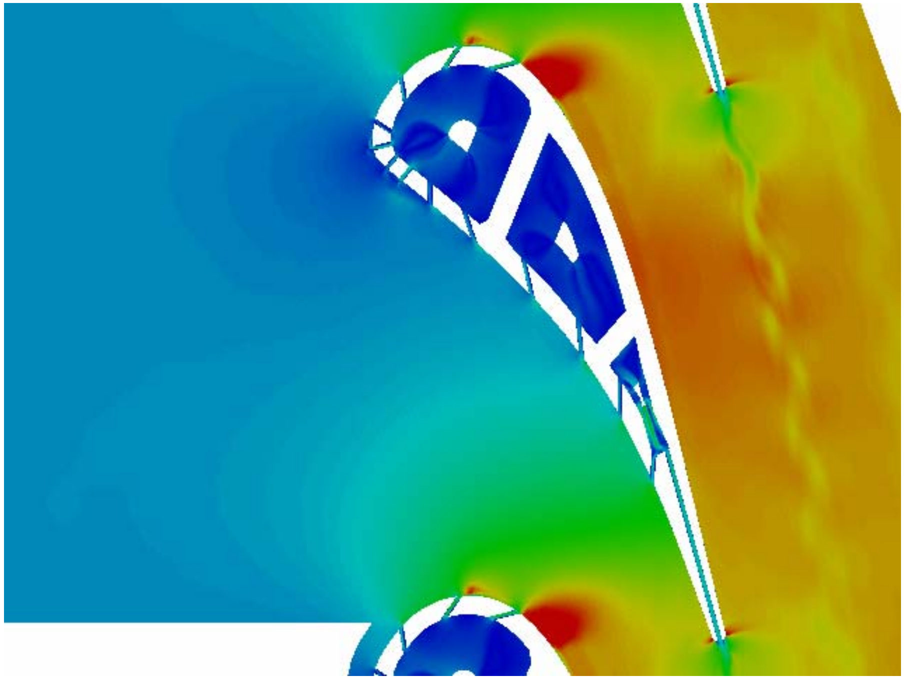
- **Effect of cooling flows on airfoil loading readily shown**
- **Comparison with uncooled experimental data shows**
  - Reduced loading due to additional aerodynamic blockage and increased velocity near wall on pressure side
  - Effect of under-expanded film cooling flow



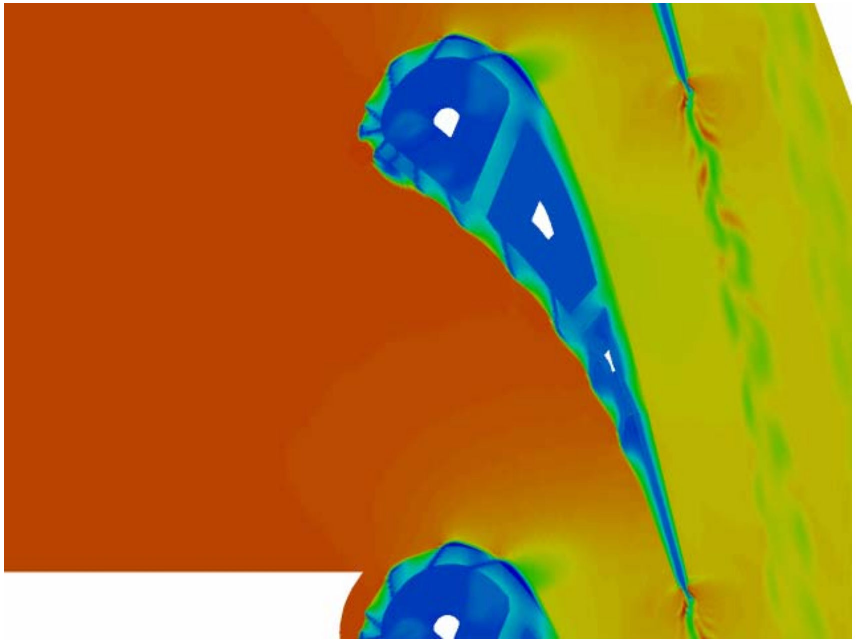
Straightforward Coupling with Optimization

- **Example: High flow unsteadiness and temperature in trailing edge (TE) region easily mitigated with additional TE film-cooling**





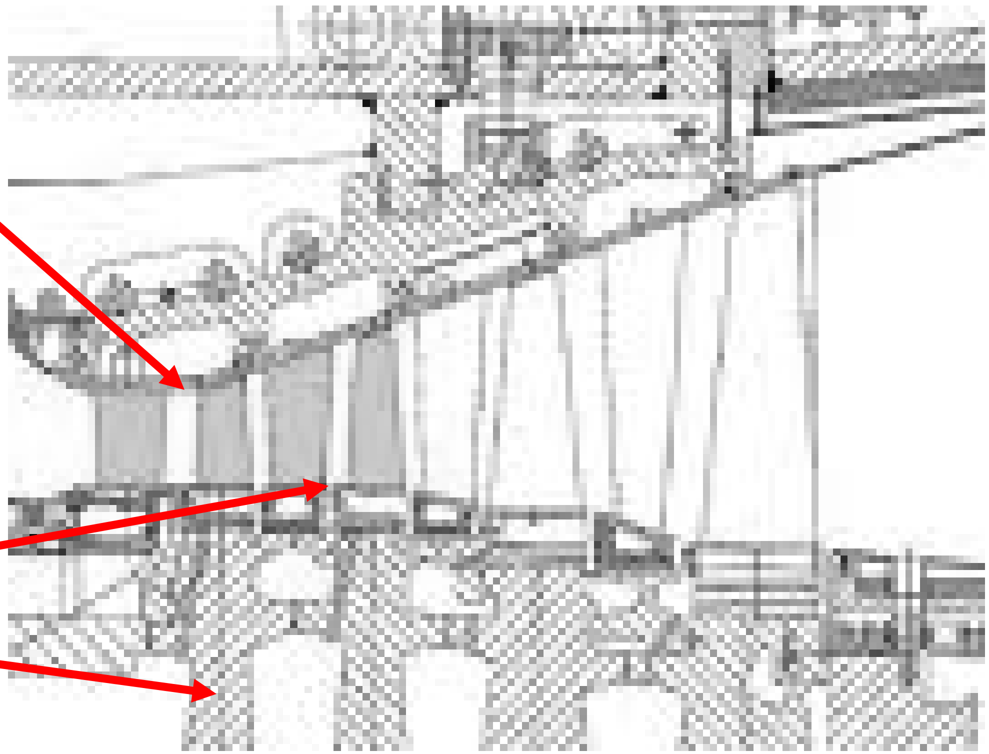
Mach Contours 0.0 0.9



Temperature Contours 673K (1,211 R) 1,766K (3,178 R)

Secondary-Air and Leakage Flows

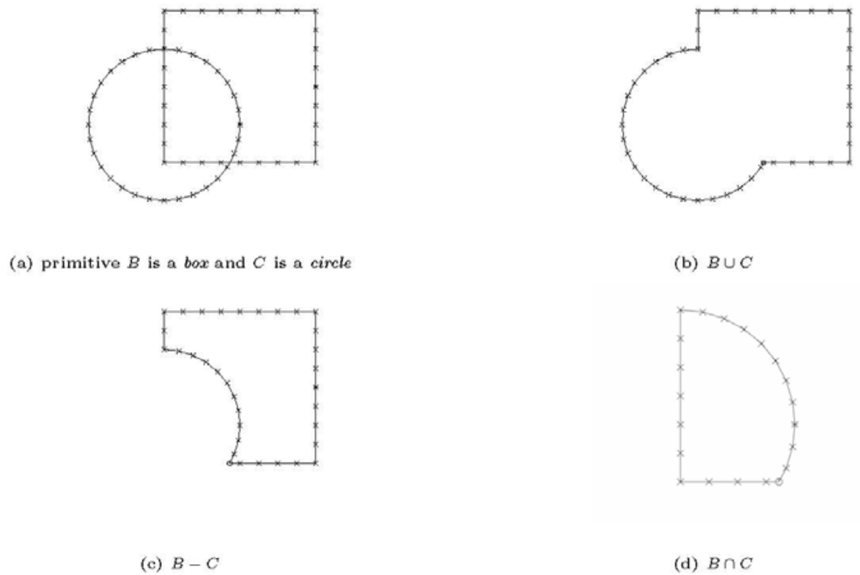
- The model and grid creation for the secondary-air system and leakage flows can also benefit from overset grids
- Leakage flows can greatly affect the aerodynamics and heat transfer in main flow-path
- Heat transfer in disks can greatly affect flow and disk life



- Need a system that can rapidly create model and grid for both secondary air and metal

CAD-Based Grid Generation

- **For each CAD primitive, construct a grid inside and outside**
- **When CAD operations are performed to construct model, apply them to the computational grids as well**
- **CAD operations consist of**
  - Union
  - Intersection
  - Difference

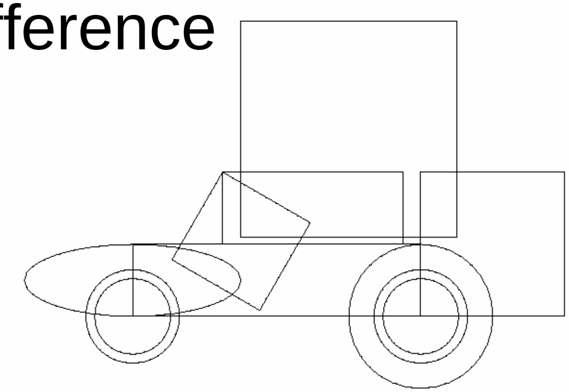


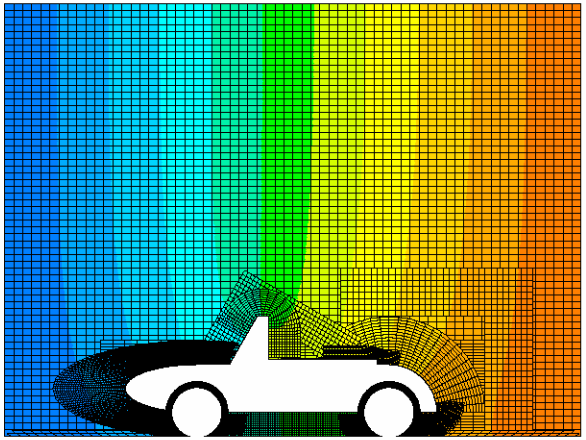
(a) primitive B is a *box* and C is a *circle*

(b) $B \cup C$

(c) $B - C$

(d) $B \cap C$

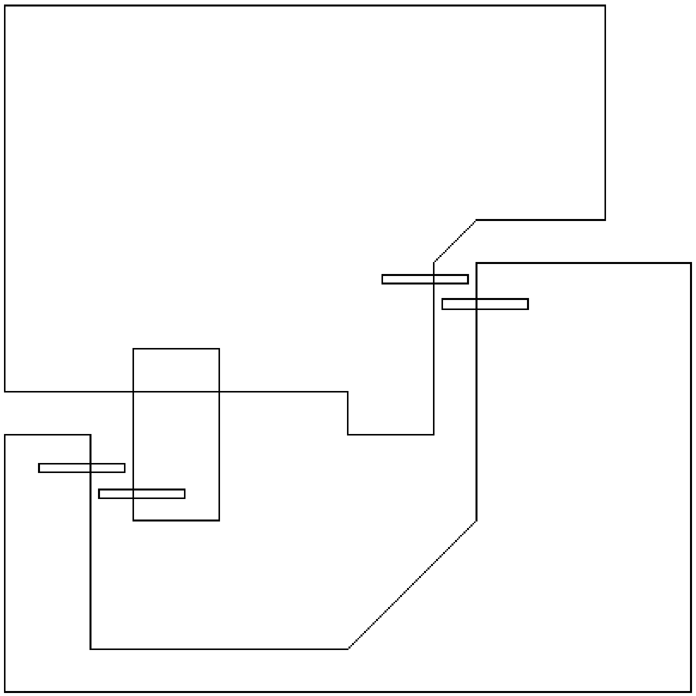




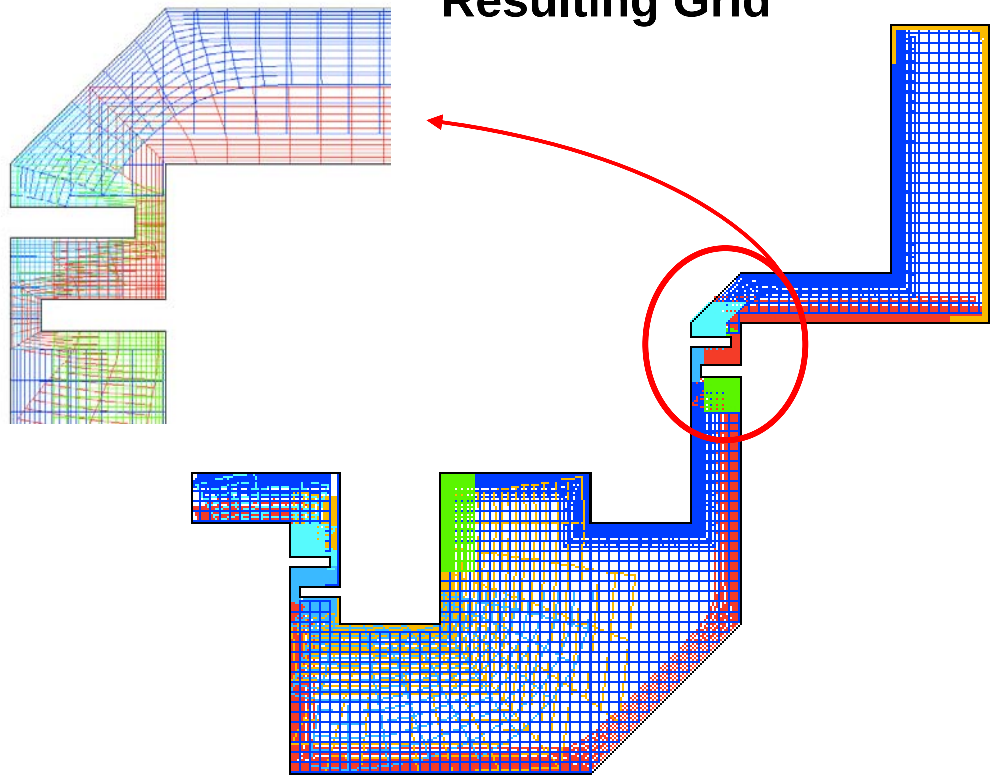
Application to Gas-Turbines

Secondary-Air System Flow Path

CAD Model



Resulting Grid



- **For more details: AIAA 2009-3991 "Automated Creation of Overset Grids Directly from Solid-Model Feature Trees"**

Summary

- **New 2D conjugate film-cooling aerothermal design/ analysis capability developed (AIAA 2010-1461)**
  - Automatically creates model and computational grid for turbine airfoil sections
  - Film cooling flow rates predicted rather than prescribed
  - Uses embedded overlaid grids for film-cooling tubes
  - Technique lends itself well to automated optimization and extension to 3D
- **New 2D multi-blade-row conjugate film-cooling aerothermal design/analysis capability demonstrated (AIAA 2011-xxxx to be presented at Aerospace Sciences Meeting in January)**
- **Extensions of MBFLO2 documented and demonstrated for embedded, overlaid grid capability**
- **Realistic transonic turbine vane and turbine stage at engine aerothermal conditions used to demonstrate procedure and produce benchmark test cases**

Acknowledgements

- **This effort was supported from the Air Force Research Laboratory in Wright-Patterson, OH under contract 09-S590-0009-20-C1**
  - John Clark served as technical monitor and co-author on these efforts