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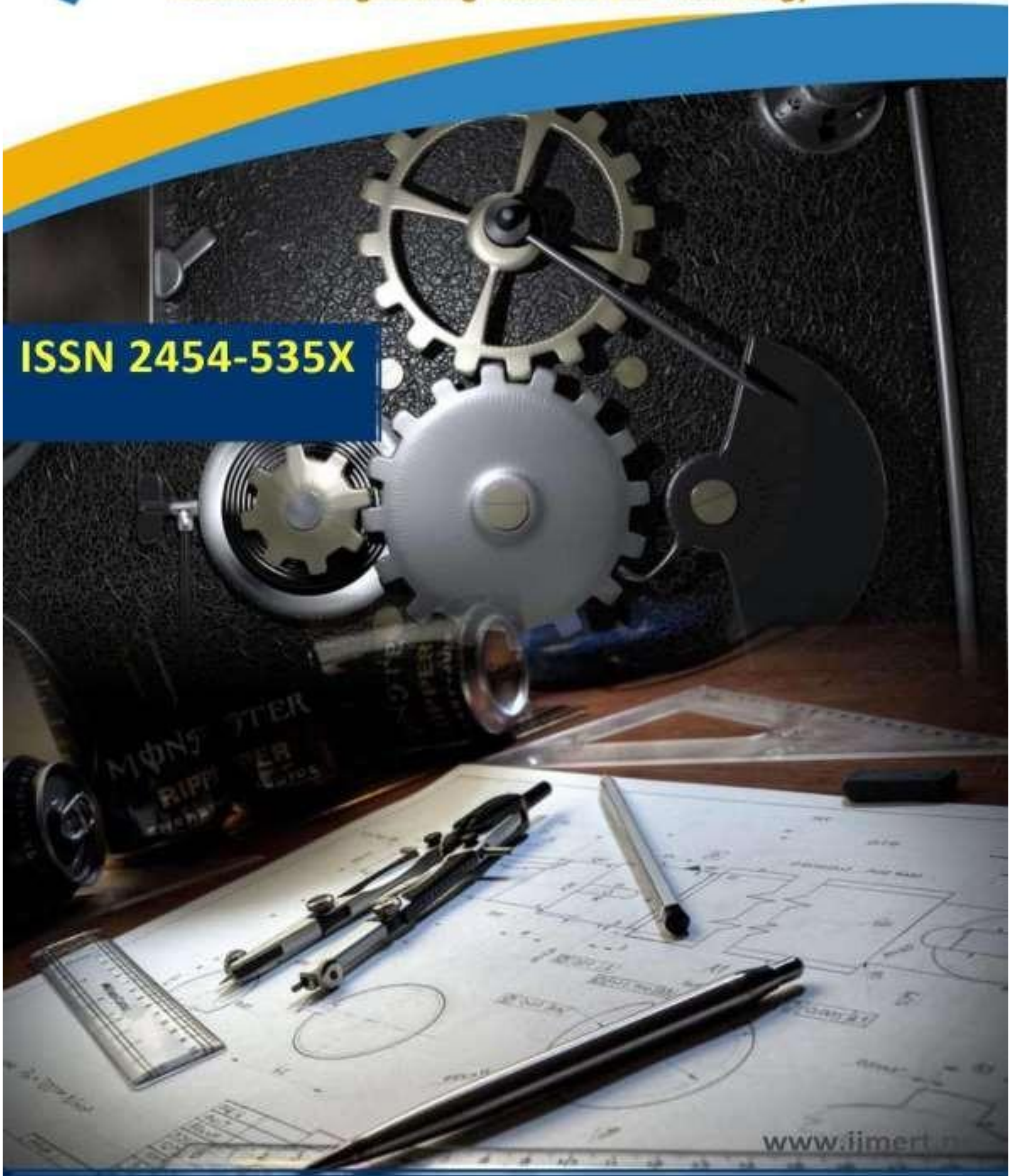

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THERMAL AND STRUCTURAL ANALYSIS OF A COOLED TURBINE BLADE USING ANSYS

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Abstract

Gas turbine blades operate under extremely high temperatures that exceed allowable metal limits. Effective internal cooling is therefore essential to maintain structural integrity and prolong service life. This study presents a coupled steady-state thermal and static structural analysis of a turbine blade incorporating ten internal cooling passages. A reduced-order modeling approach is implemented in ANSYS Workbench, where three-dimensional solid elements represent the blade and one-dimensional fluid elements simulate coolant flow.

The thermal analysis evaluates temperature distribution in both solid and coolant domains, while the structural analysis determines thermally induced stresses resulting from constrained expansion. Results show significant temperature gradients between the hot external surface (568 K) and cooled internal regions (minimum 338 K). The maximum von Mises stress reaches 2.79×10^9 Pa near critical cooling passages. The study demonstrates that reduced-order thermal-fluid modeling provides computational efficiency while maintaining physical accuracy for preliminary design evaluation.

1. Introduction

Increasing turbine inlet temperature (TIT) improves gas turbine efficiency but exposes blades to extreme thermal loads. Modern engines may operate above 1600 K, whereas allowable metal temperatures are much lower. This mismatch necessitates advanced cooling strategies.

Internally cooled blades use compressor bleed air routed through embedded passages. Heat is removed via forced convection, reducing blade metal temperature. However, non-uniform cooling produces steep thermal gradients that generate thermal stresses due to constrained expansion.

Thermal-stress analysis is typically conducted using a sequential approach: Perform steady-state thermal analysis.

Map temperature field to structural model.

Compute thermally induced stresses.

Full conjugate heat transfer (CHT) simulations are computationally expensive. Therefore, reduced-order modeling using empirical convection coefficients offers an efficient alternative. This study adopts such an approach to evaluate thermal performance and stress behavior of a cooled turbine blade.

2. Literature Review

Extensive experimental and numerical research has been conducted on turbine blade cooling.

NASA benchmark studies provided detailed heat-transfer data for turbine geometries under engine-like conditions. These datasets established empirical film-cooling and convection correlations widely used for validation.

Reduced-order FEM models using:

Surface-effect convection elements

One-dimensional fluid elements

Solid thermal elements

have been shown to provide reliable predictions when calibrated with experimental heat-transfer coefficients.

Sequential thermo-structural coupling has been validated for steady-state blade analysis. Literature confirms that thermal gradients often dominate stress magnitude, especially near cooling holes and blade roots.

Thus, reduced-order FEM remains a practical and accepted method for engineering analysis.

3. Materials

3.1 Blade Material

The blade is modeled as homogeneous isotropic carbon steel (simplified representation).

Thermal Properties

Thermal conductivity: 43 W/m·K

Mechanical Properties

Young’s Modulus: 2.0×10^{11} Pa

Poisson’s ratio: 0.30

Thermal Expansion

Coefficient of thermal expansion: $1.08 \times 10^{-5}\ \mathrm{K}^{-1}$

Material behavior is assumed:

Linear elastic

Temperature independent

This simplifies analysis while maintaining physical realism for methodology demonstration.

3.2 Coolant Fluid Properties

The coolant is modeled using 1D fluid elements.

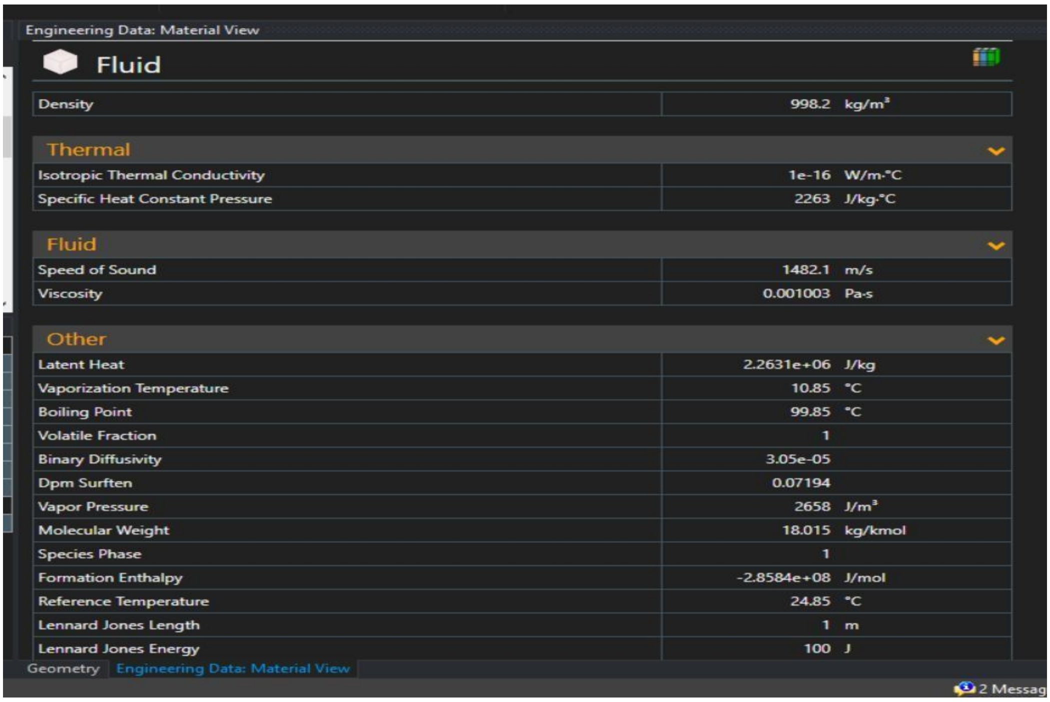
Specific heat: 2260 J/kg·K

Thermal conductivity: 1.0×10^{-16} W/m·K

The extremely low conductivity suppresses artificial axial diffusion, ensuring heat transfer occurs primarily via convection.

Coolant temperature rise is governed by:

$$\dot{m}\, c_p\, dT = hA\,(T_s - T_f)$$



Fluid

Density	998.2	kg/m^3
Thermal		
Isotropic Thermal Conductivity	1e-16	W/m·°C
Specific Heat Constant Pressure	2263	J/kg·°C
Fluid		
Speed of Sound	1482.1	m/s
Viscosity	0.001003	Pa·s
Other		
Latent Heat	2.2631e+06	J/kg
Vaporization Temperature	10.85	°C
Boiling Point	99.85	°C
Volatile Fraction	1	
Binary Diffusivity	3.05e-05	
Dpm Surften	0.07194	
Vapor Pressure	2658	J/m^3
Molecular Weight	18.015	kg/kmol
Species Phase	1	
Formation Enthalpy	-2.8584e+08	J/mol
Reference Temperature	24.85	°C
Lennard Jones Length	1	m
Lennard Jones Energy	100	J

Wax Fluid

4. Geometry and Modeling Methodology

4.1 Blade Geometry

The blade consists of:

Pressure surface

Suction surface

Leading and trailing edges

Ten cylindrical internal cooling passages

Passages are modeled as straight cylindrical channels with varying cross-sectional areas.

4.2 Analysis Workflow

Sequential Coupling:

Steady-state thermal analysis

Temperature mapping

Static structural analysis

Thermal boundary conditions:

External surface temperature: 568 K

Internal convection (film coefficients applied)

Structural constraints:

Fixed support at blade root faces

4.1.2 Internal Cooling Passage Network

Embedded within the blade interior are **ten cylindrical cooling passages** that extend from the blade root region toward the blade tip. These passages represent an idealized internal cooling gallery network through which compressed air flows to extract heat from the blade material. The passages are distributed throughout the blade cross-section so that cooling effectiveness is achieved in regions of high thermal loading, particularly near the leading edge and mid-chord regions.

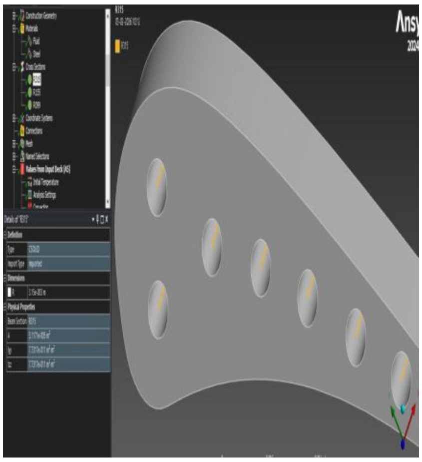
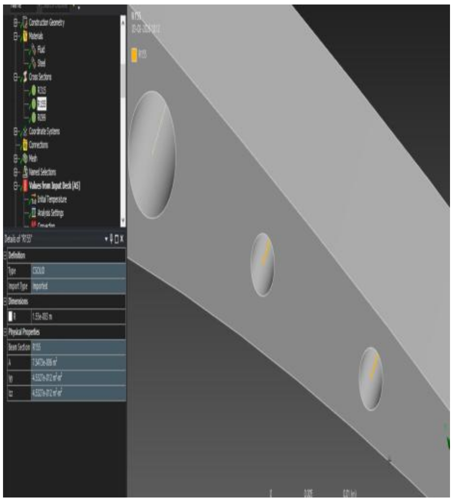
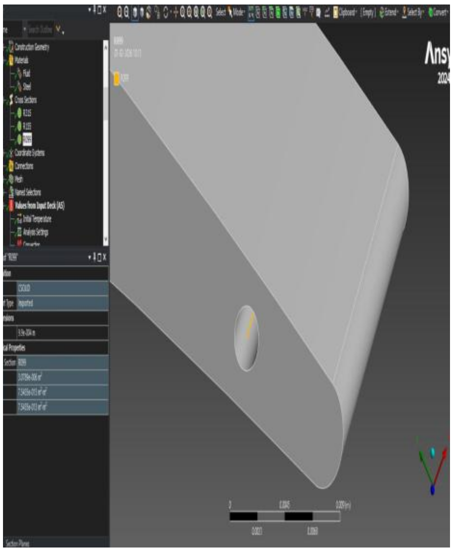


Figure 6.2 of the source NASA document illustrates the blade cross-section and the spatial arrangement of these cooling passages. In the present finite element model, the passages are idealized as straight, smooth cylindrical channels with constant cross- sectional area. This assumption allows the internal coolant flow to be represented using one-dimensional fluid elements, which significantly reduces model complexity and computational cost.

First set of Fluid



Second set of fluid



SOLID278 thermal elements

Structured sweep mesh

Hexahedral topology

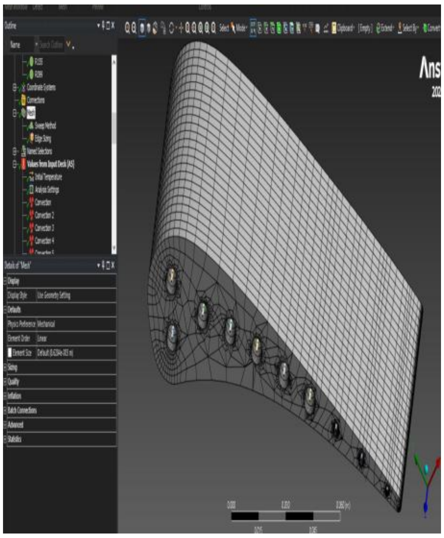
Mesh

Third set of Fluid

Fluid with same cross section area

5. Mesh Methodology

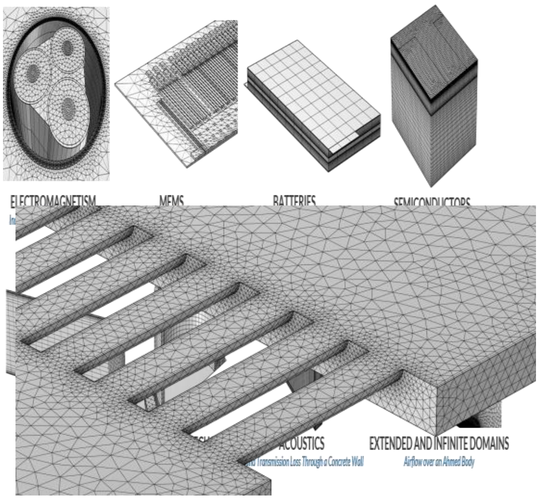
5.1 Solid Mesh



Mesh refinement applied near cooling passages to capture thermal gradients.

5.2 Fluid Mesh

FLUID116 1D elements
to full CFD.



24 divisions along each passage

Upwind scheme for stability

This reduces computational cost compared

6. Boundary Conditions

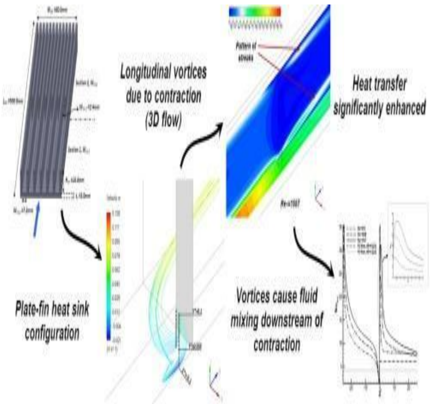
6.1 Thermal Conditions

External:

Uniform temperature = 568 K

Internal cooling passages:

Inlet temperature: 334–453 K



Mass flow rate: 0.00253–0.0243 kg/s

Film coefficient: 2.85×10^5 – 8.96×10^5 W/m²K

6.2 Structural Constraints

Fixed support at root

Thermal load from mapped temperature field

No external mechanical loads

7. Results and Discussion

7.1 Temperature Results

Solid Region

Maximum: 568 K

Minimum: 338.29 K

Fluid Region

Maximum: 562.32 K

Minimum: 333.99 K

Cooling passages significantly reduce local metal temperature.

Axial temperature rise (Hole 1):

Fluid: 348.83 K → 385.28 K

Solid: 357.21 K → 391.51 K

This confirms effective convective heat removal.

2.7959 × 10^9 Pa (near cooling hole 10) Hole 1 axial stress:

Peak: 7.1469 × 10^8 Pa

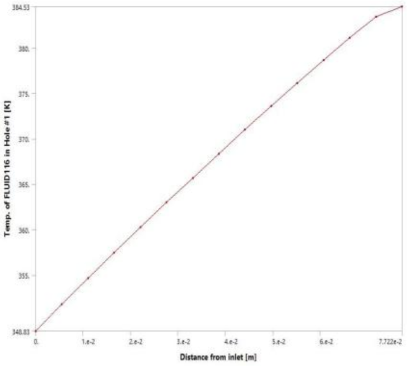
Steep temperature gradients exist

Geometric discontinuities are present

Thermal expansion is constrained

7.4 Discussion and Engineering Implications

The results confirm that internal convection cooling significantly reduces blade metal temperatures, particularly near critical regions. However, the presence of strong thermal gradients and constrained thermal expansion leads to high thermal stresses, especially near small-diameter cooling holes and blade root regions.



7.2 Structural Results

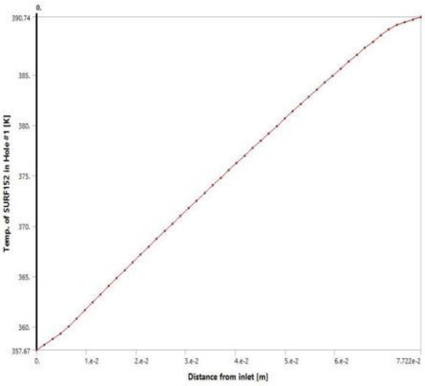
Maximum von Mises stress:

High stresses occur where:

These findings emphasize the need for:

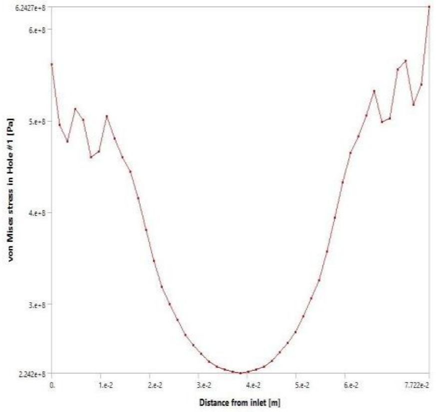
- Optimized cooling passage layout,
- Balanced coolant mass flow distribution,
- Careful control of temperature gradients to mitigate thermal stress concentrations.

Graph between fluid and its distance



Graph of surface and inlet distance

Graph of Stress in hole and its Inlet



Key observations:

Internal cooling effectively reduces metal temperature. Steep gradients generate high thermal stresses

.

Cooling holes introduce stress concentrat

Reduced-order modeling provides:

Faster computation

Suitable accuracy for design studies

Feasible workflow for parametric optimization

8. Engineering Implications

Optimization must balance cooling efficiency and structural reliability.

9. Conclusion

This study presented a coupled thermal-structural analysis of an internally cooled turbine blade using ANSYS Workbench.

Major findings: Maximum blade temperature:
568 K Minimum cooled region temperature: 338 K Maximum coolant temperature:
562 K Maximum von Mises stress: 2.79 × 10^9 Pa

Internal convection cooling significantly lowers blade temperature but introduces large thermal stresses due to constrained expansion and geometric discontinuities.

The reduced-order fluid-solid coupling method provides an efficient and practical alternative to full CFD-based conjugate heat transfer simulations. It is well suited for preliminary design evaluation, academic research, and parametric optimization studies.

9. References

In addition to the NASA contractor reports listed above, the following literature provides foundational background on turbine blade heat transfer, internal cooling techniques, film cooling, and thermo-mechanical analysis using finite element methods:

Classical Turbine Heat Transfer & Cooling Literature

1. **Han, J. C., Dutta, S., & Ekkad, S. V. (2012).**

   Gas Turbine Heat Transfer and Cooling Technology.

   CRC Press, Boca Raton, FL.

   A comprehensive reference covering internal cooling, film cooling, heat- transfer correlations, and design practices for gas turbine blades and vanes.

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Internal Cooling Passage and Convection Correlations

4. **Han, J. C. (2004).**

   Heat Transfer and Friction Characteristics in Rectangular Channels with Rib Turbulators.

   ASME Journal of Heat Transfer, 126(2), pp. 206–213.

   Widely used correlations for internal cooling passages relevant to turbine blade design.

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   A Review of Turbine Blade Cooling

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6. **Nowinski, J. L. (1978).**

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   Pergamon Press, Oxford.

   Provides the theoretical basis for thermal stress analysis used in coupled thermo-structural simulations.

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   U.S. Program on Materials Technology for Ultra-Supercritical Coal Power Plants.

   Journal of Materials Engineering and Performance, 14(3), pp. 281–292. *Relevant for understanding high-temperature material behavior under thermal gradients.*

Finite Element Modeling and Reduced-Order Approaches

8. **ANSYS, Inc. (2025).**

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   Provides the theoretical formulation of SOLID278, SURF152, and FLUID116 elements used in this study.

9. **ANSYS, Inc. (2025).**

   ANSYS Mechanical APDL Element Reference.

   Detailed description of coupled thermal-fluid and surface-effect elements for convection modeling.

10. **Versteeg, H. K., & Malalasekera, W. (2007).**

    An Introduction to Computational Fluid Dynamics: The Finite Volume Method.

    Pearson Education.

    Useful for understanding the limitations and motivations behind reduced- order models compared to full CFD.