8–12 January 2024
Orlando, FL

Transition prediction in hypersonic regime on complex geometries with RANS-based models

L. Cutrone[1], A. Schettino[1], José I. Cardesa[2], Grégory Delattre[2], James G. Coder[3], Steven Qiang[3], E. Vogel[4], M. Choudhari[4]

[1] Centro Italiano Ricerche Aerospaziali (CIRA), Italy
[2] French Aerospace Lab (ONERA), Université de Toulouse, France
[3] Pennsylvania State University, USA
[4] NASA Langley, USA

Hypersonic Transition

Hypersonic flight is defined as flight in the higher atmosphere at a speed of more than Mach 5.

The recent revival of hypersonic flights is primarily motivated by:

- Prominent private enterprises (such as SpaceX, Boeing, and Lockheed Martin) spearheading the creation of advanced, extensively reusable reentry vehicles and ultra-fast aircraft.
- Emerging military threats (hypersonic missiles) with the necessity of improved reconnaissance capabilities and novel weapon interceptors

Challenges for the hypersonic flights

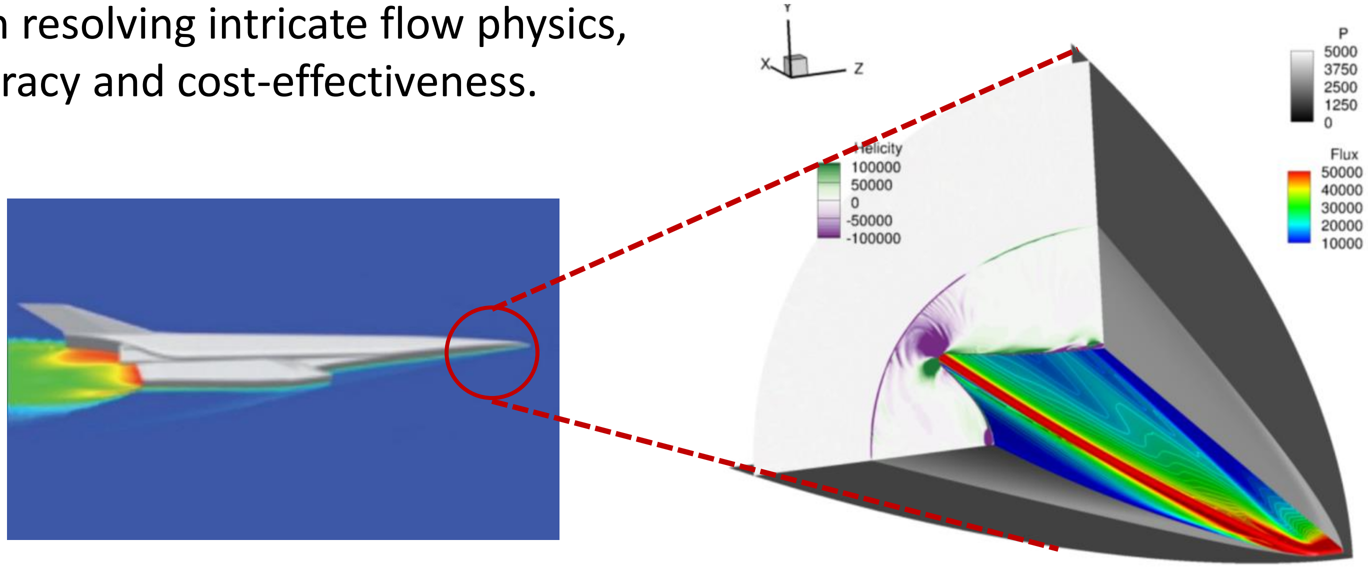
- Heat and heat management (intense heat generated by air compression)
- Aerodynamic efficiency (increased friction) and structural integrity (increased pressure)
- Stability and control, reentry and manoeuvring (increased aerodynamic instabilities)

Transition prediction within RANS frameworks

RANS computations, though inherently limited in resolving intricate flow physics, achieve a trade-off between computational accuracy and cost-effectiveness.

RANS still the current standard today

1. Hypersonic flow simulations around complex geometries (3D unstructured grids, heavily partitioned domains)
2. Simulations on full body geometries (coupling aero/propulsion within same code)



Scope of the paper

- **Assessment of RANS Transition models for hypersonic transition predictions**
  - Initial Local-Correlation Transition Models (LCTM) based on the concept of intermittency
  - Recently developed models (fully algebraic, hypersonic variant, etc.)
  - Based on linear stability and amplification factor (AFT)

- **Validation with respect to Experimental data**

- **Comparison of different CFD solvers**
  - 1 commercial solver: Ansys FLUENT
  - 2 research solvers: CEDRE (ONERA), and OVERFLOW (NASA, PSU)

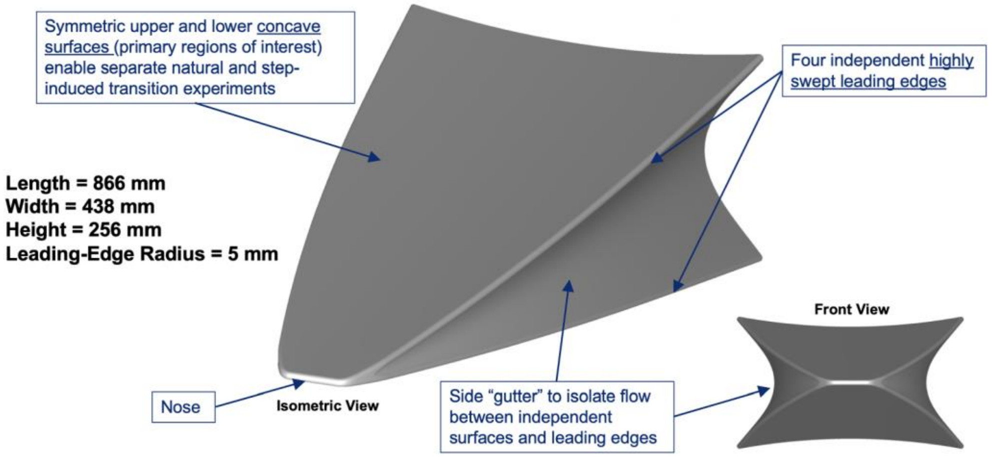
Activities

1. **Cross-model comparisons** keeping the CFD code the same

2. **Sensitivity analysis to model input parameters** (across codes and models)

3. **Cross-code comparisons**
   - Same test case
   - Same boundary conditions
   - Same computational mesh
   - Same turbulence and transition models
     (to cross-check numerics)

RUN SETUP



The Boundary Layer Transition (BOLT) flight experiment was a project lead by Johns Hopkins University Applied Physics Laboratory under the support of AFRL/AFOSR

MAIN GEOMETRICAL FEATURES

- Two primary concave surfaces (upper and lower faces) to conduct the main transition experiments: one smooth and one rough
- Four independent swept leading edges to perform different experiments examining distributed roughness transition

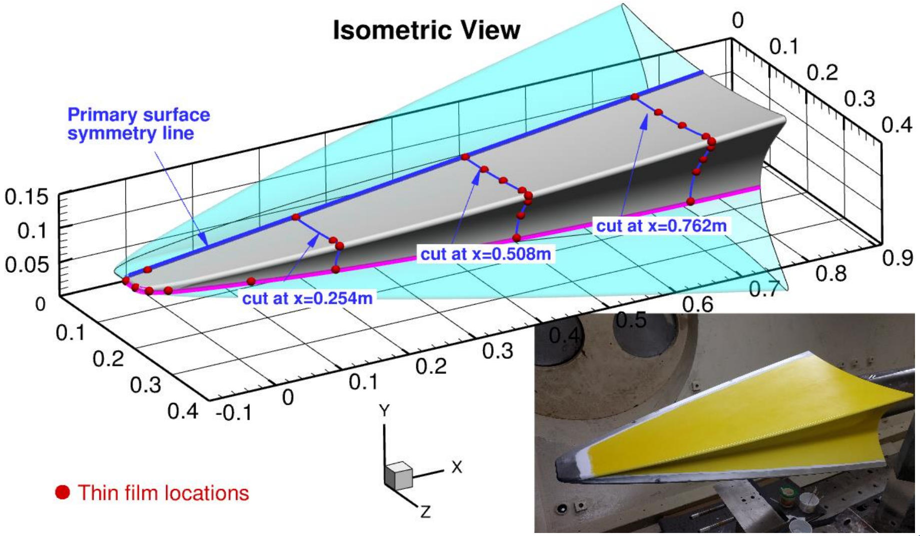
CUBRC experiments, 1:1 model

	RUN-03
Mach	5.17
$Re_L/10^6$	3.93
α,β	0,0

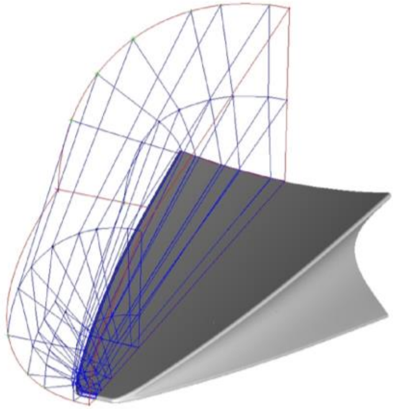
Experimental Data:

Thermal sensitive paint TSP

37 thin films



CFD SETUP



Multi-block, Hexahedral meshes*

- Grid C: 3.5M
- Grid M: 24M
- Grid F: 60M

Wall first cell height:
$\Delta y_1 = 1 \cdot 10^{-6}\text{m} \quad (\Delta y_1^+ < 1)$

**Point-matched versions converted in unstructured and overset formats*

[1] D.C. Berridge, G. McKiernan, T.P. Wadhams, M. Holden, B.M. Wheaton, T.D. Wolf, and S.P. Schneider. Hypersonic ground tests in support of the boundary layer transition (bolt) flight experiment. In 2018 Fluid Dynamics Conference, page 2893, 2018

TRANSITION MODELS

MODELS

#	Transition Model		Type	Turbulence Model[1]	Crossflow	Run & Results
1	2009 Langtry Menter	$\gamma - Re_\theta$	PDE	SST2003	1A: No (Baseline)	PennState
					1B: Yes	
2	2015 Menter (Fluent version[2])	γ	PDE	SST2003-KT[3] SST2003-V	2A: No (Baseline)	CIRA Centro Italiano Ricerche Aerospaziali; ONERA THE FRENCH AEROSPACE LAB
					2B: Yes (Normal change of vorticity)	CIRA Centro Italiano Ricerche Aerospaziali
3	2022 Menter	γ	Algebraic	SST2003-KT SST2003-V	No	CIRA Centro Italiano Ricerche Aerospaziali; ONERA THE FRENCH AEROSPACE LAB
4	2022 Liu et al	γ	PDE	SST2003-V	4A: No (Baseline)	NASA; ONERA THE FRENCH AEROSPACE LAB
					4B: Yes (Helicity)	
5	AFT2019b	$\gamma - \tilde{n}$	PDE	SA	5A: No (Baseline)	PennState
					5B: Yes (Helicity)	

[1]according to nomenclature used at https://turbmodels.larc.nasa.gov/

[2]Fluent User Guide (V2023R1) reports a variant with respect to the one in *Flow Turbulence Combust* **95**, 583–619 (2015)

[3]Fluent User Guide (V2023R1) reports a variant with respect to the one in *Turbulence, Heat and Mass transfer* **4**, 625–632 (2003)

TRANSITION MODELS

#	Transition Model
1	2009 Langtry Menter
2	2015 Menter (Fluent version[2])
3	2022 Menter
4	2022 Liu et al
5	AFT2019b

Models 1, 2, 4 are based on the concept of intermittency and solve for an additional PDE

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho U_j \gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\gamma}\right)\frac{\partial \gamma}{\partial x_j}\right]$$

$$P_\gamma = F_{length}\,\rho S \gamma\,(1-\gamma)\,F_{onset}$$

$$F_{\text{onset1}} = \max(F_{\text{onset,s}}, F_{\text{onset,cf}})$$

(streamwise: $F_{\text{onset,s}}$; crossflow: $F_{\text{onset,cf}}$)

- **Model-1** solves a PDE for Re_θ, **Models 2** and **4** use an algebraic correlation
- **Model-2B** $$F_{\text{onset,cf}} = \min\left[\max\left[100\left(\frac{C_{RSF}}{150} G\Psi Re_v\right)\right]\right]$$
  - Derived from C1 correlation of Arnal
  - Criterion based on wall normal change of the normalized vorticity vector
  - pressure gradient parameter
- **Model-4B** $$F_{\text{onset,cf}} = \frac{\Delta H_{cf} Re_v}{f(Ma_{eL}, T_{eL}) C_{f,crit}}$$
  - Criterion based on local helicity (not Galilean invariant)
  - Depends on k
  - No dependence on surface roughness
  - Cf,crit is a design parameter reflecting wind tunnel noise

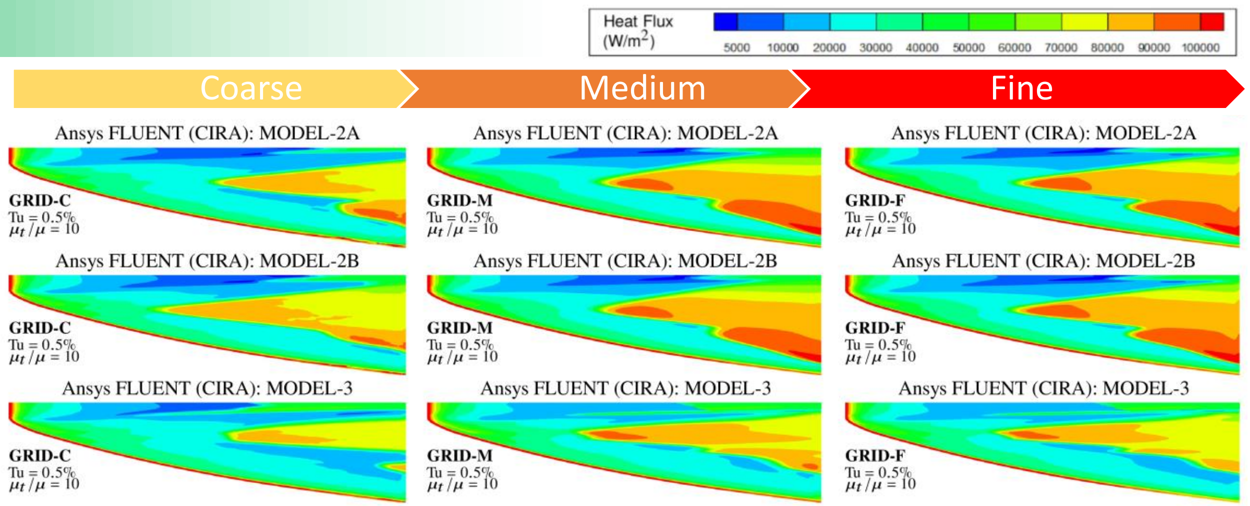
Model-3 introduces a purely algebraic formulation for intermittency

Model-5 relies on an a modified Intermittency and an (logarithmic) Amplification Factor Transport (AFT) equations

CODE DESCRIPTION – MESH SENSITIVITY 1/2

Overview of ANSYS® FLUENT® @ CIRA

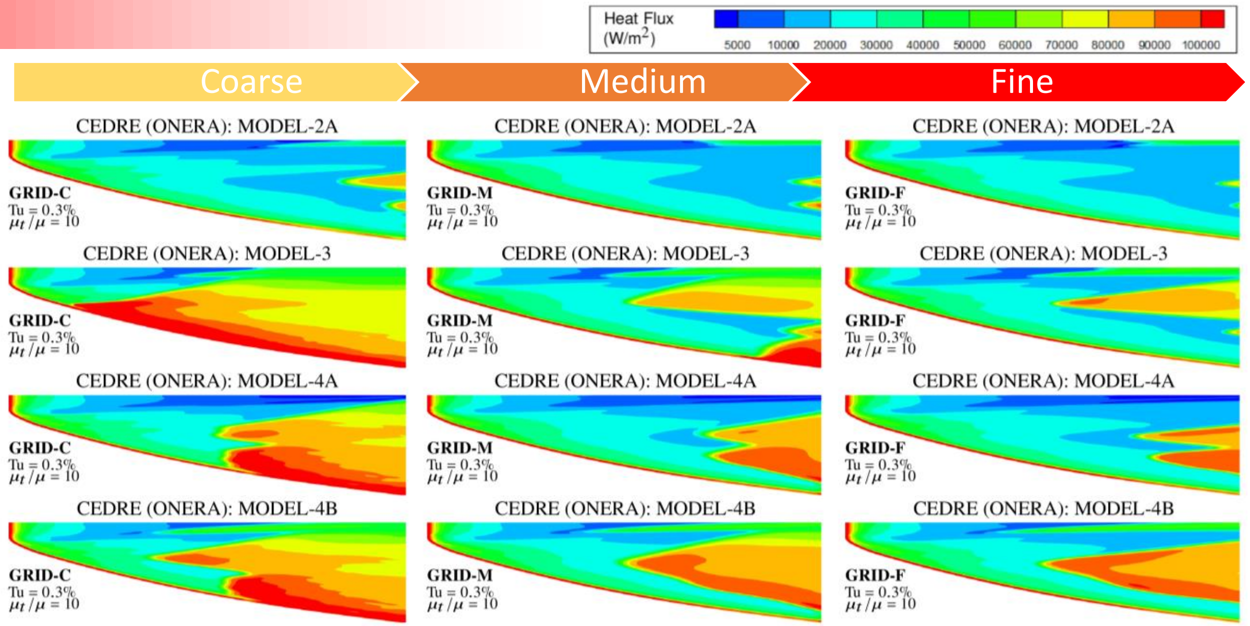
- Commercial CFD code
- Used as Reference Solver, owing to its contribution to the development of transition models (by F. Menter)



- AUSM+ upwind flux scheme
- Multidimensional linear reconstruction, with Minmod limiter
- Implicit Euler temporal scheme with ILU factorization
- Hexahedral Unstructured mesh
- SST2003-KT turbulence model

Overview of ONERA CEDRE

- multi-physics software suite developed by French aerospace lab (ONERA)
- CHARME, part of CEDRE, is the flow solver for Turbulent and Transitional RANS equations



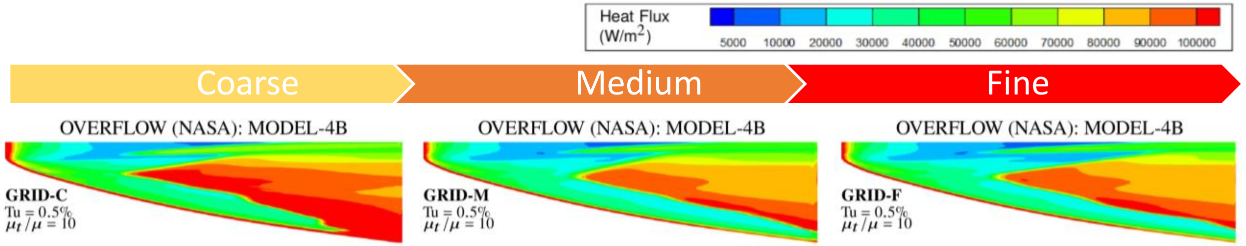
- AUSM+ upwind flux scheme
- Multislope MUSCL reconstruction, with van Leer limiter
- implicit Euler temporal scheme GMRES method
- Hexahedral Unstructured mesh
- SST2003-V turbulence model

CODE DESCRIPTION – MESH SENSITIVITY 2/2

Overview of NASA OVERFLOW 2.3e

- ➢ Developed by NASA Langley Research Center.
- ➢ Wide range of applications, from incompressible flows to the hypersonic regime.

- HLLE++ upwinded flux
- SSOR and the van Albada limiter
- <u>Overset mesh (point matched in the present case)</u>
- <u>SST2003-V turbulence model</u>

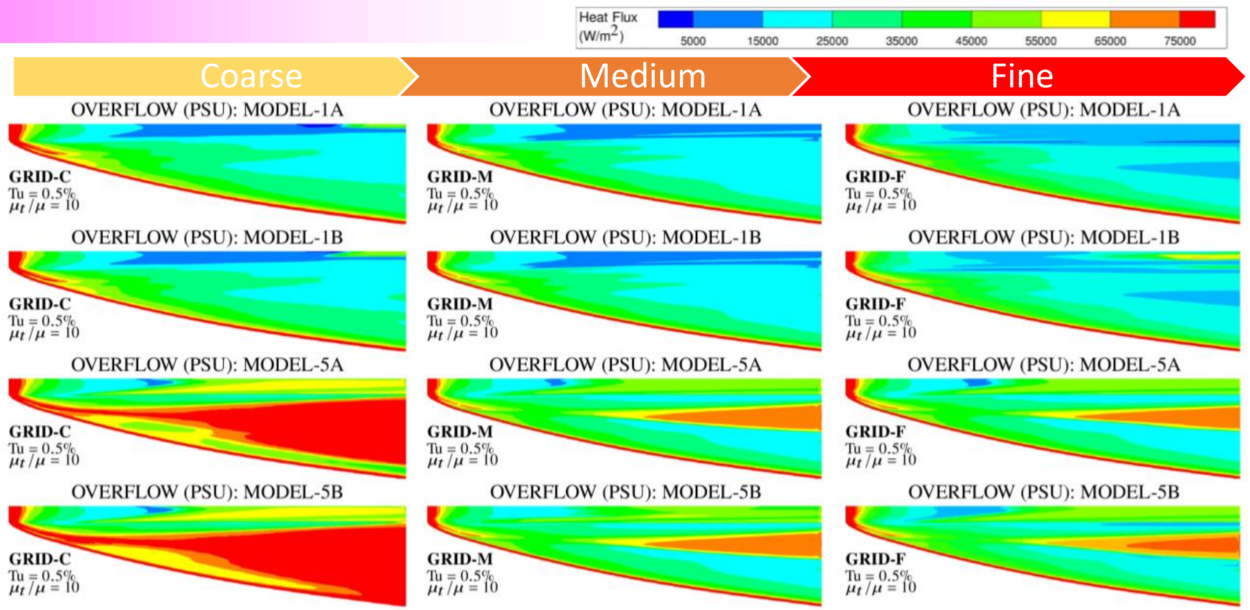


Overview of NASA OVERFLOW @ PSU

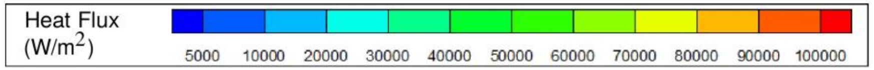
- ➢ Used as a development platform for the development of new transition models, like the Amplification Factor Transition model, AFT

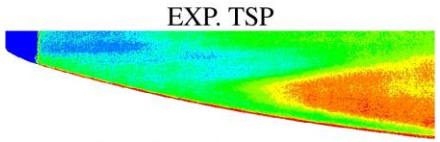
- HLLE++ upwinded flux
- SSOR and the van Albada limiter

- <u>SST2003 turbulence model</u>
- <u>Spalart-Allmaras 1 equation turbulence model</u>



FREESTREAM TURBULENCE SENSITIVITY





Turbulent intensity level $Tu = 100\sqrt{\frac{2}{3}\frac{k}{U_e^2}}$

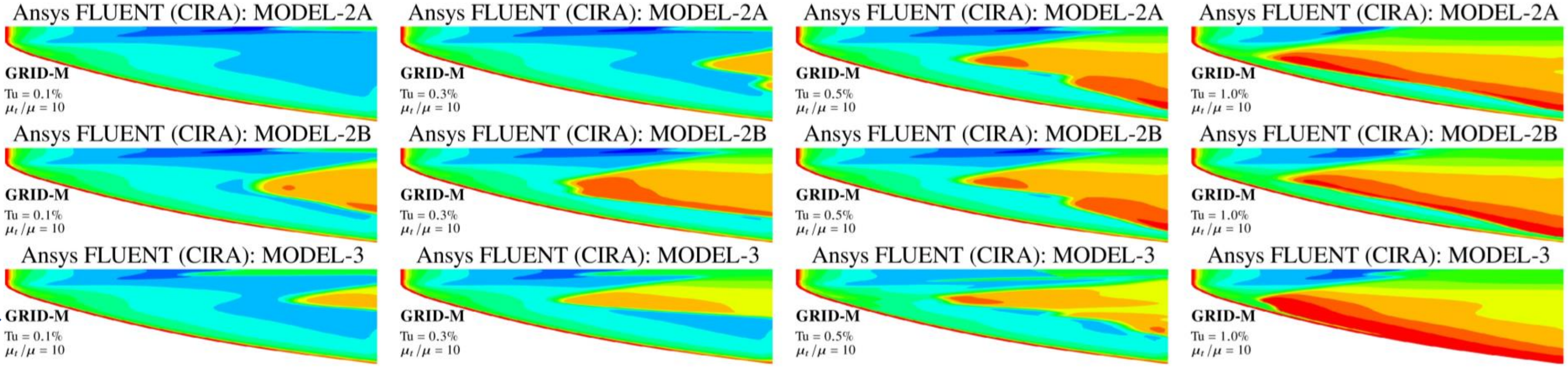
Tu=0.1% | **Tu=0.3%** | **Tu=0.5%** | **Tu=1%**

- Baseline Model-2 strongly dependent on freestream *Tu*
- Crossflow correlation triggers the transition also at low *Tu*

$$F_{\text{onset1}} = \max(F_{\text{onset},s}, F_{\text{onset,cf}})$$

(streamwise: $F_{\text{onset},s}$; crossflow: $F_{\text{onset,cf}}$)

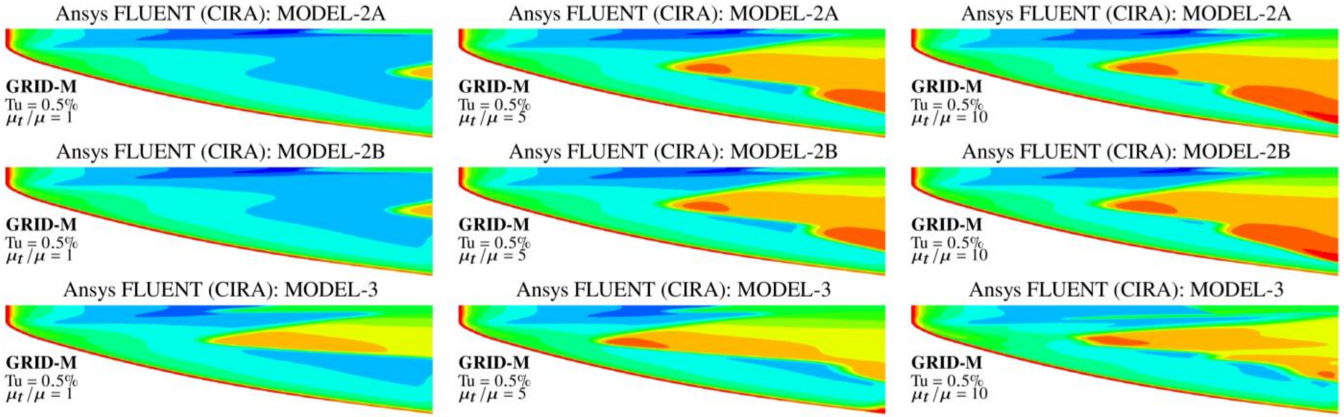
- Model-3 less sensitive to *Tu* (the model does not include a crossflow function)



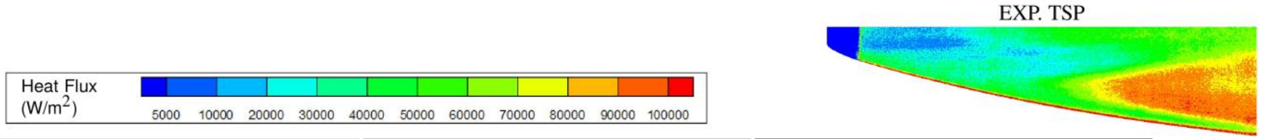
Viscosity ratio $RMUT = \frac{\mu_t}{\mu}$

RMUT=1 | **RMUT=5** | **RMUT=10**

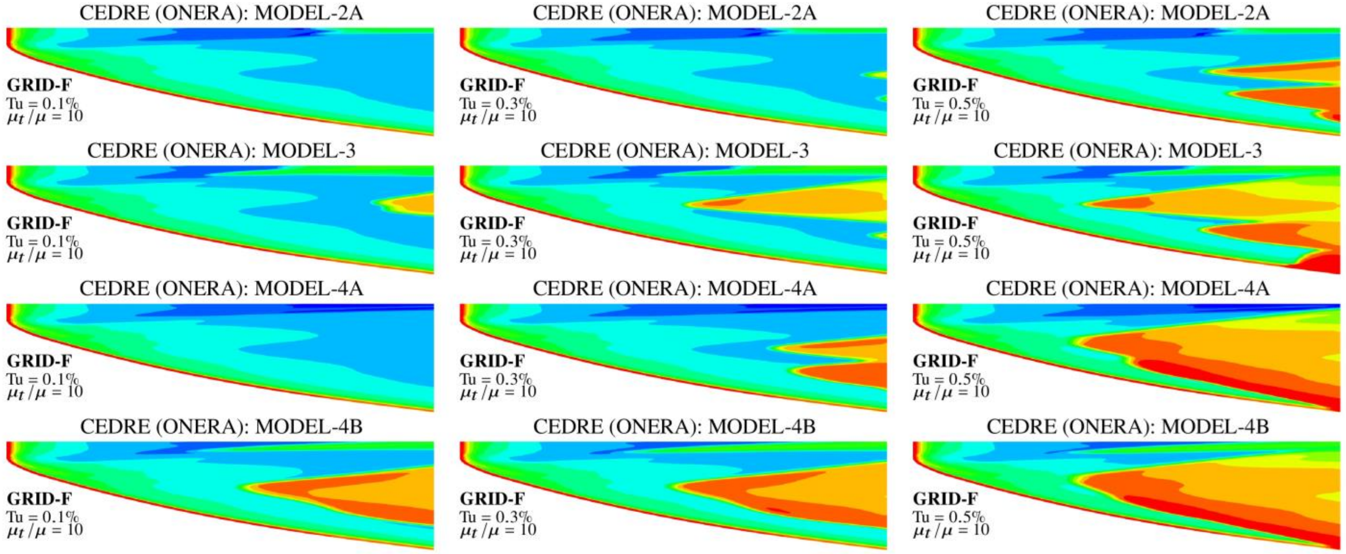
- As the viscosity ratio increases, the dependency on viscosity ratio decreases in Model-2 solutions.
- Model-3 predictions show substantially lower sensitivity to the viscosity ratio



FREESTREAM TURBULENCE SENSITIVITY



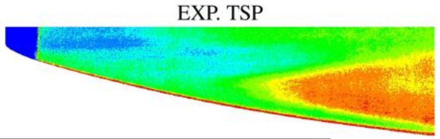
Turbulent intensity level	$Tu = 100\sqrt{\frac{2}{3}\frac{k}{U_e^2}}$	Tu=0.1%	Tu=0.3%	Tu=0.5%

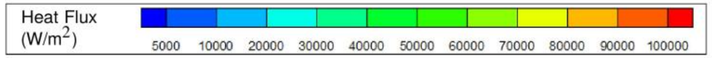


- Both models that rely only on streamwise correlation for the onset function are strongly dependent on the freestream *Tu*, with an earlier transition for increasing freestream *Tu*.
- Model-3 still demonstrates some dependency on the freestream *Tu*, but not as prominent as observed in Model-2.
- The impact of crossflow transition is evident in both the transition front shape within the mid-span region of the primary surface and the streamwise symmetry region.

Models incorporating a crossflow correlation successfully predicted transition even at low freestream turbulent intensity levels

FREESTREAM TURBULENCE SENSITIVITY



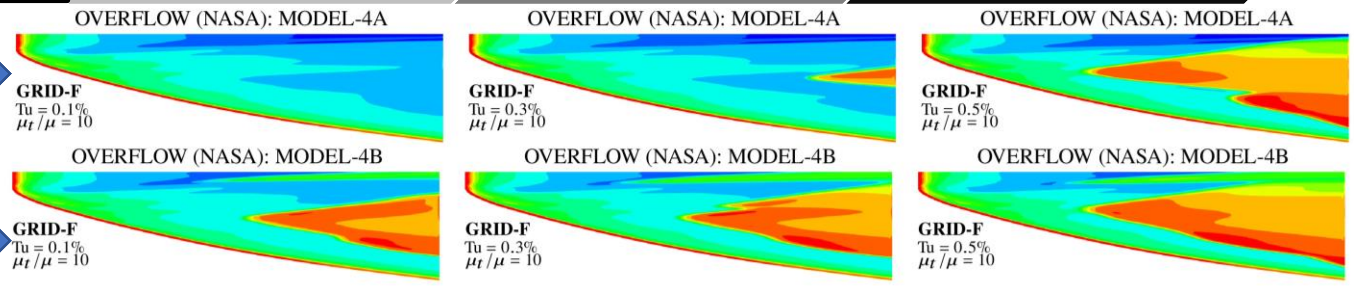


Turbulent intensity level

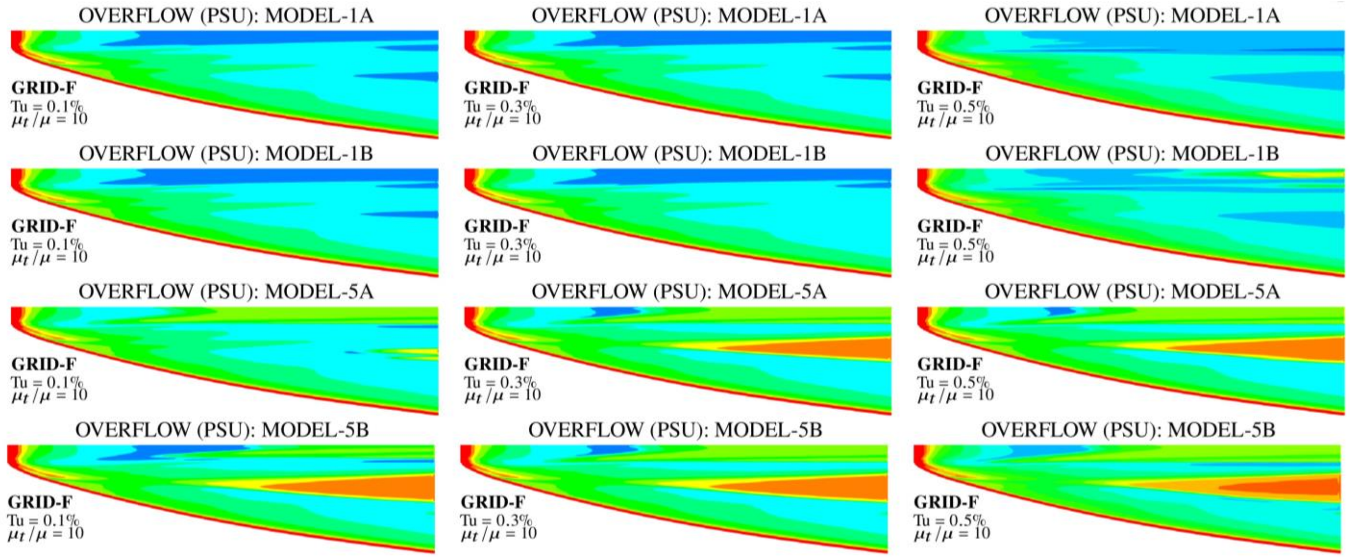
$$Tu = 100\sqrt{\frac{2}{3}\frac{k}{U_e^2}}$$

Tu=0.1% | **Tu=0.3%** | **Tu=0.5%**

- MODEL-4A shows strong sensitivity to the *Tu* level, leading to the downstream shift in the transition front as the freestream turbulence level decreases.
- Crossflow transition correlation appears to play a significant role in initiating the transition at lower *Tu*



- Observations suggest that the crossflow transition correlation plays a small but significant role for both MODEL-1 and MODEL-5.



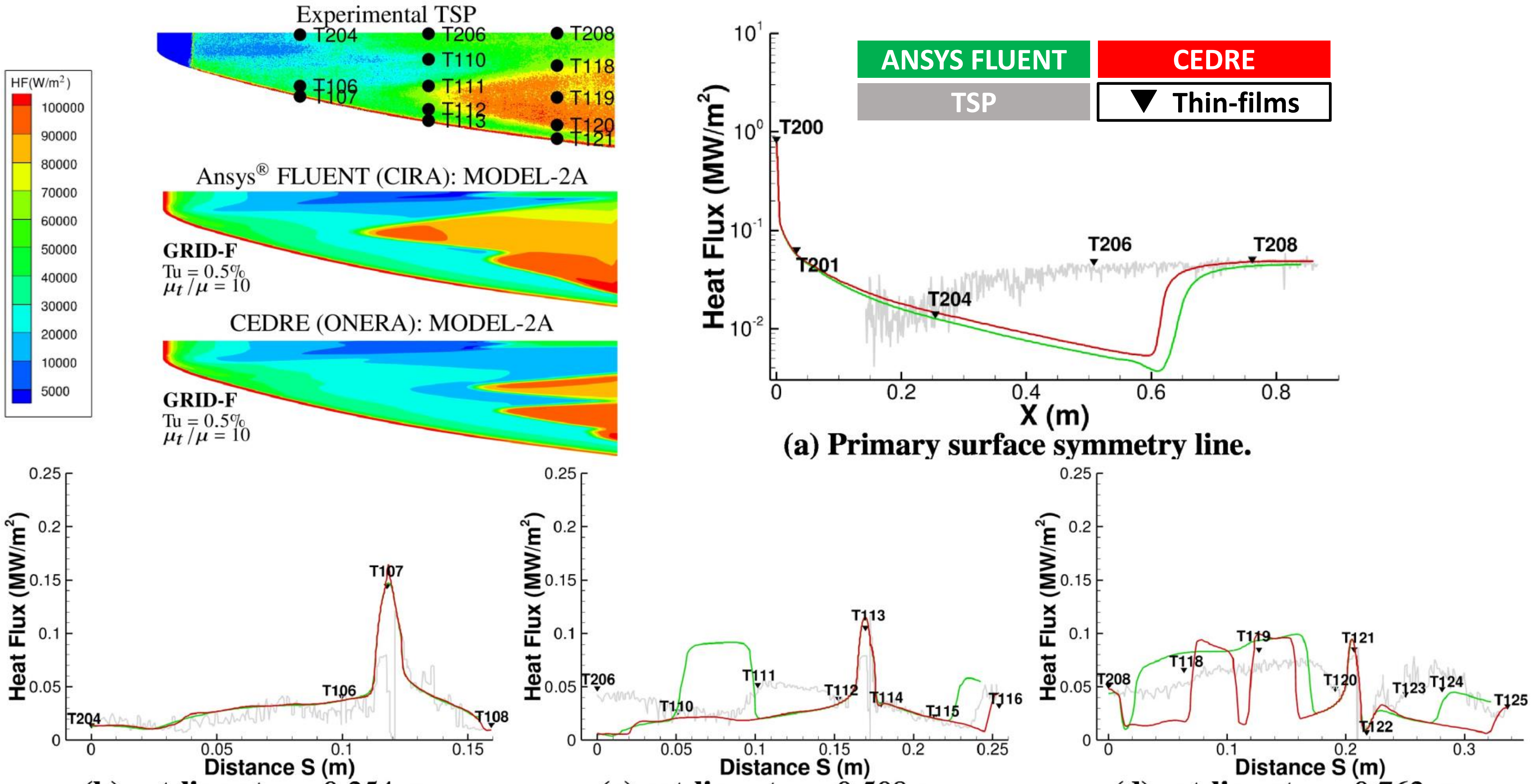
CROSS-CODE COMPARISONS

MODELS

#	Transition Model		Type	Turbulence Model	Crossflow	Run & Results
1	2009 Langtry Menter	$\gamma - Re_\theta$	PDE	SST-2003	1A: No 1B: Yes	PennState
2	2015 Menter (Fluent version)	γ	PDE	SST-2003-KT SST-2003-V	2A: No 2B: Yes (Normal change of vorticity)	2A: CIRA Centro Italiano Ricerche Aerospaziali, ONERA THE FRENCH AEROSPACE LAB 2B: CIRA Centro Italiano Ricerche Aerospaziali
3	2022 Menter	γ	Algebraic	SST-2003-KT SST-2003-V	No	CIRA Centro Italiano Ricerche Aerospaziali, ONERA THE FRENCH AEROSPACE LAB
4	2022 Liu et al	γ	PDE	SST-2003-V	4A: No 4B: Yes (Helicity)	NASA, ONERA THE FRENCH AEROSPACE LAB
5	AFT2019b	$\gamma - \tilde{n}$	PDE	SA	5A: No 5B: Yes (Helicity)	PennState

CROSS-CODE COMPARISONS

2	2015 Menter (Fluent version)	γ	PDE	SST-2003-KT SST-2003-V	2A: No	



(a) Primary surface symmetry line.

(b) cut-line at $x = 0.254$ m

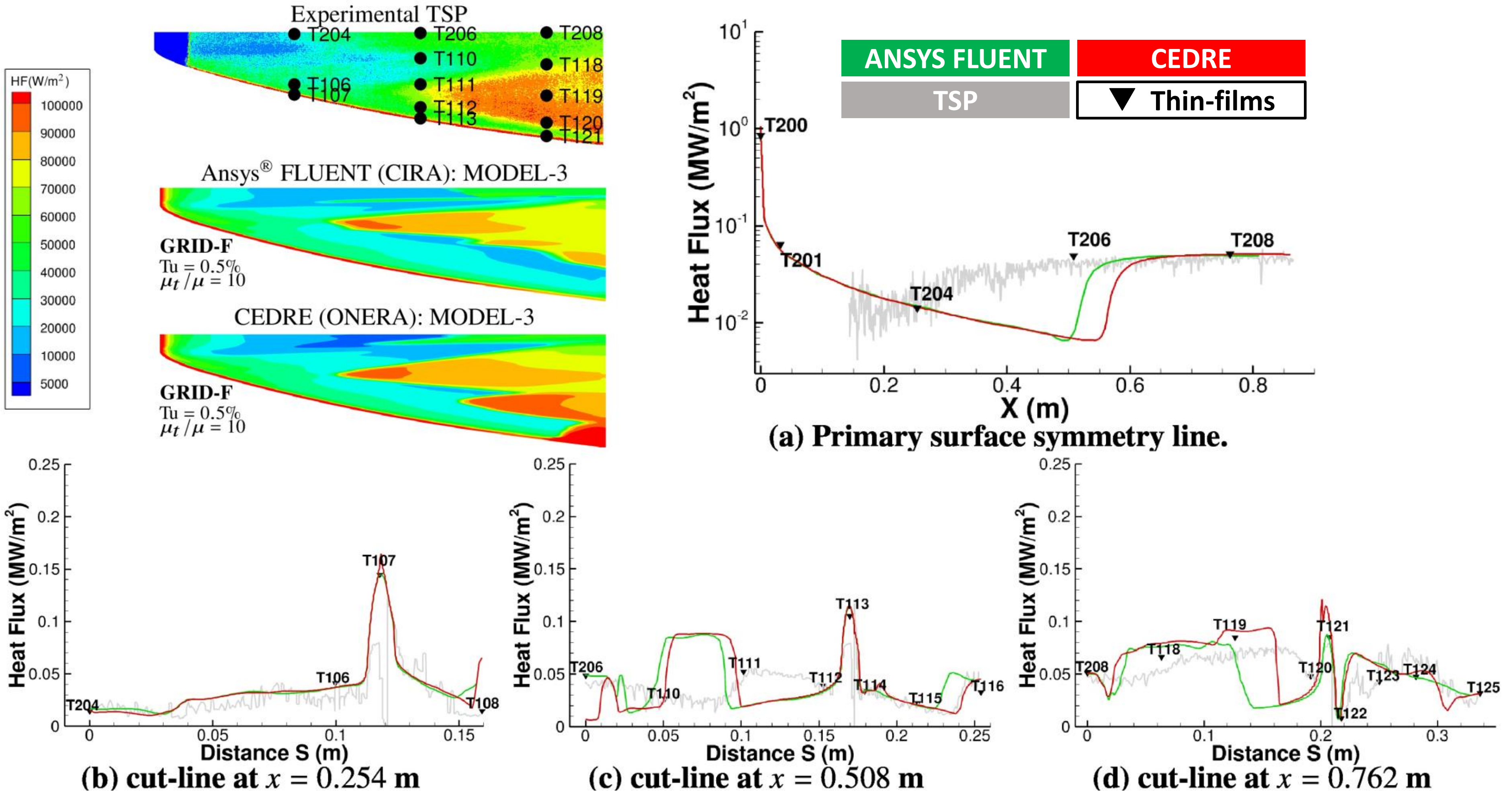
(c) cut-line at $x = 0.508$ m

(d) cut-line at $x = 0.762$ m

- Some disagreements are observed in the shape of the transition front, with Fluent results ahead.
- The Ansys Fluent solver appears to employ customized versions of the SST model and MODEL-2, with partial documentation found in the UG
- None of the codes are able to capture the gradual increase of heat flux on the symmetry line as from TSP profile

CROSS-CODE COMPARISONS

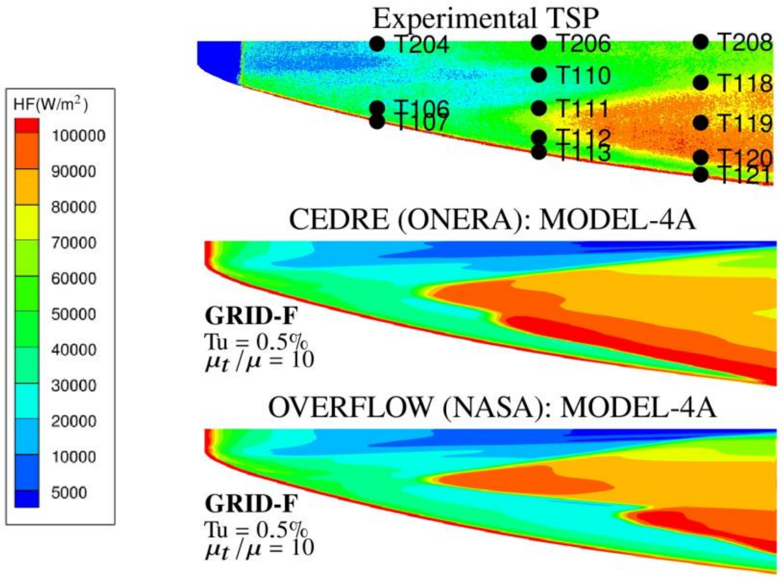
3	2022 Menter	γ	Algebraic	SST-2003-KT SST-2003-V	No	CIRA Centro Italiano Ricerche Aerospaziali / ONERA THE FRENCH AEROSPACE LAB

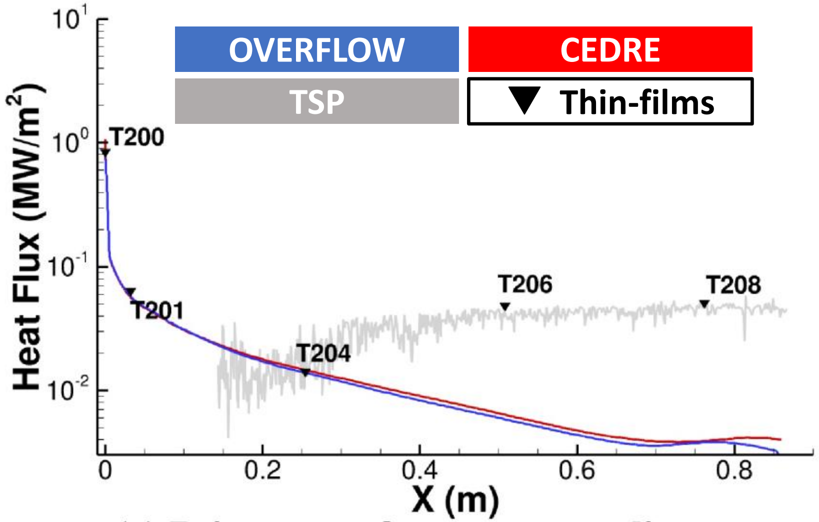


- Better agreement is observed in the shape of the transition front
- Fluent isless sensitive to mesh resolution
- Ansys Fluent and ONERA codes use similar versions of the SST model (Fluent use a customized version only partially documented)
- None of the codes are able to capture the gradual increase of heat flux on the symmetry line as from TSP profile

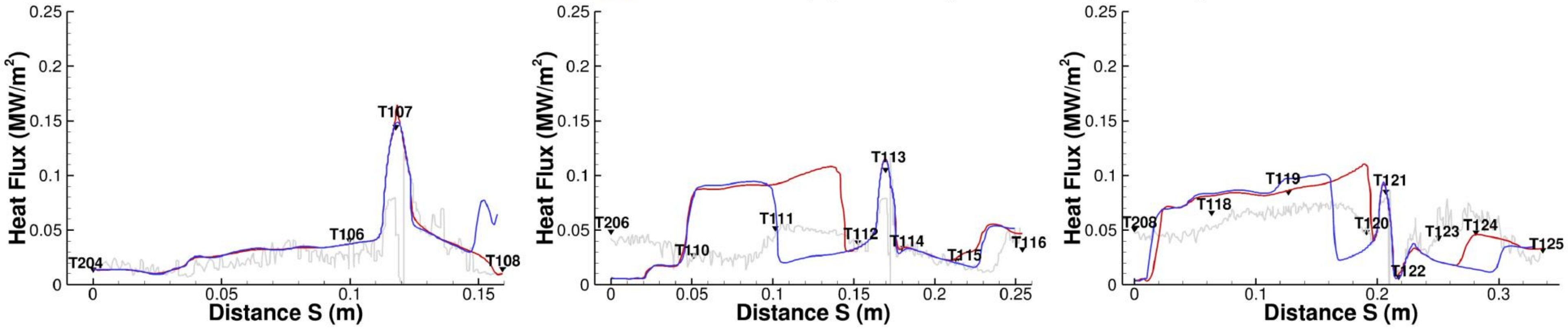
CROSS-CODE COMPARISONS

3	2022 Menter	γ				
4	2022 Liu et al	γ	PDE	SST-2003-V	4A: No 4B: Yes (Helicity)	NASA / ONERA THE FRENCH AEROSPACE LAB





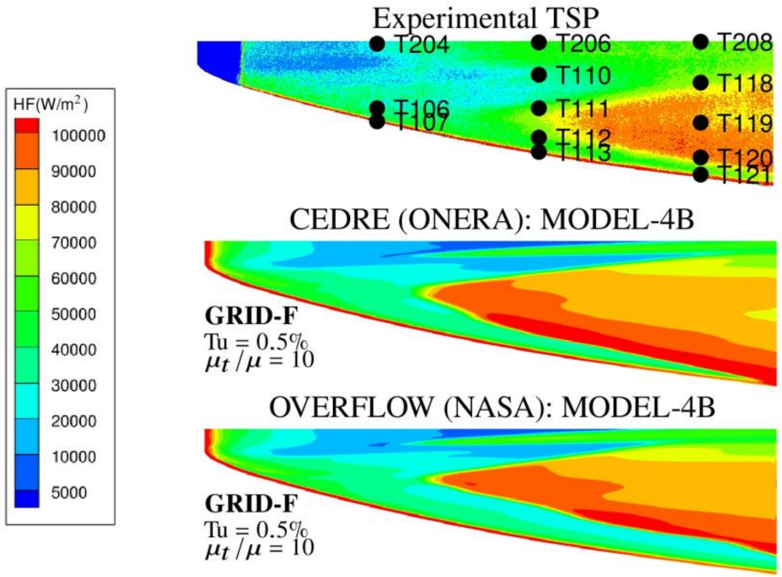
(a) Primary surface symmetry line.

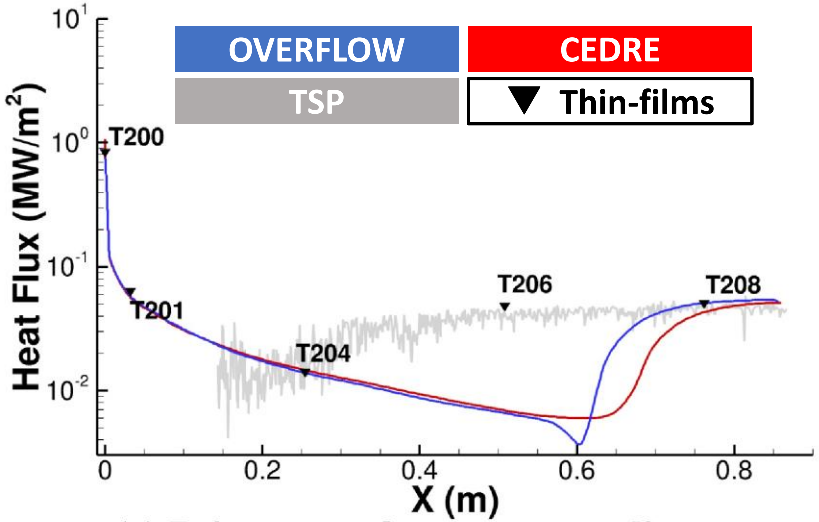


- Some disagreements between the two solvers are observed in the transition preditions for the outboard region (without crossflow)
- Detailed analysis has revealed this phenomena to be associated with the change in SST variables across the shock in each simulation
- NASA and ONERA solvers use similar (but not identical) versions of the SST model
- None of the solvers predict transition along the symmetry line

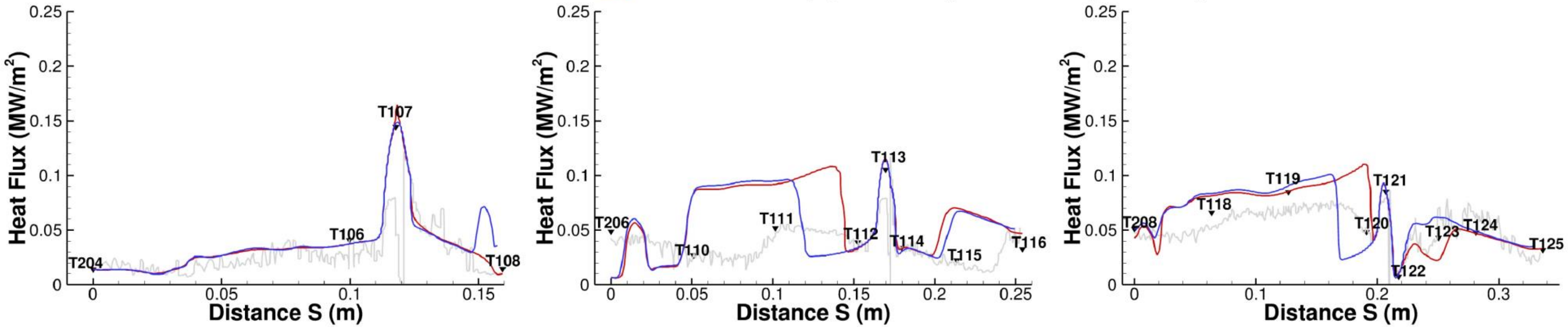
CROSS-CODE COMPARISONS

4	2022 Liu et al	γ	PDE	SST-2003-V	4A: No 4B: Yes (Helicity)	





(a) Primary surface symmetry line.



- Agreement greatly increases
- Marginal differences only in the precise boundary of the transition front (mostly near the edges of the model)
- Transition is also triggered on the symmetry line, albeit delayed with respect to TSP data.

CONCLUSIONS

- A comparative study of the performance of various transition models has been carried out by computing a common test case that corresponds to a full-scale BOLT model experiment at the CUBRC facility
- Three different CFD solvers have been cross compared: Ansys FLUENT, CEDRE (ONERA), and OVERFLOW (NASA).
- The sensitivity of the predicted transition front to parameters such as mesh resolution, free-stream turbulence intensity, and viscosity ratios has been thoroughly examined.

- A noteworthy trend emerged among models incorporating a crossflow correlation, as they successfully predicted transition even at low freestream turbulent intensity levels

FUTURE WORKS

- Cross-facility validation with experiment from ONERA Meudon (scale 1:3) and DLR (scale 1:2)

- Refinement of these models to better capture complex transition phenomena and to improve the accuracy of predictions

Acknowledgments

The authors would like to thank the NATO STO Research Task Group AVT-346 “Predicting Hypersonic Boundary Layer Transition on Complex Geometries.

NASA contributions are supported by the NASA Hypersonic Technologies Project (HTP) and the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at the Ames Research Center

Any questions?