Numerical Study of the Effect of the Wall to Gas Temperature Ratio on the Transition

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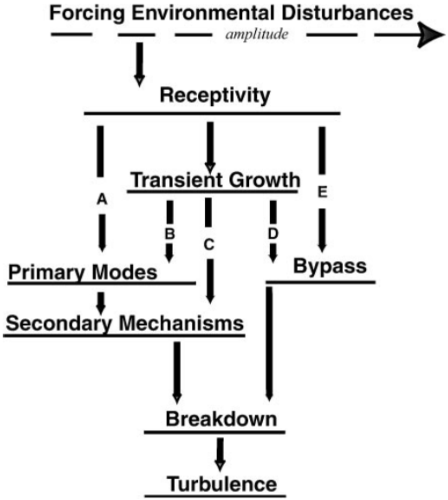
Laminar to Turbulent Transition



Unsteady Three Dimensional Stochastic Phenomenon

- Low disturbance Natural Transition

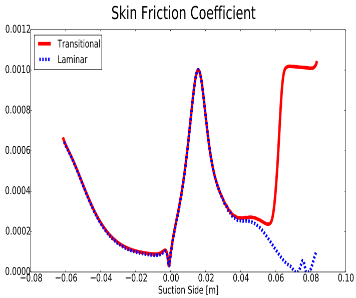
⋮

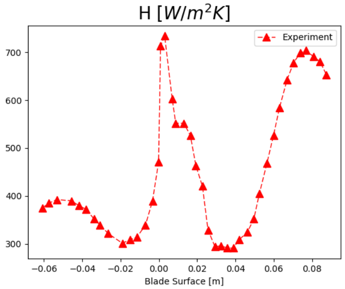
⋮

- High Disturbance Bypass Transition
- High Disturbance Separation Induced Transition

$\boxed{\text{Turbomachinery} \rightarrow \text{High Levels of } Tu}$

Transition in Turbomachinery





Why so important ?

- 75% of profile losses are attributed to the Suction Side boundary layer
- Thermal and Aerodynamic fields strongly coupled

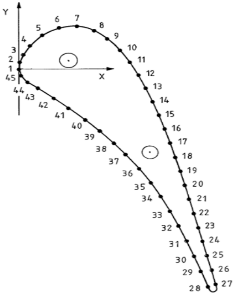
A reliable transitional boundary layer prediction model could help to...

- Improve aerodynamic and thermal performances
- Improve design strategies

Previous Studies

VKI

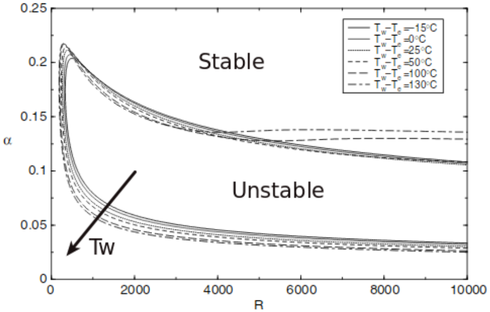
- Experimental study
- Reconstruction of intermittency through the wall heat flux



Some effects seem to be present

Literature

- Numerical study
- Framework of natural transition



Heating of the flow causes destabilization

Results valid only for natural transition

What we know so far:

From the experimental side

- Experimental campaign at VKI underlines alteration of the location of transition varying the T_{ratio}
- Experimental results on bypass transition from [6] underline the appearance of turbulent spots increasing $\frac{T_0}{T_{wall}}$

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From the numerical side

- Linear Stability Theory underlines that Temperature has some effects on natural transition [4]
- Turbulence Transition models seem to see some effects on T_w on the transition [1]

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- Experimental campaign at VKI underlines alteration of the location of transition varying the T_{ratio}
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- However it is a very difficult phenomenon to observe and interpret

From the numerical side

- Linear Stability Theory underlines that Temperature has some effects on natural transition [4]
- Turbulence Transition models seem to see some effects on T_w on the transition [1]
- It is unclear the effect and if this effect is physical or not

Main Tools and Objective

Main Objective

- Understand the capabilities and the limitation of the transition models in case of thermal field

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Approach

- Numerical simulation with state of the art turbulent transition models and comparison with experimental results

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Approach

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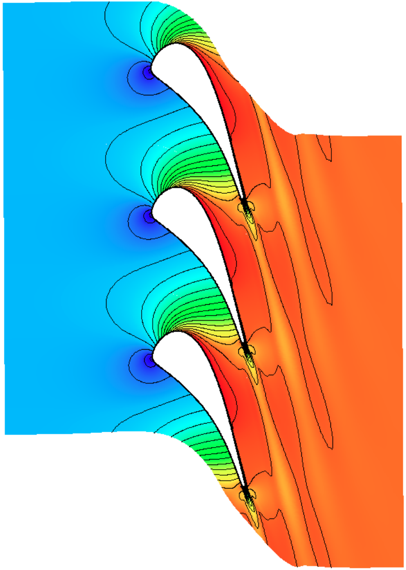
Limitations

- Transition models tuned on simple benchmark cases
- Fully validated on airfoils only from the aerodynamic point of view
- Not reliable validations in case of strong thermal field

Test Case and Approach

LS89 Transonic Cascade



Experimental Approach

- Same *Reynolds* and *Mach*
- Because T_{wall} ∼const

we reach the right $T_{ratio} = \frac{T_0}{T_{wall}}$ varying T_0

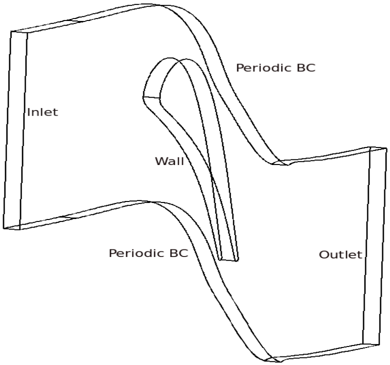
Numerical Approach

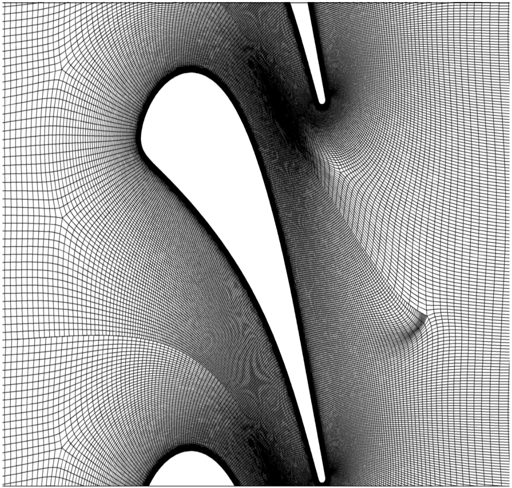
Same *Re* and *Mach*, we reach the same temperature ratio:

- Keeping the $T_{wall} = const$ and changing T_0
- Keeping Free Stream constant and varying the $T_{wall} = const$

We have same *Reynolds*, *Mach* and T_{ratio} in both cases, we expect a similar behaviour.

Computational Domain and Mesh





Boundary Conditions

- INLET: P_0, T_0, Tu, L_0
- OUTLET: P_{static}

Mesh Properties

- $y+ \sim 1$ first cell node
- Non matching periodicity $\rightarrow$ avoid high skeweness

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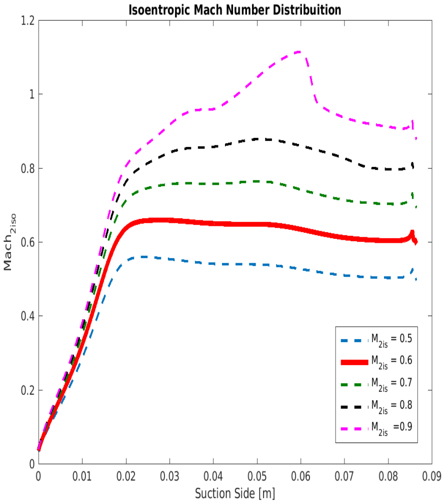
Looking for good working conditions

Parameters affect transition

- $\lambda \propto \frac{1}{U_\infty} \frac{dU_\infty}{ds}$
- Re
- $FSTI$

$\boxed{T \text{ influence} \ll \frac{dp}{ds} \text{ influence}}$



Good working point

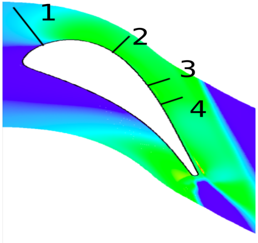
- $Re = 0.9 \cdot 10^6$
- $Mach_{2iso} = 0.55$

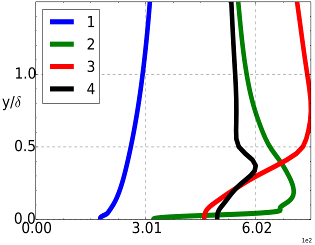
$\boxed{\text{Trade off between : Avoiding too big pressure gradients and preserve compressibility}}$

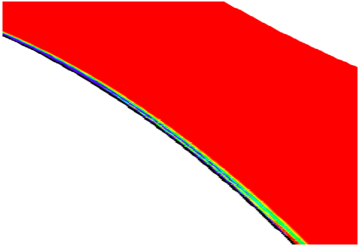
Insight $\gamma - Re_\theta$

- Evolution if $\gamma \sim \frac{\Delta T_{turb}}{\Delta T_{tot}} \in [0\ 1]$
- Evolution of $Re_\theta = \frac{U\theta}{\nu}$ momentum thickness Reynolds Number

$$\tilde{Re_\theta} = f(Tu, \frac{dp}{ds}) \rightarrow DIFF \text{ in } bl \rightarrow Re_\theta = f(\tilde{Re_\theta})\ P_\gamma = f(Re_v, Re_\theta) \rightarrow \gamma$$







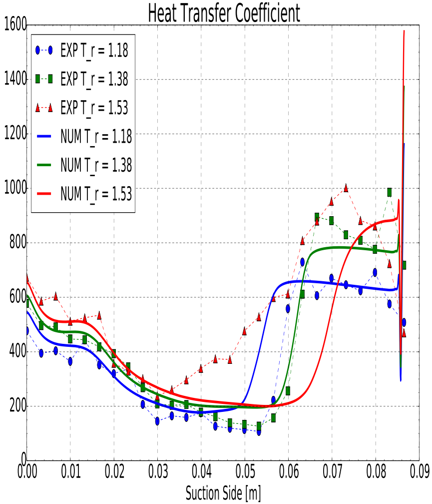
$$\frac{D(\rho k)}{Dt} = \gamma \cdot P_{k_T} - \gamma \cdot D_{k_T} + DIFF(k_T)$$

Final result $\gamma \rightarrow$ Production of turbulent kinetic energy

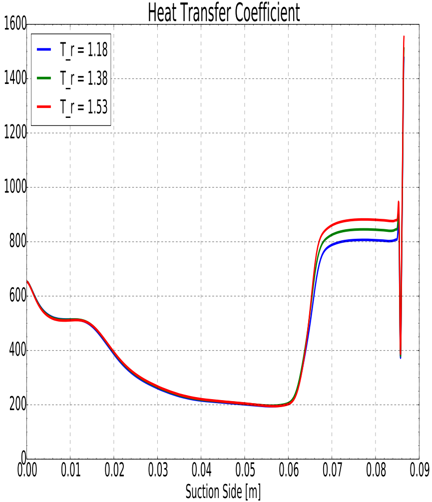
$\gamma - Re_\theta$ Results

$Mach = 0.55 \quad Re = 9.5 \cdot 10^5, \; Tu = 0.8\%$

Constant Blade Temperature

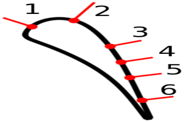


Constant Free Stream Conditions

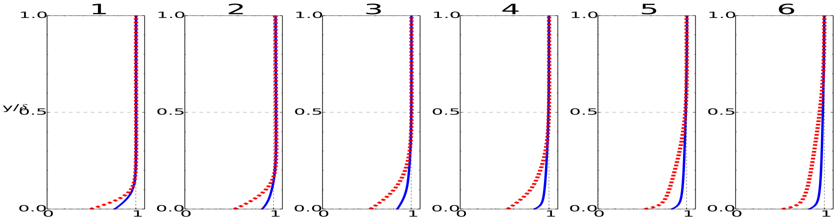


Comparison ν

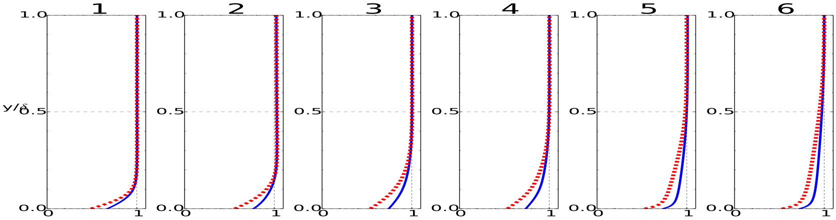
● $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$



T_{wall} = const



FreeStream = const



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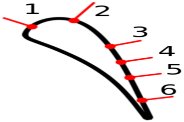
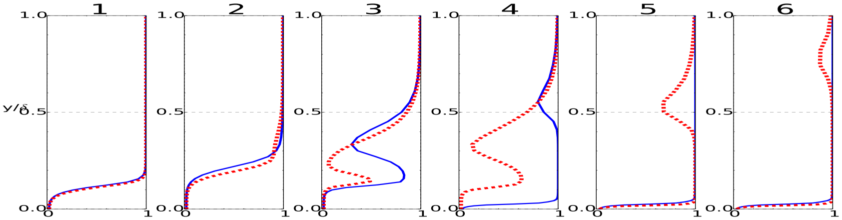
Comparison Intermittency

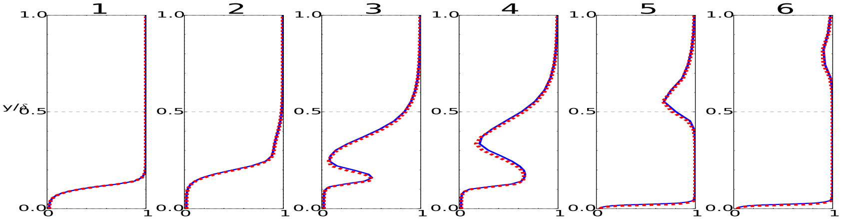
$\frac{T_\infty}{T_{wall}} = 1.53$ $\frac{T_\infty}{T_{wall}} = 1.18$



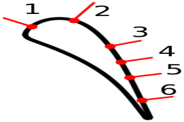
$T_{wall} = const$



$FreeStream = const$

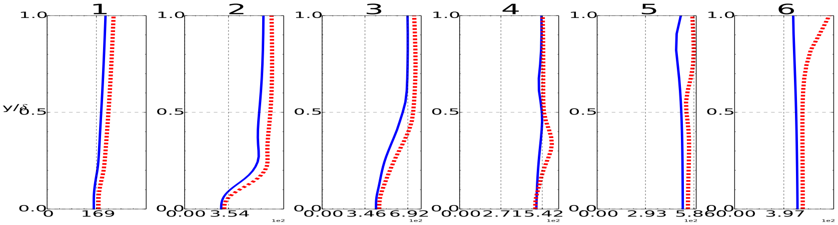


Comparison Momentum thickness Reynolds

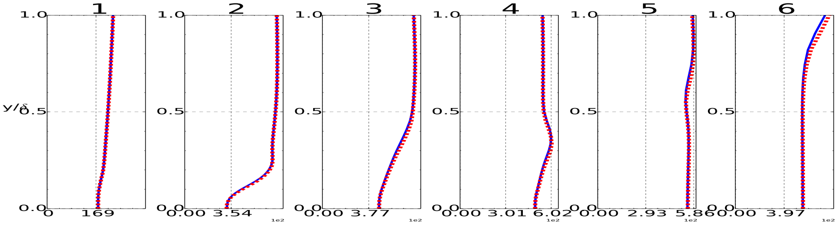


- $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$

$T_{wall} = const$



$FreeStream = const$



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$k - k_l - \omega$ Physical Meaning

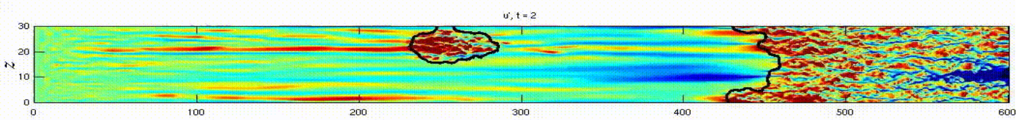
Model Composed by 3 equations

- Original $\boldsymbol{k - \omega - SST}$
  - 1 eq for $\boldsymbol{k_T} \rightarrow$ small scales
  - 1 eq for $\boldsymbol{\omega}$
- 1 eq for the evolution of $\boldsymbol{k_l} \rightarrow$ larger scales

Basic Idea

Energy transferred from the large scales to the smaller ones

[1]



Growth of $\boldsymbol{k_l}$ Breakdown Turbulent Flow $\boldsymbol{k_T}$

[1] DNS from Tamer Zaki's Research Group

Implementation

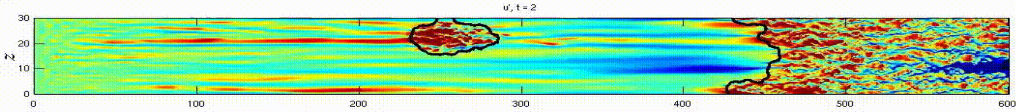
$$\frac{D(\rho k_T)}{Dt} = P_{k_T} + D_{k_T} + TRANS_{k_l \to k_T} + DIFF(k_T) \qquad (1)$$

$$\frac{D(\rho k_l)}{Dt} = P_{k_l} + D_{k_l} - TRANS_{k_l \to k_T} + DIFF(k_l) \qquad (2)$$

$TRANS_{k_l \to k_T}$ regulate the passage of energy

$TRANS_{k_l \to k_T} \quad \sim \quad \beta = 1 - e^{-\frac{\phi}{A}} \quad \sim \quad \boxed{\phi = max[\frac{k_T}{\nu\Omega} - C_{BP}, 0]}$

2



kl develops $\quad \frac{k_T}{\nu\Omega} > C_{BP} \to \phi_{BP} > 0 \quad k_l \to k_T$

[2] DNS from Tamer Zaki's Research Group

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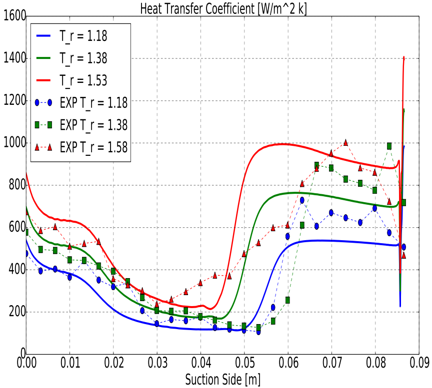
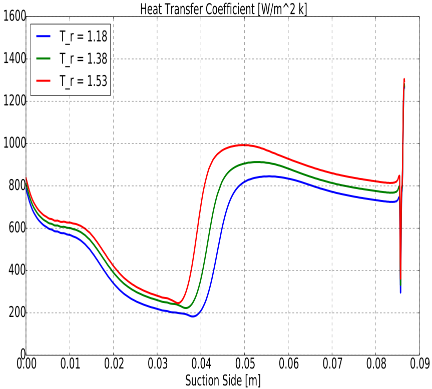
$k - k_l - \omega$ Results

$Mach = 0.55 \quad Re = 9.5 \cdot 10^5 \quad Tu = 0.8\%$

Constant Blade Temperature



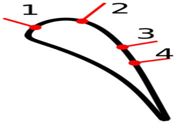
Constant Free Stream Conditions



$\boxed{\text{Remarkable fact} \rightarrow \text{Same behaviour in both cases}}$

Model's Quantities

● $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$



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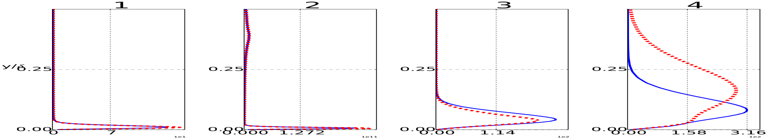
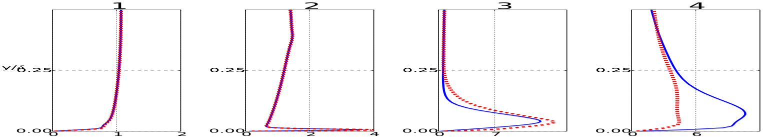
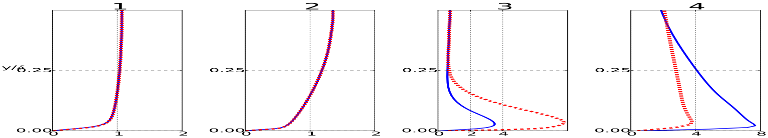
$$\frac{k_l}{(k_l)_\infty}$$



$$\frac{k_t}{(k_t)_\infty}$$



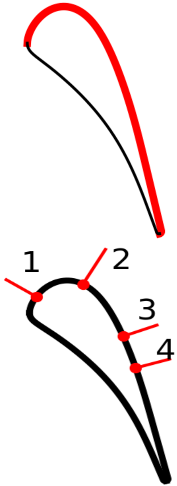
Energy Transfer

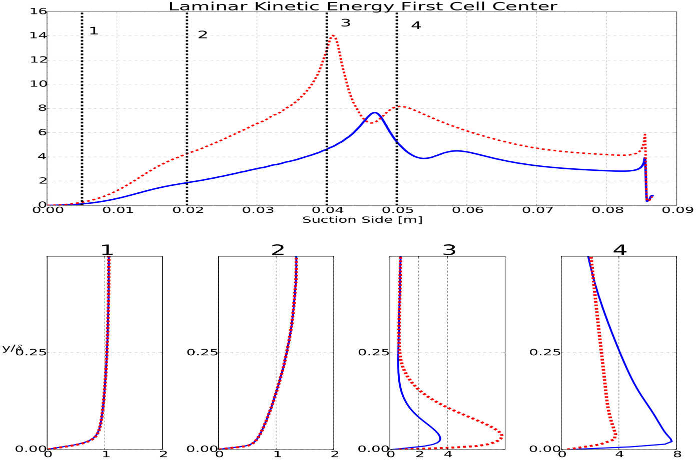


Laminar Kinetic Energy

$$TRANS_{k_l \to k_T} \sim \beta = 1 - e^{-\frac{\phi}{A}} \sim \boxed{\phi = max[\frac{k_T}{\nu\Omega} - C_{BP}, 0]}$$

T_{ratio} affects $\frac{k_T}{\nu\Omega}$ that leads a different values of $TRANS_{k_l \to k_T}$





Conclusions

Experiments

The flow results destabilized increasing the temperature ratio.

$\gamma - Re_\theta$

- Disagree with experimental results
- The behaviour is not conserved for the case at constant Free Stream
- Strong effect of the FreeStream on the value of Re_θ

$k - k_l - \omega$

- The temperature ratio seems to destabilize the flow
- Similar behaviour compared to the experimental results
- The behaviour is the same for both cases
- Threshold function influenced by more physical quantities

Future Challenges

- Better understanding of the role of the temperature ratio from the experimental side. A lot of conjoint effects very difficult to decouple one from each other.
- Better understanding of the real limits of the transition models with a proper calibration for this kind of conditions.
- High order simulation to have a deeper insight on the physics of the process (LES...)

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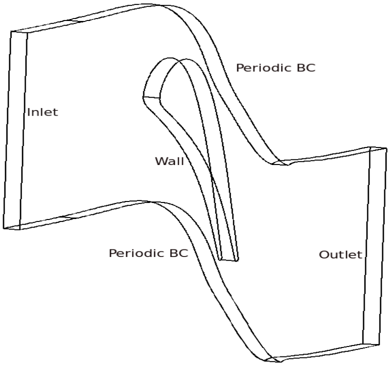
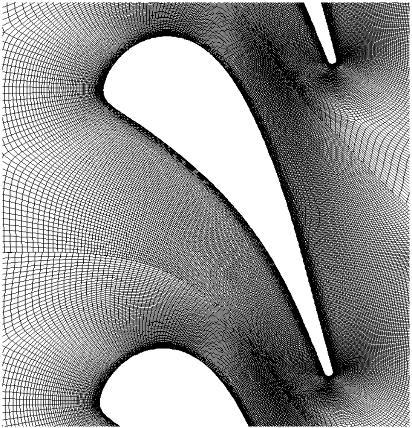
Simulation set up



Boundary Conditions

- INLET: P_0, T_0, Tu, L_0
- OUTLET: P_{static}

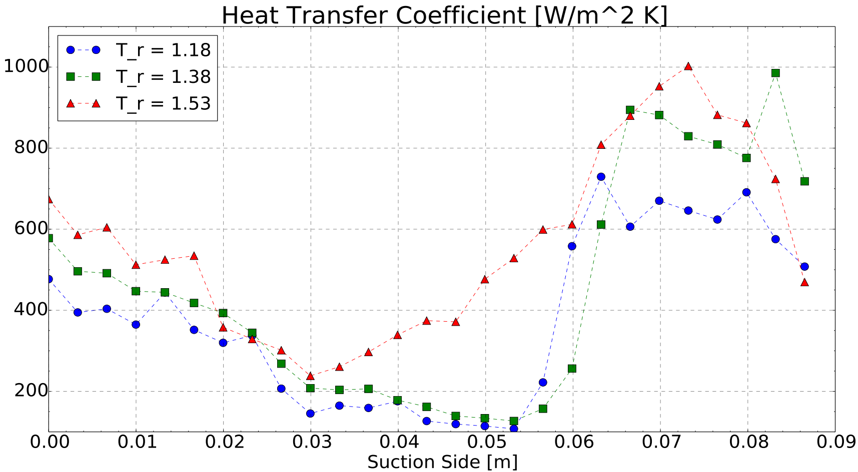


Mesh Prop

- $y+ \sim 1$ first cell node
- Non matching periodicity $\rightarrow$ avoid high skeweness

Trends from experiments

$Mach = 0.55 \quad Re = 9.5 \cdot 10^5 \quad Tu = 0.8\%$

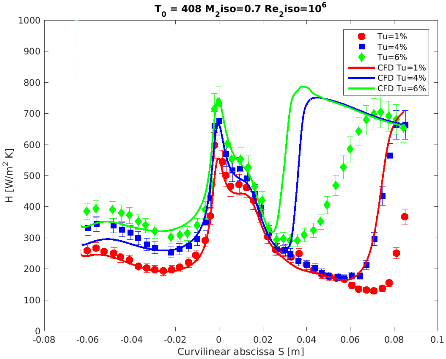


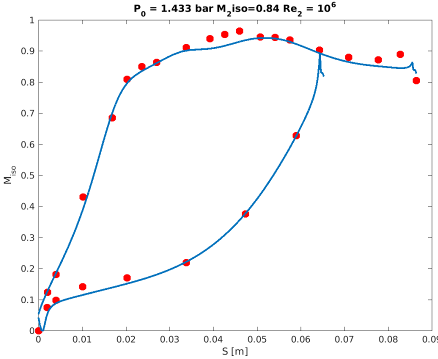
Experimental Results

The Temperature ratio seems to have some effects on the transition

Flow Conditions : $Mach_{2iso} = 0.7$ $Re_{2iso} = 10^6$

●	EXP
—	CFD





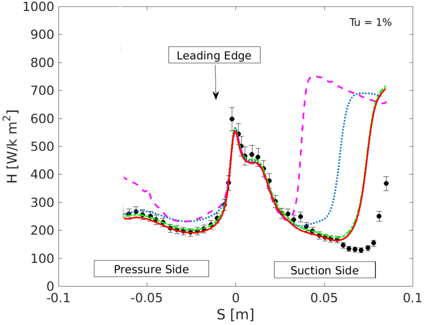
- reasonably good agreement in the laminar and turbulent part
- some discrepancy [3]

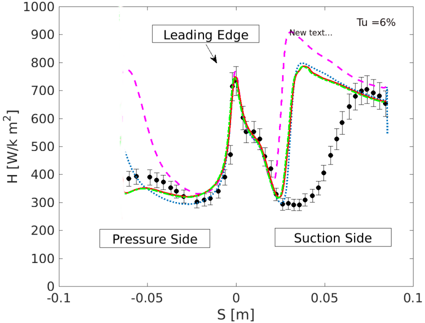
- kinematic field quite good described

Grid Independence

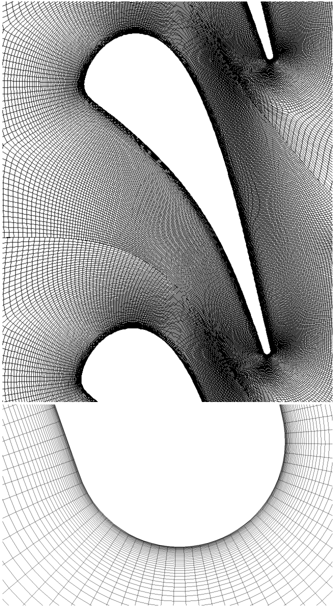
	INLET	OUTLET
$T_0[k]$	408	-
M_{iso}	-	0.7
Re_{iso}	-	10^6
Tu %	1-6	-
$L_0[mm]$	8	-

	Grid Nodes
●	Exp
magenta dashed line	50K
blue dotted line	80K
green dashed line	120K
red solid line	200K

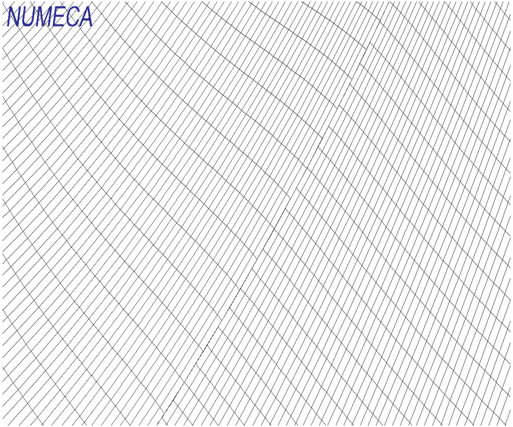




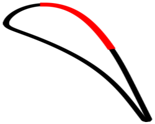
Mesh Properties



- Structured mesh with 4HO Topology 120.000 cells
- $y+ \sim 1$ in the first node cell

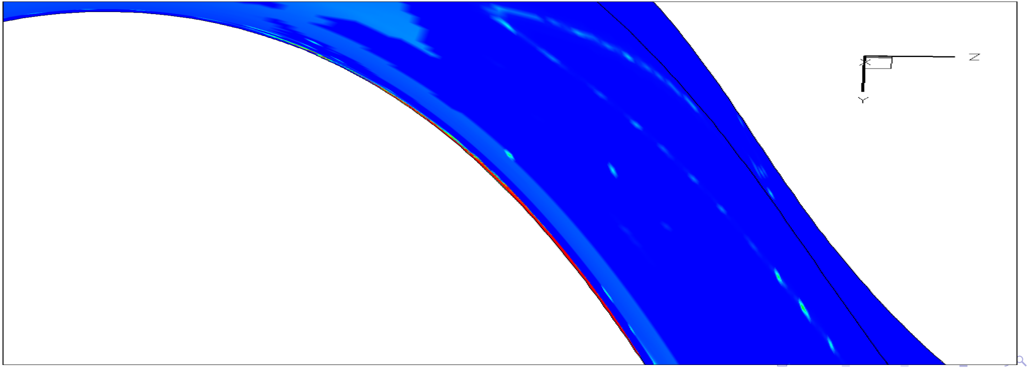


Behaviour Explanation 1



value of $\frac{k_T}{\nu\Omega}$ influenced mainly by ν (guessed)

$$\Delta = \left|\left(\frac{k_T}{\nu\Omega}\right)_{T_r=1.53} - \left(\frac{k_T}{\nu\Omega}\right)_{T_r=1.18}\right|$$



Insight $\gamma - Re_\theta$

$$\partial_t(\rho\gamma) + \partial_j(\rho u_j\gamma) = P_\gamma - E_\gamma + \partial_j((\mu + \mu_T/\sigma)\partial_j\gamma) \quad (3)$$

$$\partial_t(\rho\tilde{Re}_\theta) + \partial_j(\rho u_j\tilde{Re}_\theta) = P_\theta + \partial_j(\sigma(\mu + \mu_T)\partial_j\tilde{Re}_\theta) \quad (4)$$

Basic Idea

$\tilde{Re}_\theta \rightarrow \mathrm{P}_\gamma = f(Re_\theta) \rightarrow$ production γ $\rightarrow$ production of k $\mathrm{P}_k \rightarrow P_k\gamma$

$$\partial_t(\rho k) + \partial_j(\rho u_j k) = P_k + \partial_j(\sigma(\mu + \mu_T)\partial_j k) \quad (5)$$

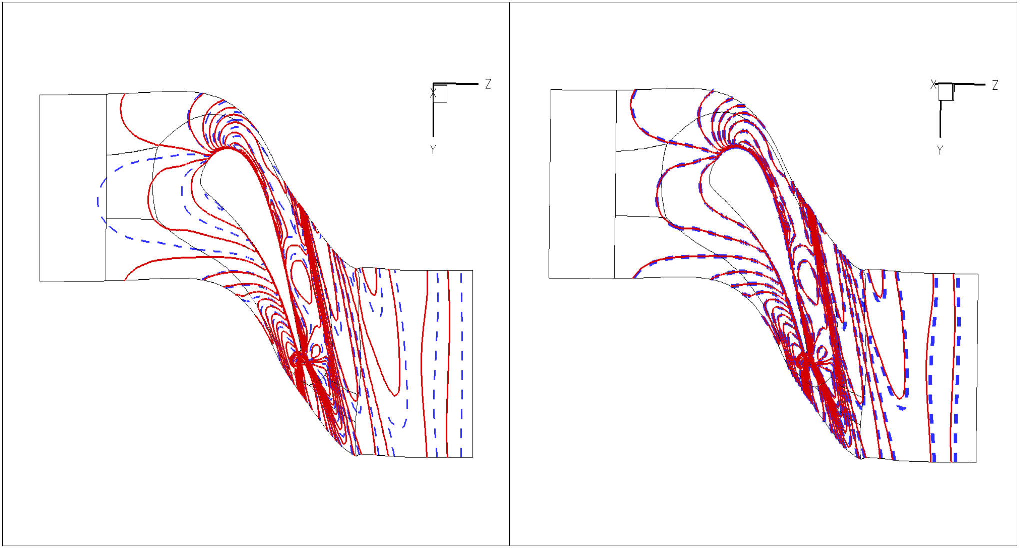
Final result

γ and Re_θ evolution $\rightarrow$ k $\rightarrow$ *turbulence*

Behaviour Explanation 3

- (red) $\frac{T_\infty}{T_{wall}} = 1.53$
- (blue) $\frac{T_\infty}{T_{wall}} = 1.18$

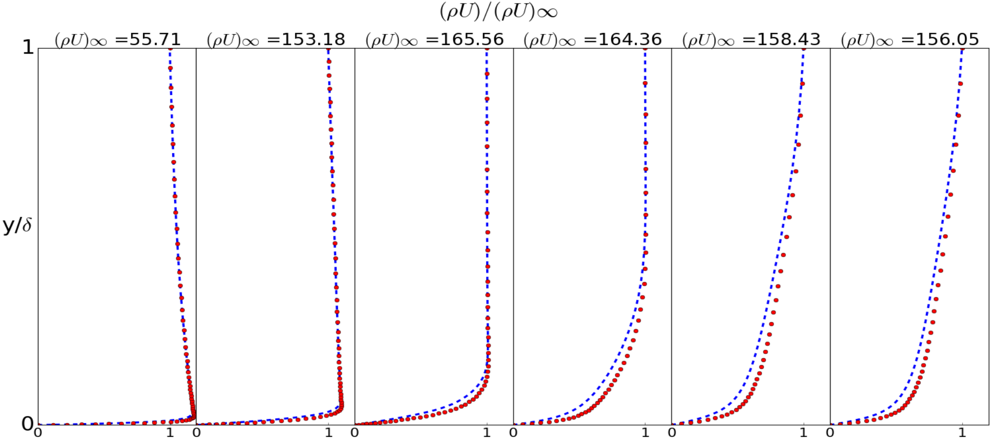
$T_{wall} = const$ | $FS = const$



Effects on Momentum Thickness

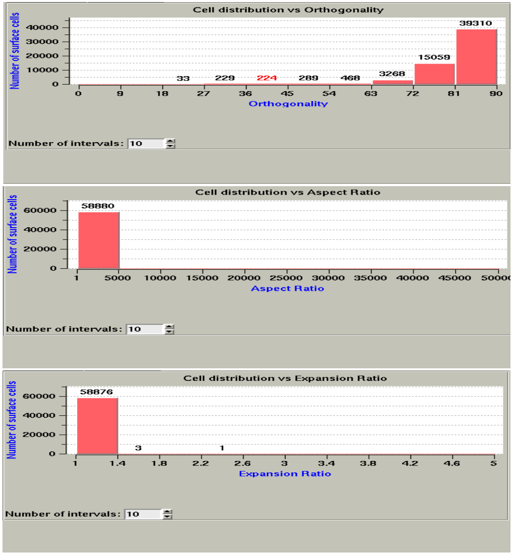
●	$\frac{T_\infty}{T_{wall}} = 1.53$
—	$\frac{T_\infty}{T_{wall}} = 1.18$

Leading – Edge $\Longrightarrow$ $\Longrightarrow$ *Trailing – Edge*



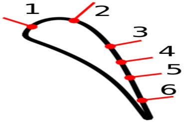
$\Delta\theta/\theta$	0.32 %	0.52 %	1.3 %	3.6 %	6.85 %	6.5 %

Mesh Quality

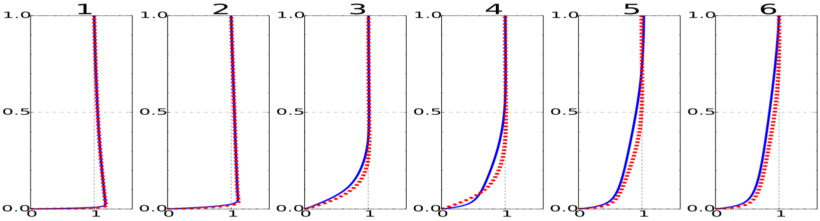


Comparison Massflow $\gamma - Re_\theta$

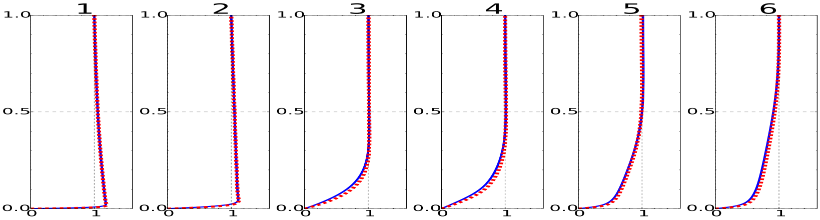
● $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$



T_{wall} = const

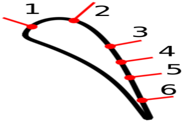


FreeStream = const

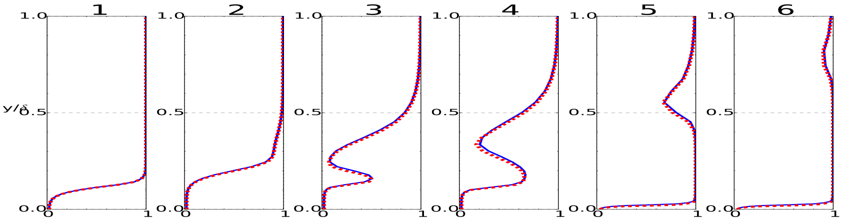


Case *FreeStream = const*: γ and Re_θ

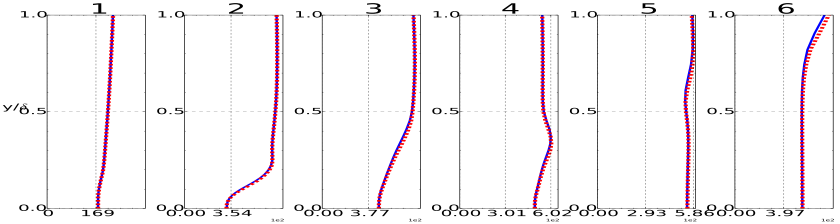
● $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$



Intermittency



Momentum Thickness Reynolds Number



$\gamma - Re_\theta$ Details

$\boldsymbol{Re_\theta = \frac{U\theta}{\nu}}$

Define $\boldsymbol{\tilde{Re_\theta} = f(Tu, \frac{dp}{ds})}$

Let $\boldsymbol{\tilde{Re_\theta}}$ diffuse inside the bl

Reconstruct $\boldsymbol{Re_\theta = f(\tilde{Re_\theta})}$

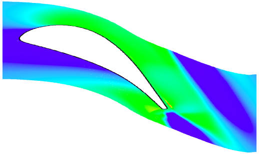
Observation : inside the bl $\boldsymbol{max(Re_v) \sim R_\theta}$ Define

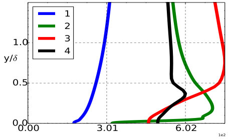
$$\boldsymbol{F_{onset} = \frac{max(Re_v)}{2.193 \cdot Re_\theta}}$$

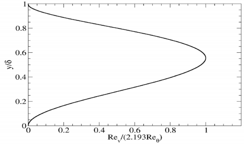
$\boldsymbol{Re_v = \frac{d_w^2 S}{\nu}}$ contains only local quantities Correlate

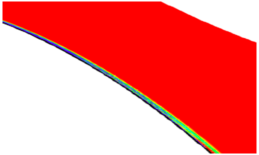
$\boldsymbol{P_\gamma \sim F_{onset}}$

$\boldsymbol{P_\gamma} \sim$ evolution of $\gamma \rightarrow \boldsymbol{k}$



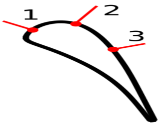






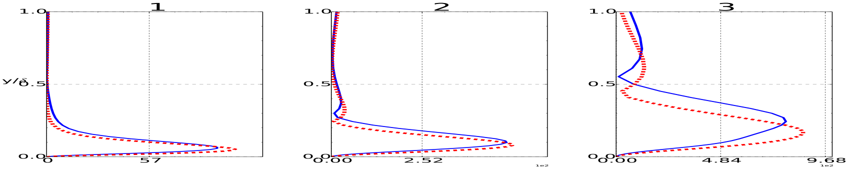
Explanation 1 $Re_{Vorticity}$

● $\frac{T_\infty}{T_{wall}} = 1.53$ ——— $\frac{T_\infty}{T_{wall}} = 1.18$

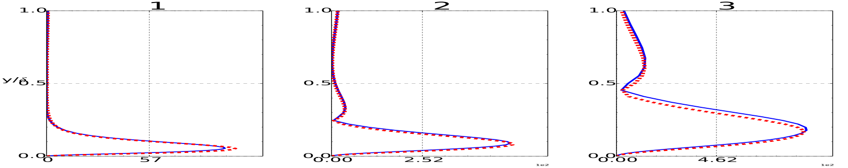


Transition triggered by $\boldsymbol{F_{onset}} \sim \frac{\boldsymbol{max(Re_v)}}{\boldsymbol{R_{\theta c}}}$ $\quad$ $\boldsymbol{Re_v = \frac{d^2 S}{\nu}}$

$T_{wall} = const \;\; Re_{vorticity}$

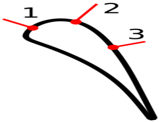


$FreeStream = const \;\; Re_{vorticity}$



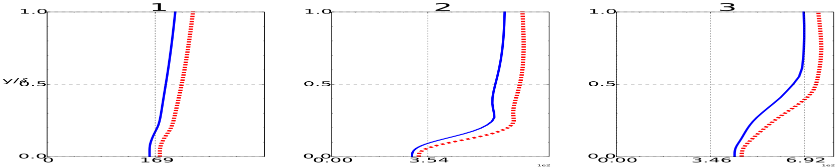
Explanation 2 $Re_{\theta c}$

- $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$

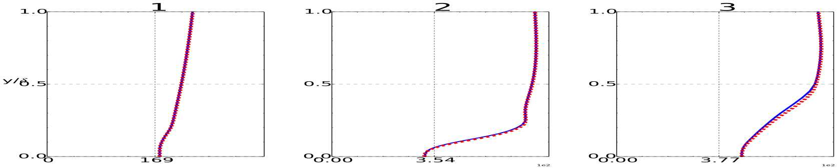


Transition triggered by $\boldsymbol{F_{onset}} \sim \frac{\boldsymbol{max(Re_v)}}{\boldsymbol{R_{\theta c}}}$

$T_{wall} = const\ \ Re_\theta$



$FreeStream = const\ \ Re_\theta$



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