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

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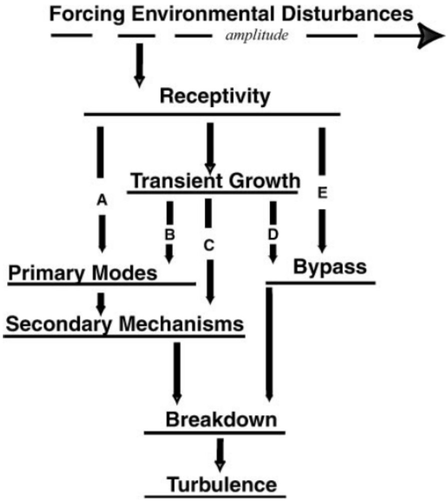
Laminar to Turbulent Transition



Unsteady Three Dimensional Stochastic Phenomena

- Low disturbance Natural Transition

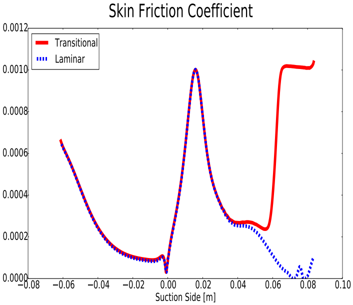
⋮

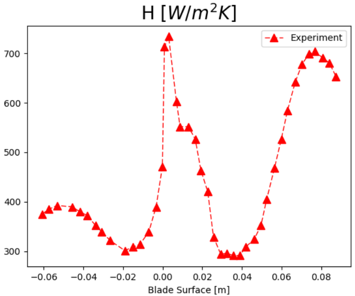
⋮

- 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

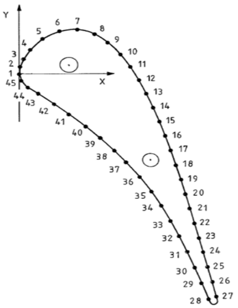
A reliable transitional boundary layer prediction model could help to...

- Improve aerodynamic and thermal performances
- Improve design strategies
- High spatial resolution

Previous Studies

VKI

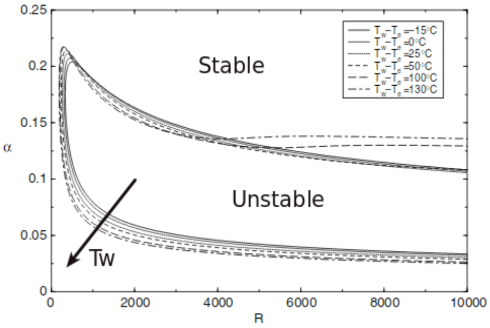
- Experimental study
- Reconstruction of intermittency through the wall heat flux



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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From the experimental side

- Experimental campaign at VKI underlines alteration of the location of transition varying the T_{ratio}
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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]
- It is unclear the effect and if this effect is physical or not

Main Tool and Objective

Main Objective

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

Approach

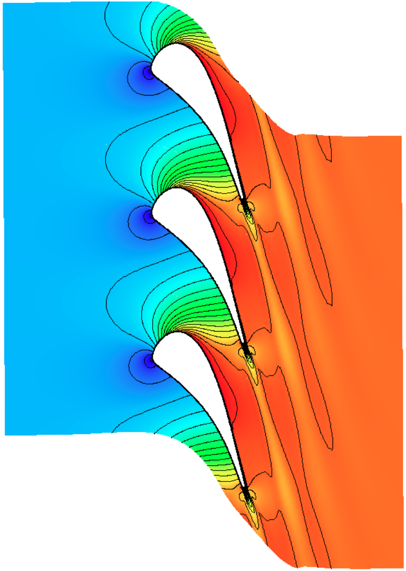
- Numerical simulation compared with experimental results

Limitation

- Transition model tuned on simple benchmark cases
- Validation on airfoil only aerodynamic
- No reliable validation in case of strong thermal field

Test Case and Approach

LS89 Transonic Cascade



Experimental Approach

- Same *Reynolds* and *Mach*
- Because T_{wall} $\sim$const

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

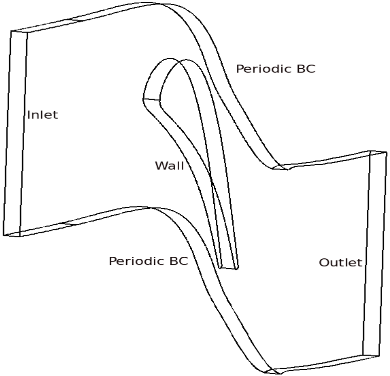
Numerical Approach

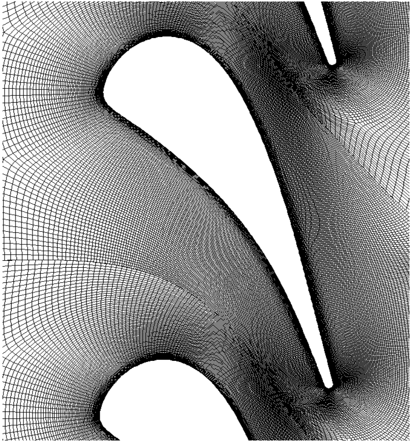
Same *Re* and *Mach*, we reach the same temperature ratio:

- 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.

Simulation set up





Boundary Conditions

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

Mesh Prop

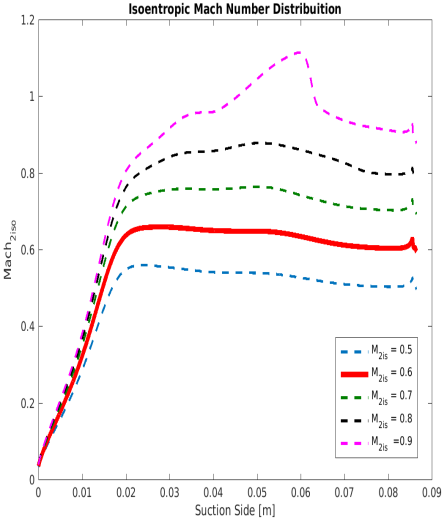
- $y+ \sim 1$ first cell node
- Non matching periodicity $\rightarrow$ avoid high skeweness

Looking for good working conditions

Parameters affect transition

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

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



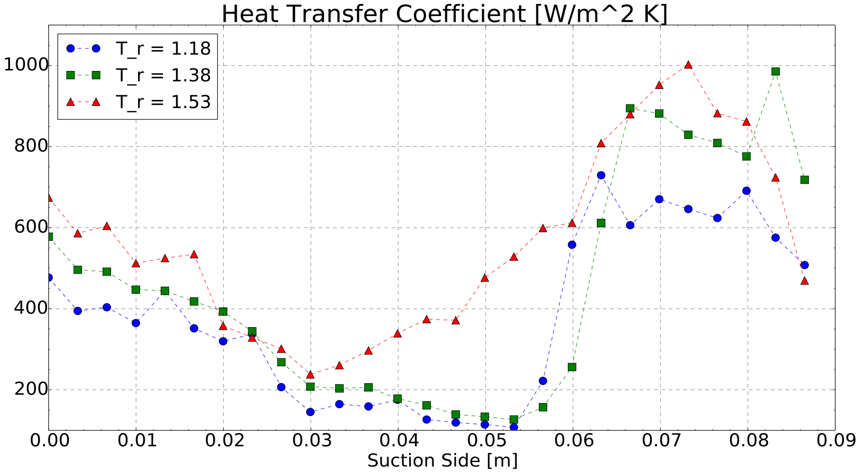
Good working point

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

Trade off between : Avoiding too big pressure gradients and preserve compressibility

Trends from experiments

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



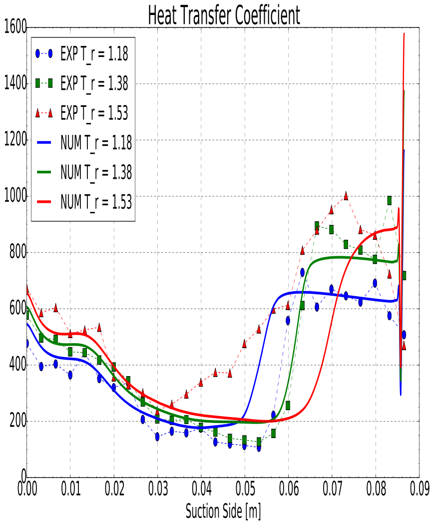
Experimental Results

The Temperature ratio seems to have some effects on the transition

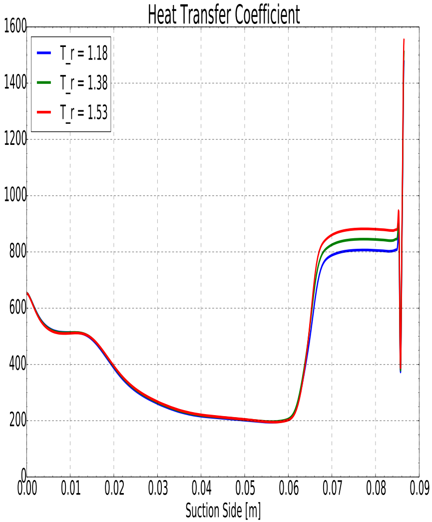
$\gamma - Re_\theta$ Results

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

Constant Blade Temperature



Constant Free Stream Conditions



Insight $\gamma - Re_\theta$

$\boxed{\text{Starting point} \rightarrow \boldsymbol{k - \omega - SST}}$

Introduction of 2 new variables $\gamma - \tilde{Re_\theta}$

$\downarrow$

Evolution of $\tilde{Re_\theta}$

$\downarrow$

$$Re_{\theta c} = f(\tilde{Re_\theta})$$

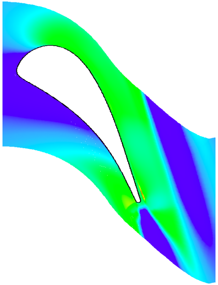
$\downarrow$

$$P_\gamma \sim F_{onset} \sim \frac{\max(Re_v)}{Re_{\theta c}}$$

$\downarrow$

Evolution of γ

$\tilde{Re_\theta}$



$\downarrow$

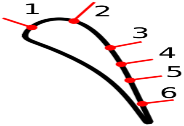
Intermittency

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

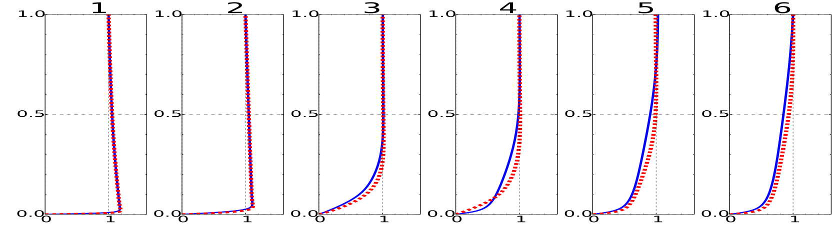
$\boxed{\text{Final result } \gamma \rightarrow \text{Production of turbulent kinetic energy}}$

Case $T_{wall} = const$: Massflow and ν

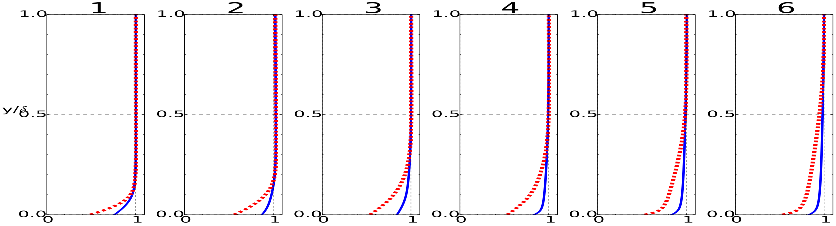
● $\frac{T_\infty}{T_{wall}} = 1.53$ ——— $\frac{T_\infty}{T_{wall}} = 1.18$



$$\frac{\rho U}{(\rho U)_\infty}$$

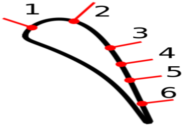


$$\frac{\nu}{\nu_\infty}$$

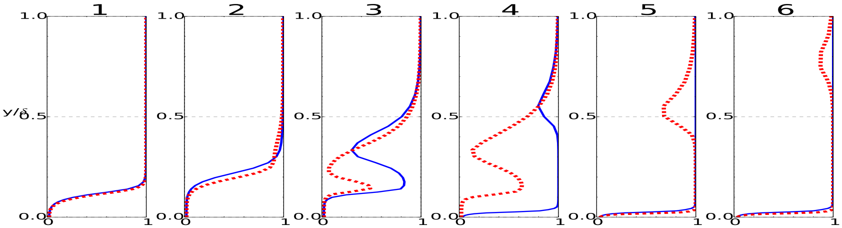


Case $T_{wall} = const$: Intermittency and Re_θ

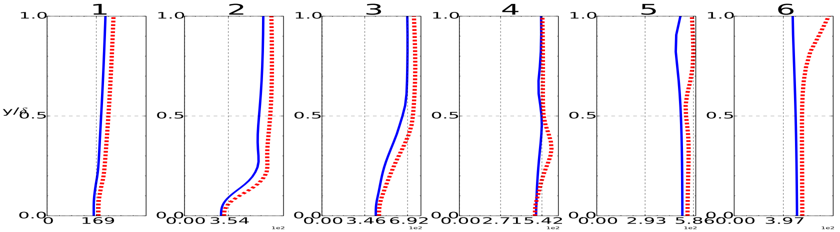
● $\frac{T_\infty}{T_{wall}} = 1.53$ ——— $\frac{T_\infty}{T_{wall}} = 1.18$



Intermittency



Momentum Thickness Reynolds Number



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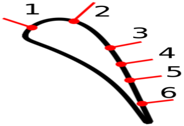
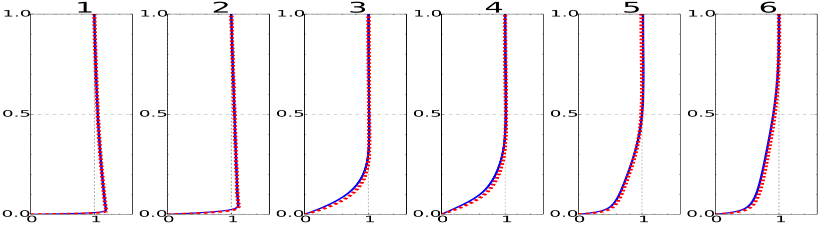
General overview
Transition in Turbomachinery
Outline of the Project
Methodology
Results from experiments
$\gamma - Re_\theta$ Results
$k - k_l - \omega$ Results
Conclusions and Future works
Backup
Bibliography

Case $FreeStream = const$: Massflow and ν

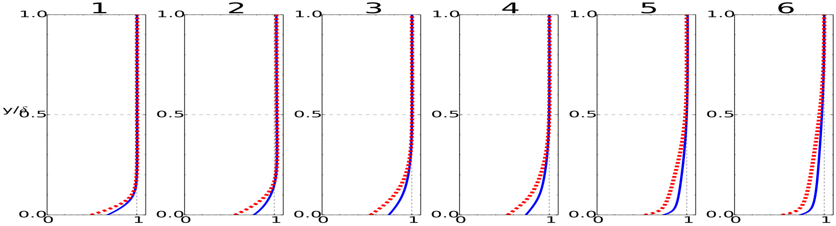
● $\frac{T_\infty}{T_{wall}} = 1.53$ ——— $\frac{T_\infty}{T_{wall}} = 1.18$



$$\frac{\rho U}{(\rho U)_\infty}$$



$$\frac{\nu}{\nu_\infty}$$



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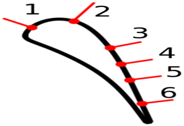
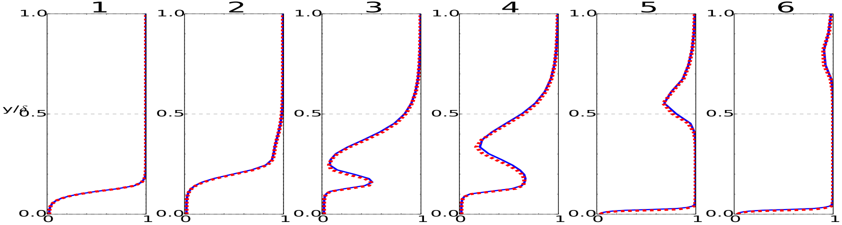
Case $FreeStream = const$: γ and Re_θ

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



Intermittency



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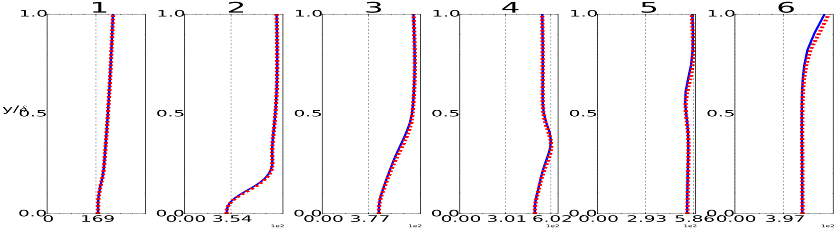
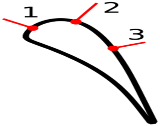


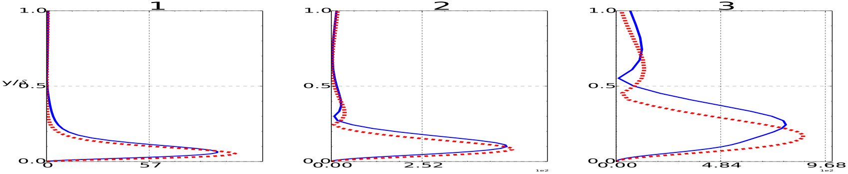
Explanation 1 $Re_{Vorticity}$

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

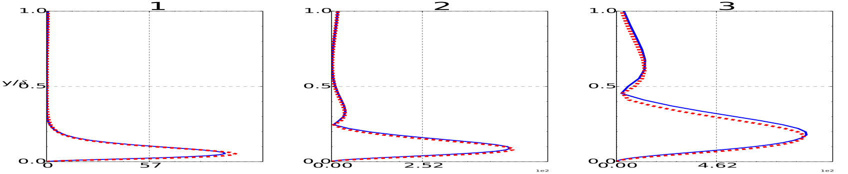


Transition triggered by $\boldsymbol{F_{onset}} \sim \frac{\boldsymbol{max(Re_v)}}{\boldsymbol{R_{\theta c}}}$ $\boldsymbol{Re_v} = \frac{\boldsymbol{d^2 S}}{\boldsymbol{\nu}}$

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

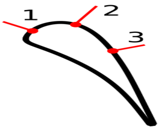


$FreeStream = const \;\; Re_{vorticity}$



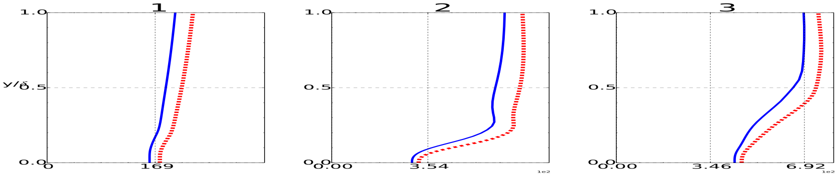
Explanation 2 $Re_{\theta c}$

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

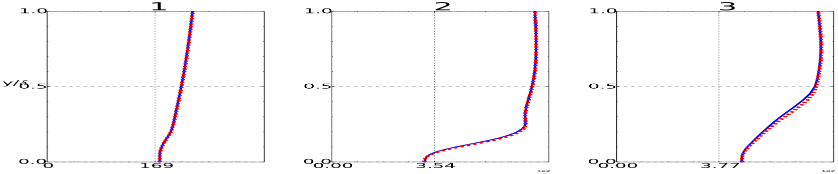


Transition triggered by $\boldsymbol{F_{onset}} \sim \frac{\boldsymbol{max(Re_v)}}{\boldsymbol{R_{\theta c}}}$

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



$FreeStream = const \;\; Re_\theta$

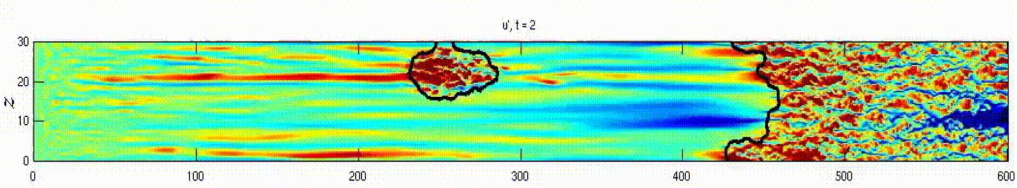


$k - k_l - \omega$ Physical Meaning

Model Composed by 3 equations

- Original $\boldsymbol{k - \omega - SST}$
  - 1 eq for $\boldsymbol{k_T}$
  - 1 eq for $\boldsymbol{\omega}$
- 1 eq for the evolution of $\boldsymbol{k_l}$ laminar kinetic energy

How laminar kinetic energy is transferred from a scale to the others [1]



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

[1] DNS from Tamer Zaki's Research Group

Implementation

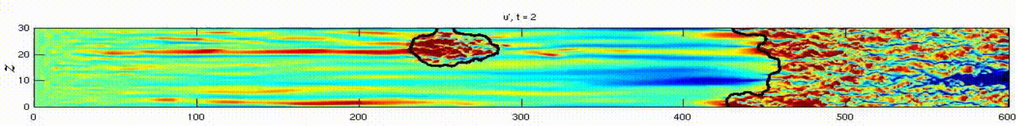
$$\frac{D(\rho k_T)}{Dt} = P_{k_T} + D_{k_T} + TRANS_{k_l \to k_T} + DIFF(k_T) \quad (1)$$

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

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

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

[2]

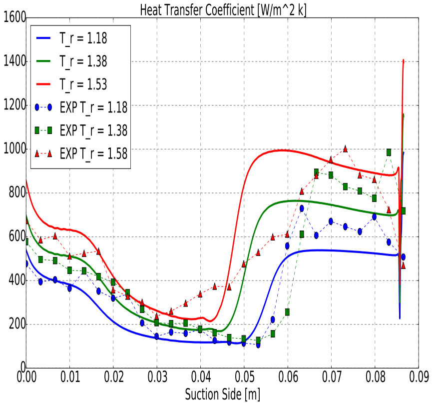


kl develops $\frac{k_T}{\nu\Omega} > C_{BP} \to \phi_{BP} > 0$ $k_l \to k_T$

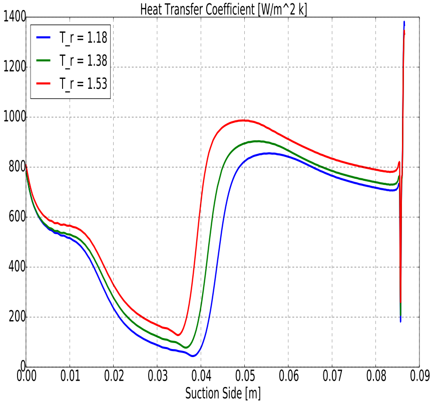
[2] DNS from Tamer Zaki's Research Group

$k - k_l - \omega$ Results
$Mach = 0.55 \quad Re = 9.5 \cdot 10^5 \quad Tu = 0.8\%$

Constant Blade Temperature



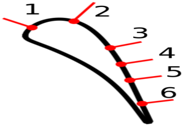
Constant Free Stream Conditions

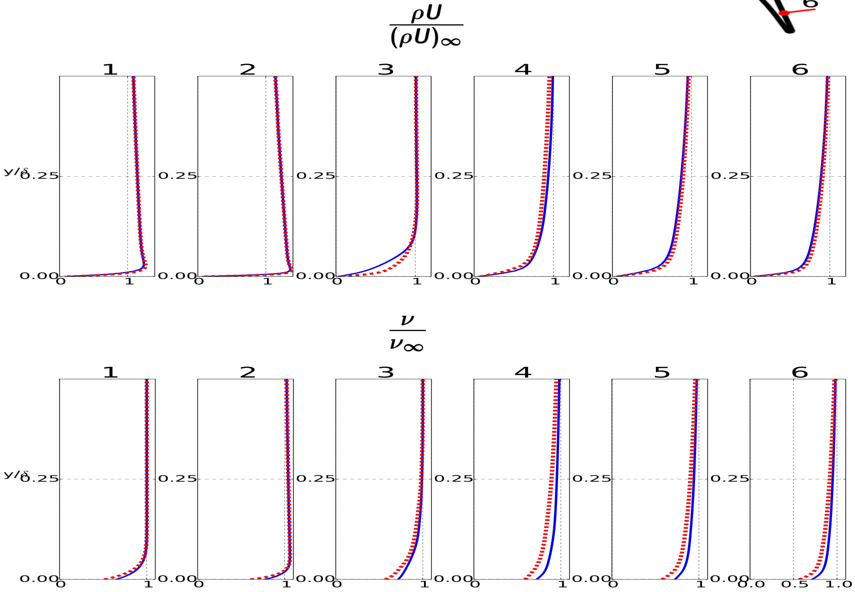


$\boxed{\text{Remarkable fact} \rightarrow \text{Same behaviour in both cases}}$

Case $T_{wall} = const$: Massflow and ν

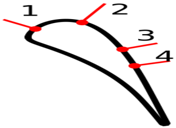
● $\frac{T_\infty}{T_{wall}} = 1.53$ —— $\frac{T_\infty}{T_{wall}} = 1.18$



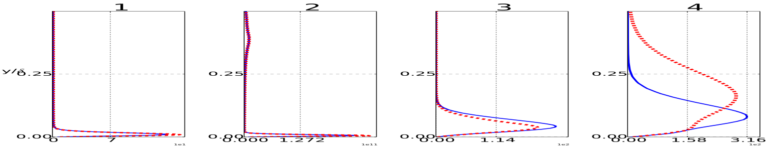


Model's Quantities

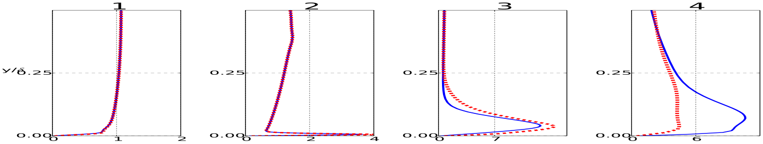
● $\frac{T_\infty}{T_{wall}} = 1.53$ ——— $\frac{T_\infty}{T_{wall}} = 1.18$



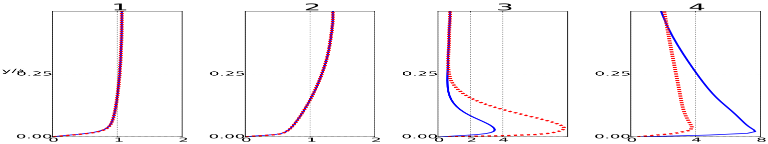
$$\frac{k_l}{(k_l)_\infty}$$



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

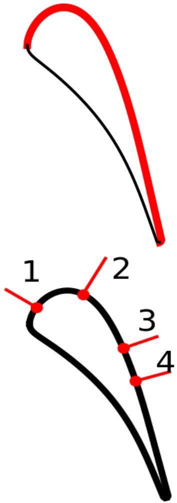


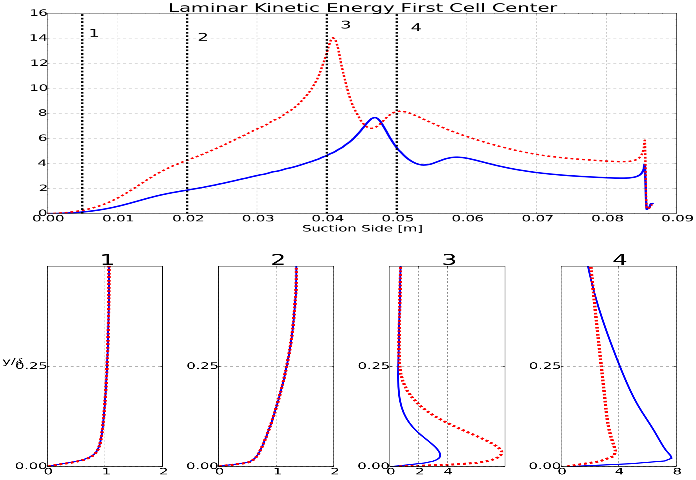
Energy Transfer



Behaviour Explanation

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





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 $Freetream = const$

$\boldsymbol{F_{onset} \sim \frac{max(Re_v)}{Re_\theta}}$, noteworthy variation of $\boldsymbol{Re_\theta}$ due to the Free Stream variation

$k - k_l - \omega$

- The temperature ratio seems to destabilize the flow
- Similar behaviour with the experimental results
- The behaviour is the same for both cases

Transition triggered by $\boldsymbol{\frac{k_T}{\nu\Omega}} \longrightarrow$ stronger dependency on physical quantities

Future Challenges

- Better understanding of the role of the temperature ratio from an experimental side. A lot of conjoint effects very difficult to decouple one from each other.
- Better understanding of the real limit of the transition model 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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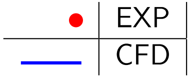
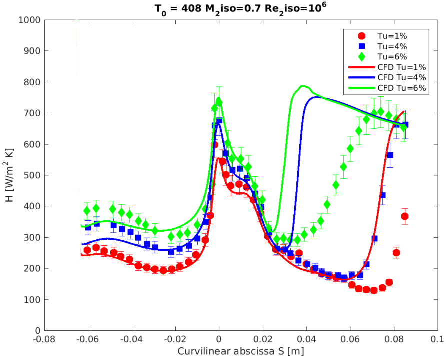
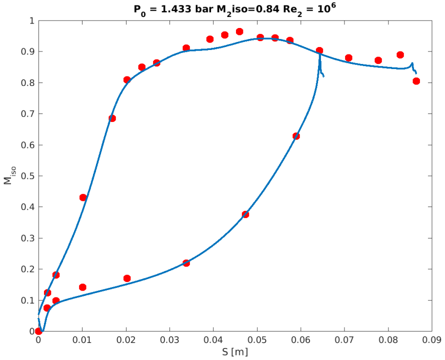
Flow Conditions : $Mach_{2iso} = 0.7$ $Re_{2iso} = 10^6$







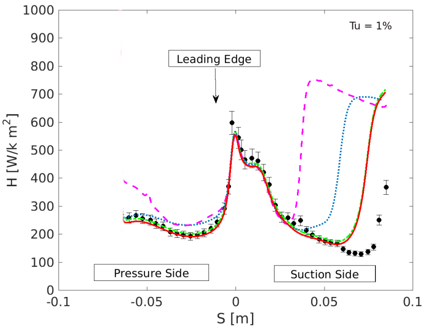
- reasonably good agreement in the laminar and turbulent part
- some discrepancy [3]

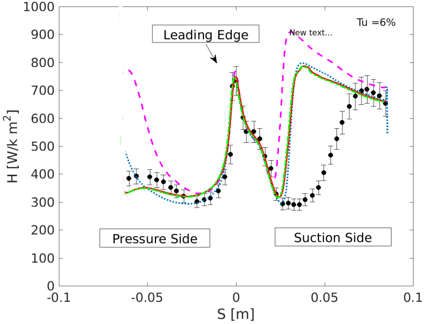
- kinematic field quite good described

Grid Independence

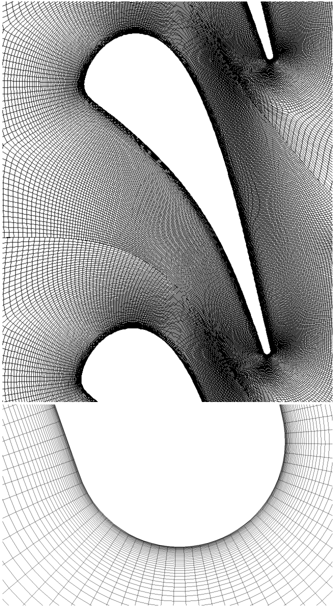
	INLET	OUTLET
$T_0[k]$	408	-
M_{iso}	-	0.7
Re_{iso}	-	10^6
Tu %	1-6	-
$L_0[mm]$	8	-

	Grid Nodes
●	Exp
	50K
	80K
	120K
	200K

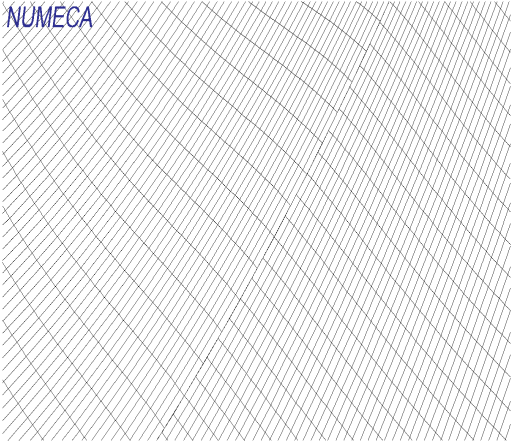




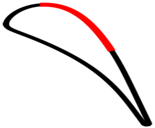
Mesh Properties



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

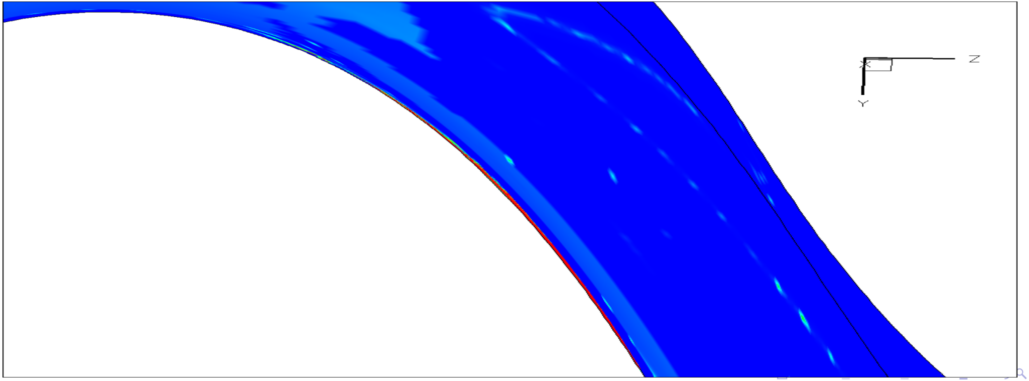


Behaviour Explanation 1



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

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



Insight $\gamma - Re_\theta$

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

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

Basic Idea

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

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

Final result

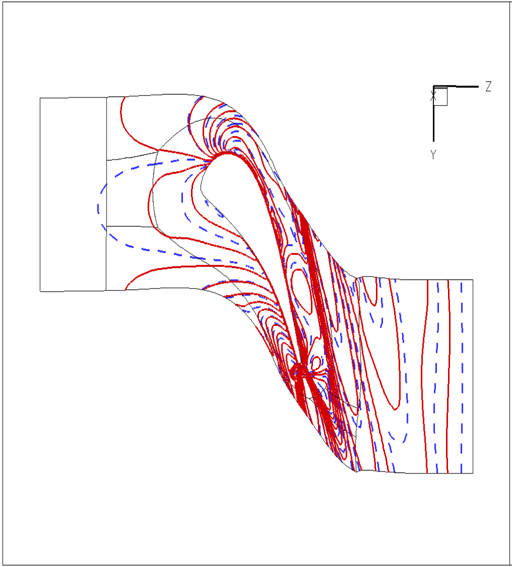
γ and Re_θ evolution $\rightarrow$ k $\rightarrow$ *turbulence*

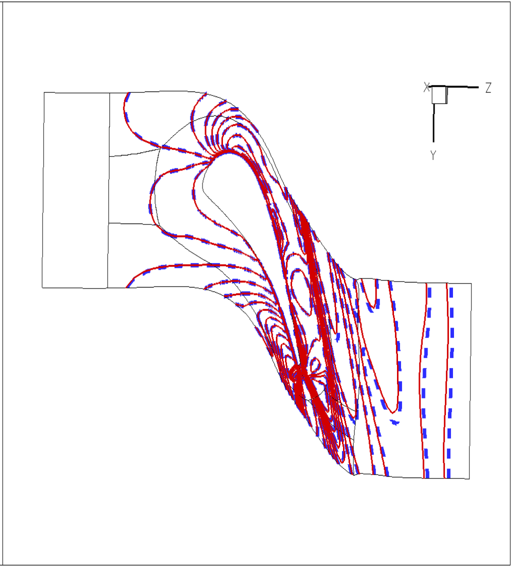
Behaviour Explanation 3

$\frac{T_\infty}{T_{wall}} = 1.6$

$\frac{T_\infty}{T_{wall}} = 1.2$

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

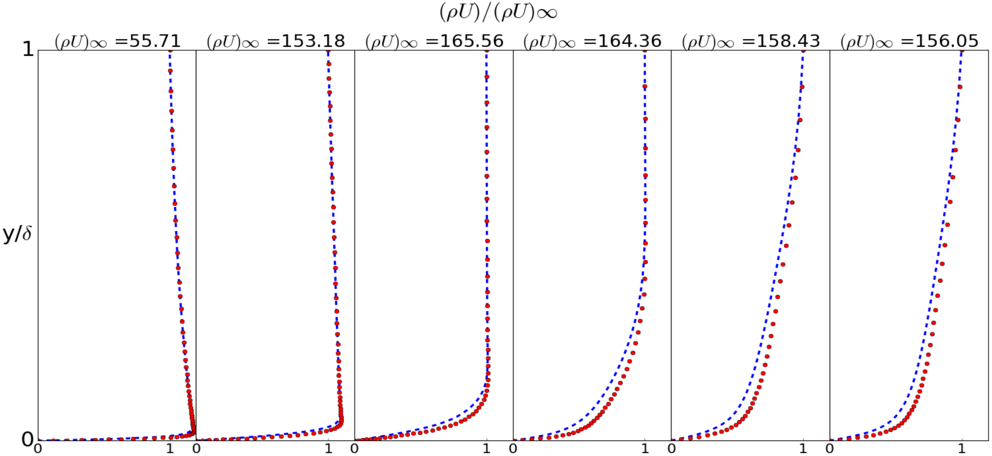




Effects on Momentum Thickness

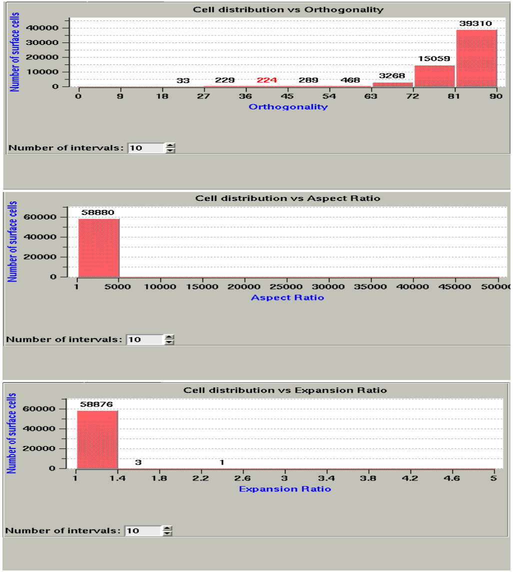
●	$\frac{T_\infty}{T_{wall}} = 1.6$
—	$\frac{T_\infty}{T_{wall}} = 1.2$

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



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

Mesh Quality



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