Aerodynamic and Convective Heat Transfer
Experiments versus Computations

What is needed ?
What is learned ?

Tony Arts

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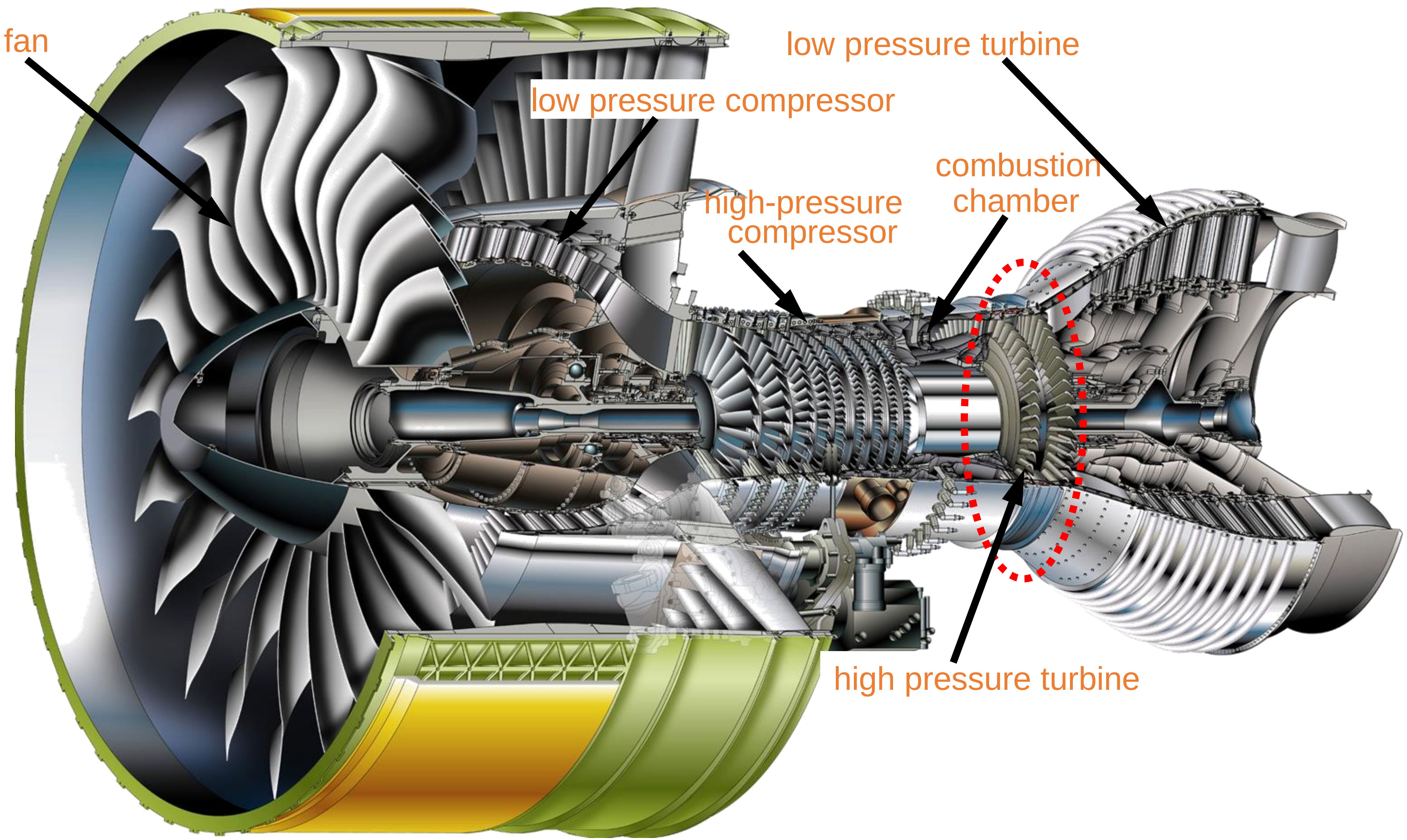
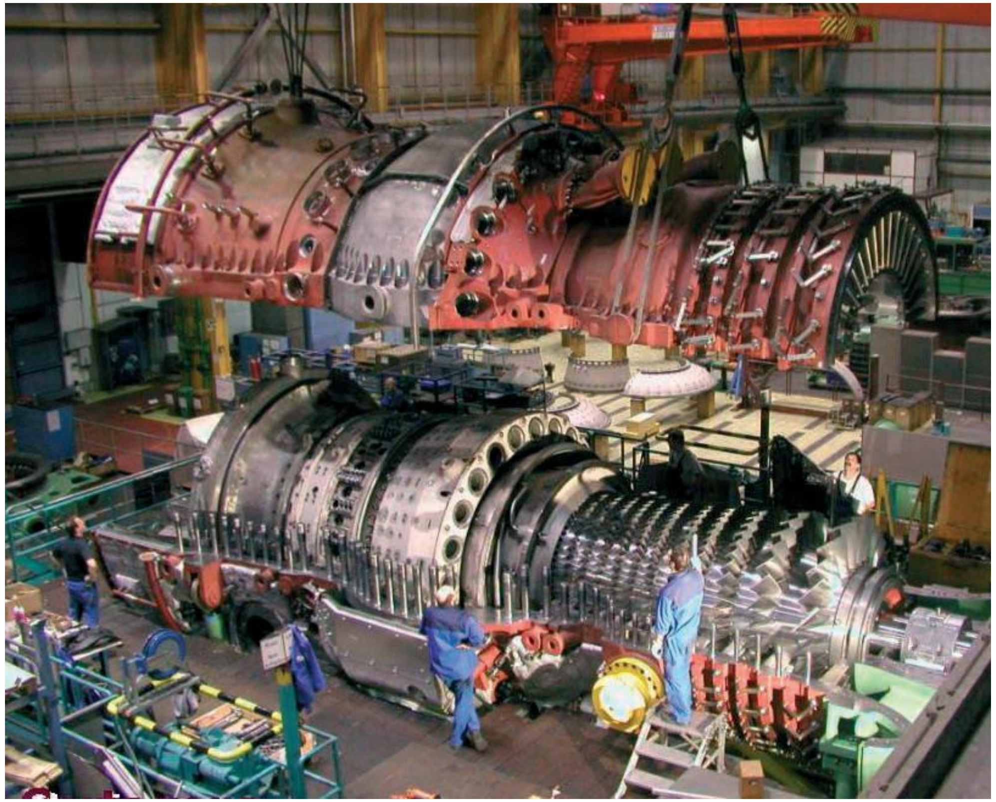
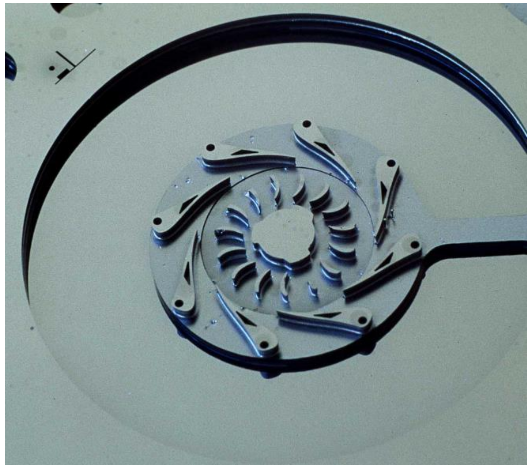
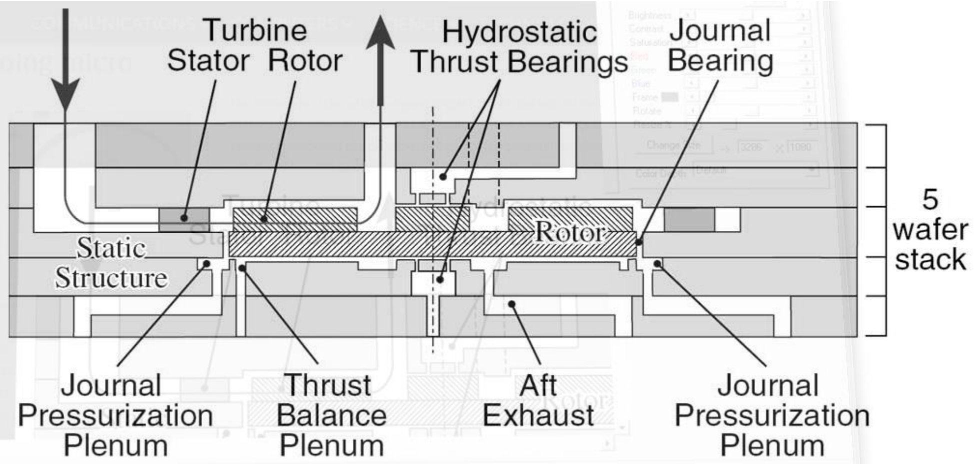

fan
low pressure compressor
high-pressure compressor
combustion chamber
low pressure turbine
high pressure turbine

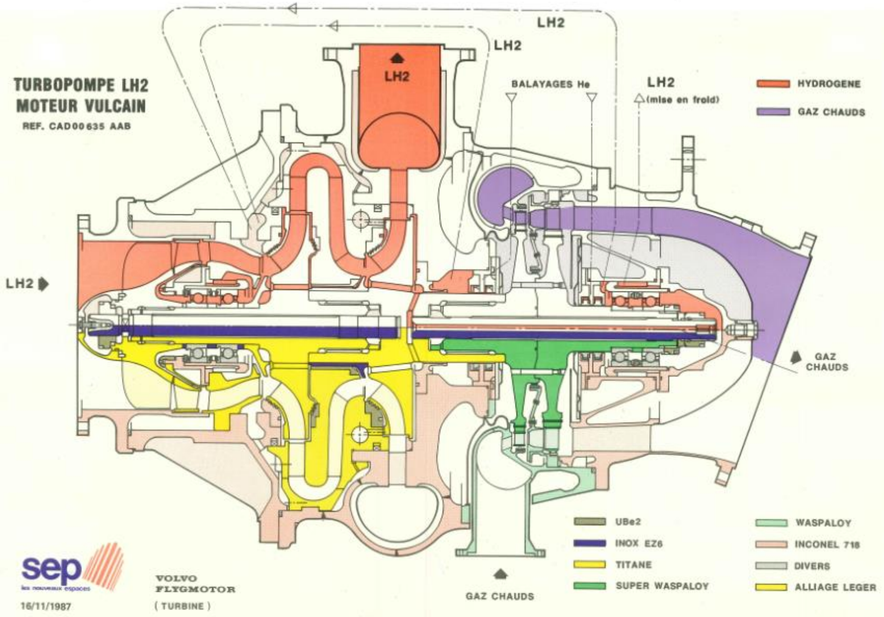
From the largest …

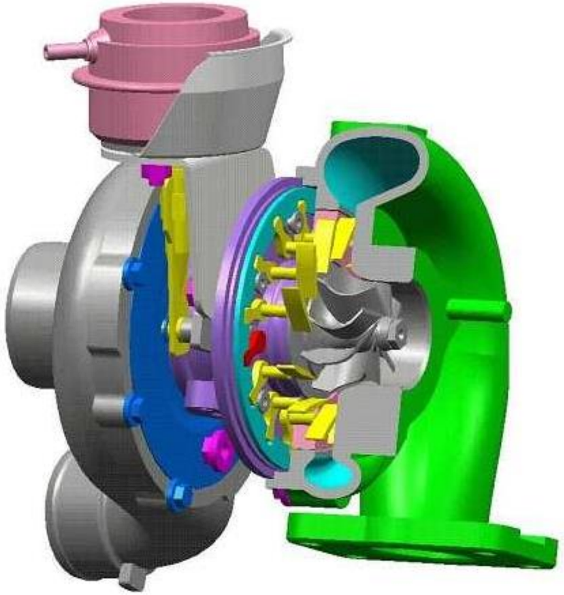


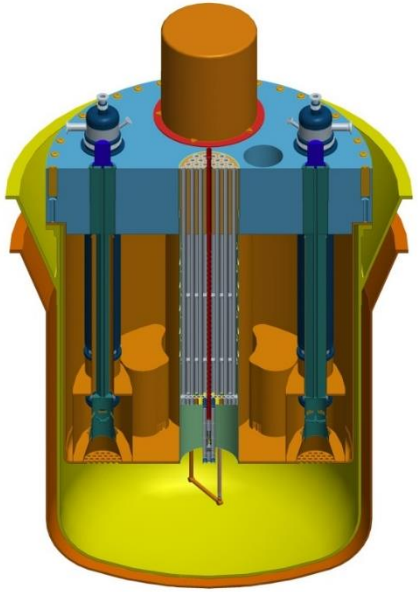
… to the smallest …

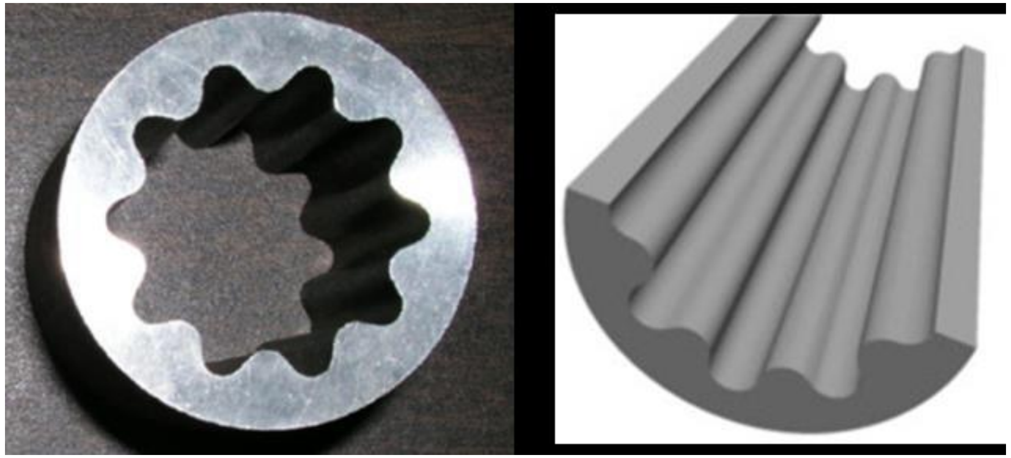





TURBOPOMPE LH2
MOTEUR VULCAIN
REF. CAD00635 AAB
LH2
LH2
LH2
BALAYAGES He
LH2
(mise en froid)
HYDROGENE
GAZ CHAUDS
LH2
GAZ CHAUDS
UBe2
INOX EZ6
TITANE
SUPER WASPALOY
WASPALOY
INCONEL 718
DIVERS
ALLIAGE LEGER
sep
les nouveaux espaces
16/11/1987
VOLVO
FLYGMOTOR
(TURBINE)
GAZ CHAUDS







Level of Testing

<u>Engine testing</u> (industry)

exact similarity, severe environment, limited instrumentation

<u>Complete component testing</u> (industry – research centers)

Geometrical scaling

Hot, cold, pressure ratio, mass flow, Reynolds number, Mach number, pressure gradient, turbulence intensity/scale/spectrum

Spatial/temporal resolution

Wider instrumentation available

Extrapolation to engine conditions?

<u>Single stage testing</u> (research centers - universities)

Blade row interactions

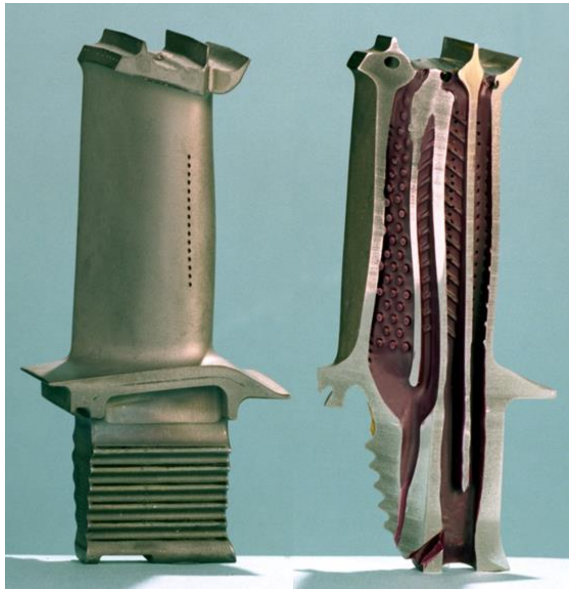
Extrapolation to engine conditions?

<u>Blade row testing</u> (cascade) (research centers – universities)

Absolute / relative flow similarity – Limitation to axial geometries

Extrapolation to engine conditions?

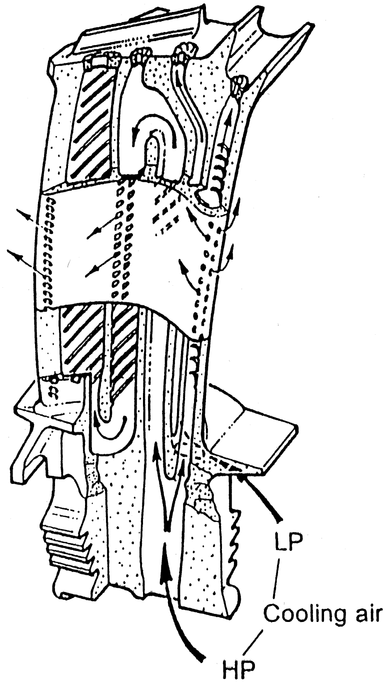
High Pressure Turbines



Challenges:

Max Gas Temperatures : 1850 K (civil – GE 90)
2000 K + (military)

Max metal Temperatures : 1350 K (Co and/or Ni based alloys, single-crystals)
Required creep temperature accuracy: 15 K (severe life time reduction)
Rotational speed (machine size)
Effects of Re, Mach (transonic), Tu, surface roughness, curvature, pressure gradient, exit combustion chamber (including swirlers), shocks, airfoil clocking (alignment)
Cooling systems
- convection, impingement, film
- TBC
- multi-perforations (security aspects)



High Pressure Turbines

What are the challenges :

CFD (Ansys-Numeca-OpenFoam-TRAF …, Universities)
"sharper" answers from the research centres and universities

Boundary layer transition:
- not a real problem on film cooled airfoils … but … (by-pass transition)
- small airfoils / low Re: validity of models? Need for representative data and test cases

Turbulence modelling (momentum and energy)
- simulation of the cooling impact (RANS, DES, LES) (memory – CPU) Chimera or statistical methods (mesh limitation)
- coupling of heat transfer modes (convection/conduction) (viscous/thermal transition)
- computations of viscous & thermal wakes (width and depth), losses and deviation

High Pressure Turbines

Experimental solutions – Numerical simulations

- Reynolds and Mach numbers
- Rotation and Biot numbers, conductivities ratio, roughness
- Temperature ratios (Gas/wall/coolant), density ratios (Gas/coolant)
- Intensity, scale and spectrum of turbulence (wakes, shocks, hot spots)
- Unsteady effects (shocks, wakes, Rotor/Stator interactions – Stator/Stator interactions)

Facilities

- Stationary (power – energy)
- Short duration – intermittent (low energy)
- Cascade / Stage (axial machines)

Boundary Conditions (Thermal)

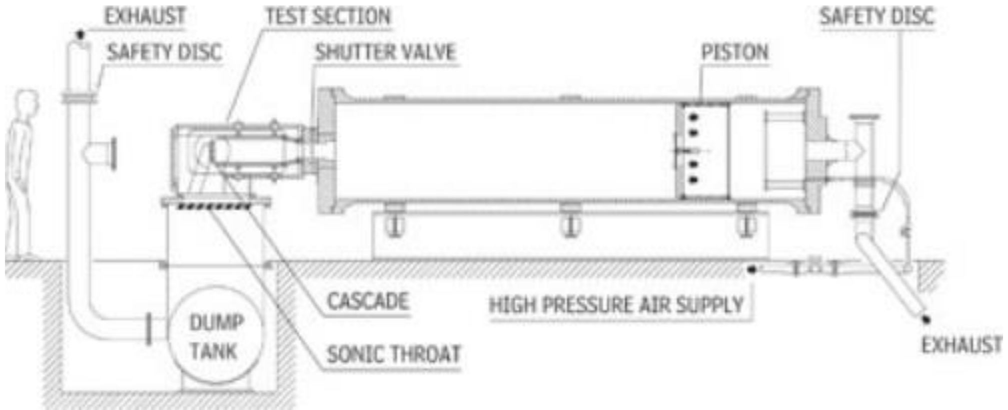
- Uniform wall Temperature
- Uniform wall heat flux
- Conjugate heat transfer (transients)

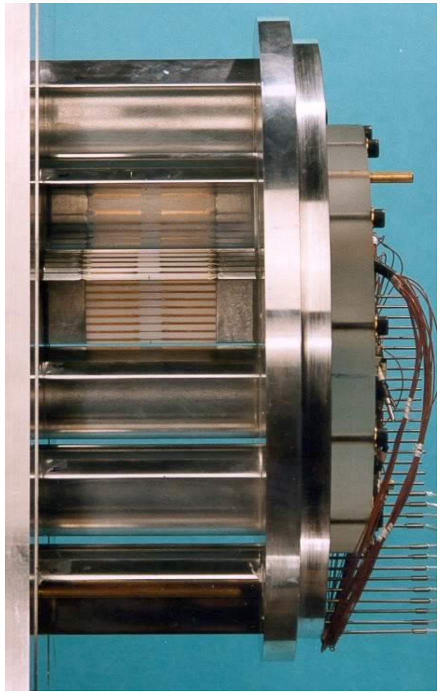
Measurement Techniques

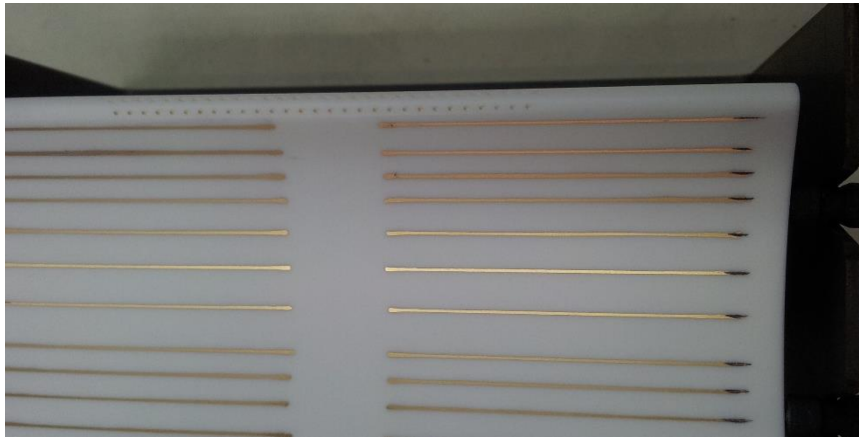
Thermocouples, Liquid crystals, Infra-red Thermography, Pressure and Temperature Sensitive Paints, Thin Films, Mass Transfer Techniques, Thermal Paints (real conditions -interpretation?), Pyrometry, Hot/Cold Wires, LDV, PIV, …

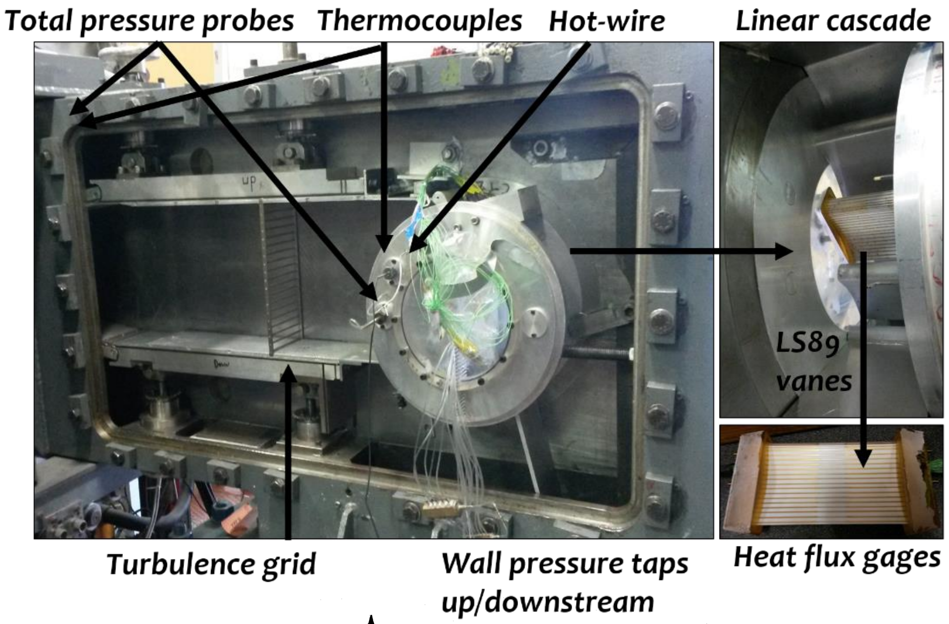
Averaged and/or time resolved measurements – data management and extraction

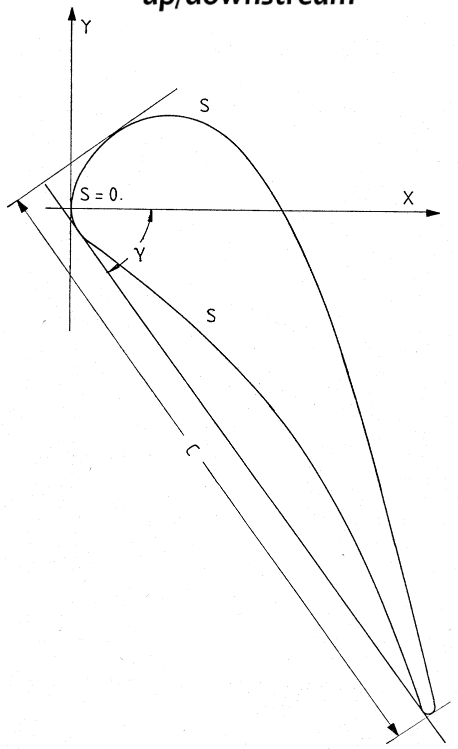
2D Cascades (aero-thermal)











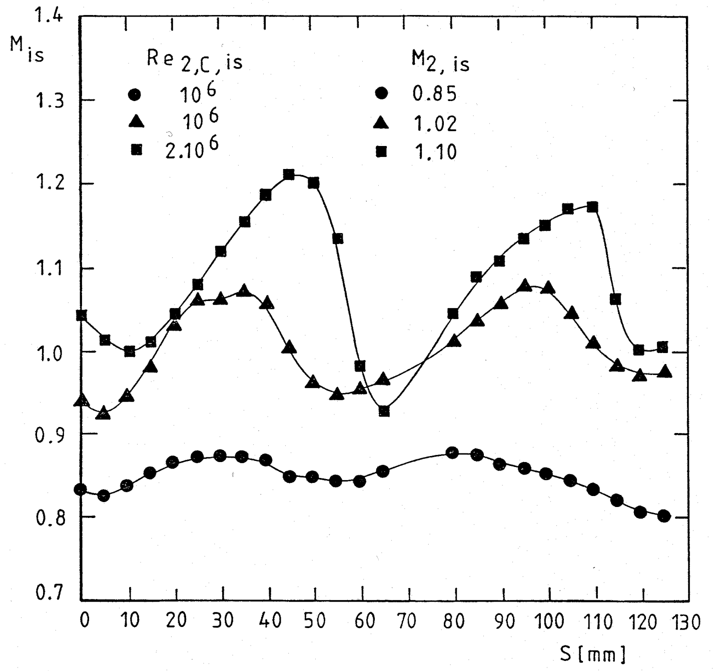
- Chord: 67.647 mm
- Pitch/Chord: 0.850
- Stagger angle: 55.0 deg (from axial)
- Throat/Chord: 0.2207
- Inlet angle: 0 deg (axial)

- $M_{2,is}$: 0.5 … 1.2
- $M_{1,is}$: ~ 0.15
- $Re_{2,is,c}$: 500,000 … 2,000,000
- Tu_1: 0.8 … 23 %
- T_{gas}/T_{wall}: 1.1 … 1.5

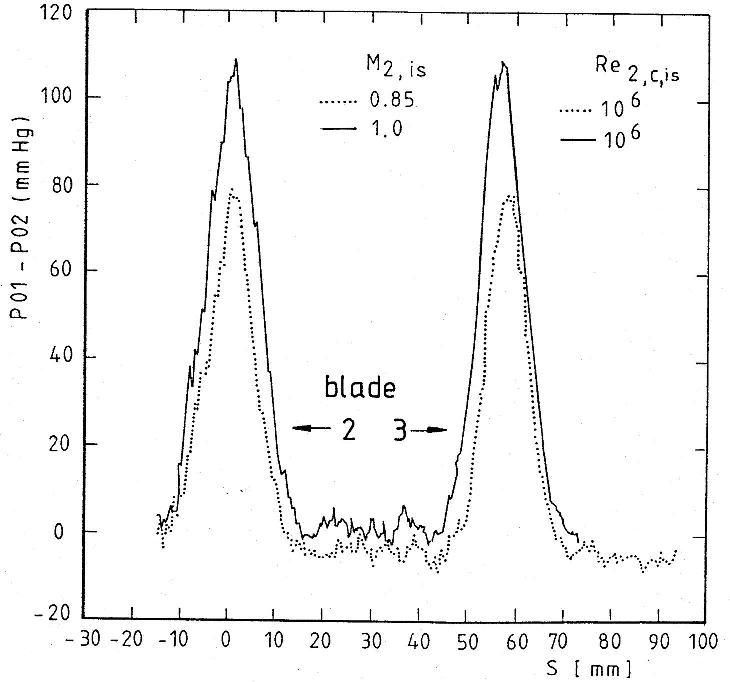
- No slip wall BC
- Isothermal wall BC
- Inlet BC: P_{01}, T_{01}, α_1
- Exit BC: P_2
- Flow duration: 0.5 s

Measurement uncertainty

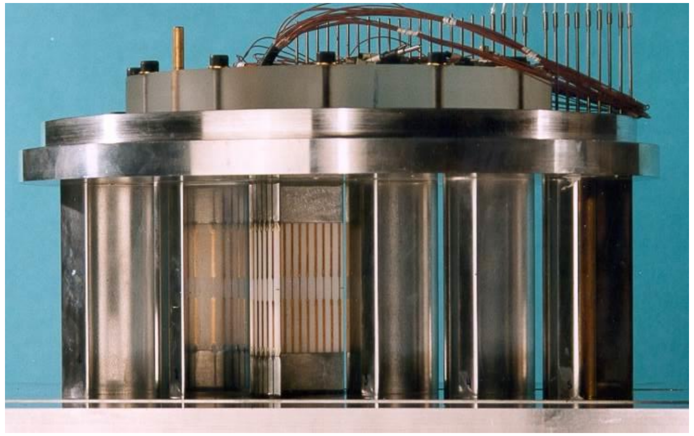
	Tr	*$M_{2,is}$*	*$Re_{2,is}$*	*$V_{1,is}$*	*h*
Uncertainty [%]	**0.8**	**2.3**	**4.1**	**9.9**	**5-9 %**

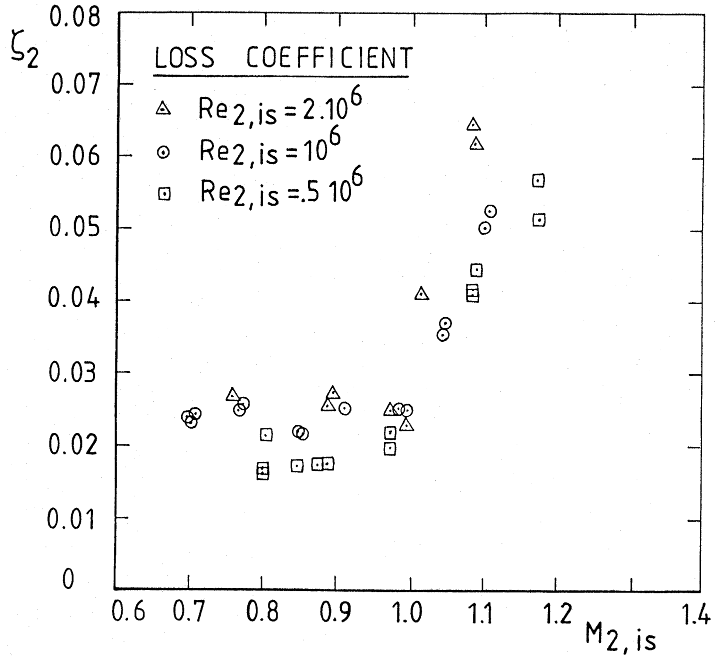


M_{is}
$Re_{2,C,is}$
10^6
10^6
2.10^6
$M_{2,is}$
0.85
1.02
1.10
S [mm]

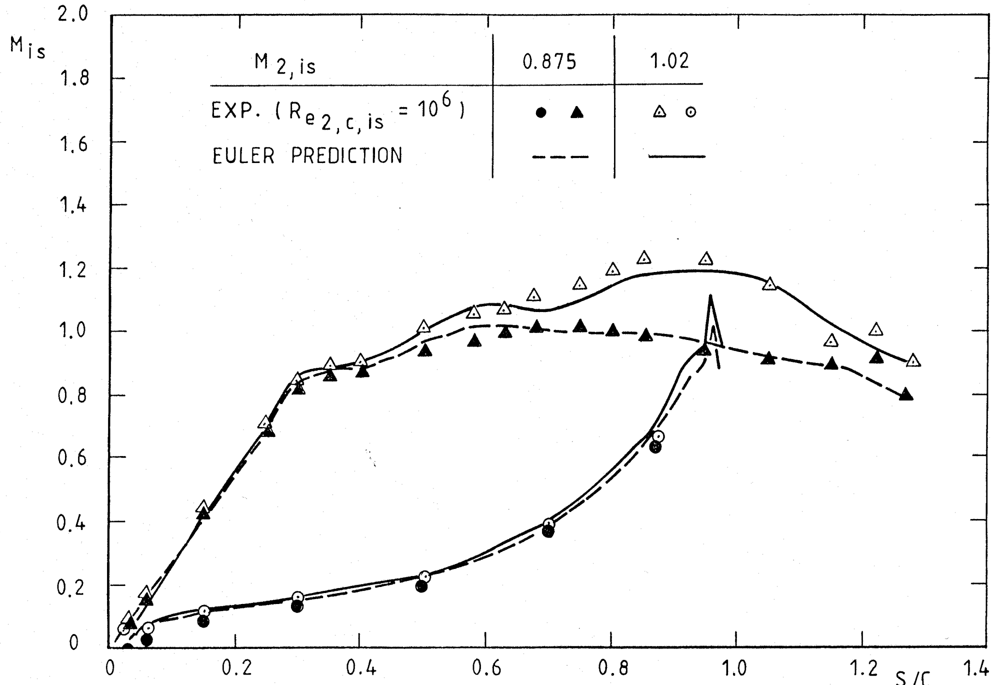


P01 - P02 (mm Hg)
$M_{2,is}$
0.85
1.0
$Re_{2,c,is}$
10^6
10^6
blade
2
3
S [mm]

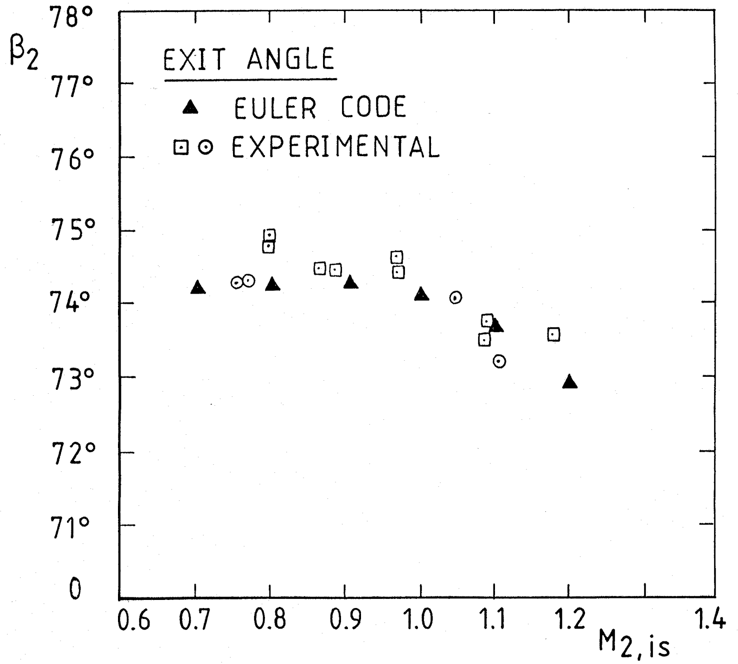




ζ_2
LOSS COEFFICIENT
$Re_{2,is} = 2.10^6$
$Re_{2,is} = 10^6$
$Re_{2,is} = .5\ 10^6$
$M_{2,is}$



M_{is}
$M_{2,is}$
0.875
1.02
EXP. ($Re_{2,c,is} = 10^6$)
EULER PREDICTION
S/C



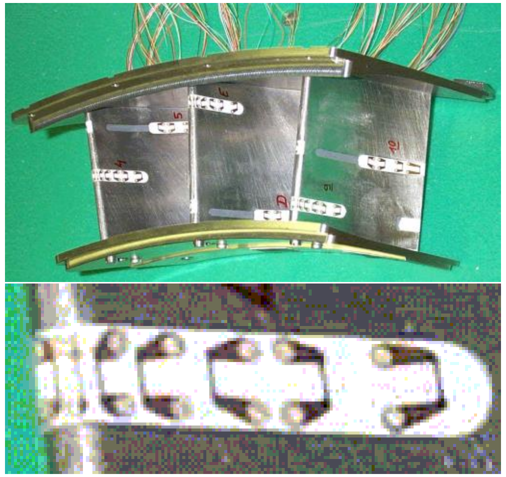
β_2
EXIT ANGLE
EULER CODE
EXPERIMENTAL
$M_{2,is}$

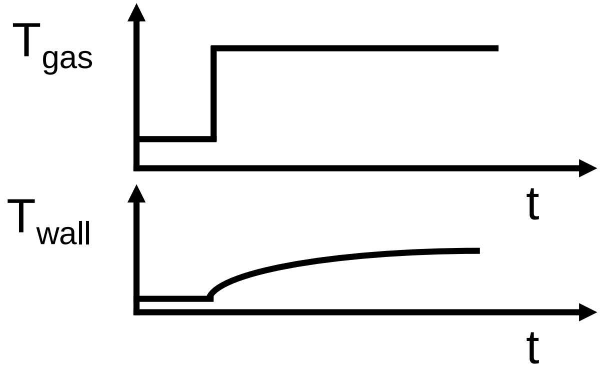
THE SINGLE LAYER HEAT TRANSFER GAUGE

Convective heat transfer coefficient

$$h = \frac{\dot{q}}{\left(T_{gas} - T_{wall}\right)}$$

$$R = R_0\left(1+\alpha\left(T-T_0\right)\right)$$



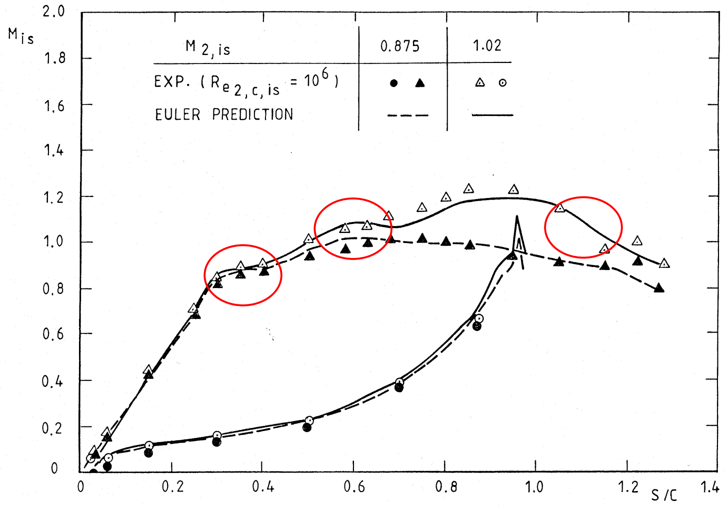


Unsteady conduction equation
to be solved:

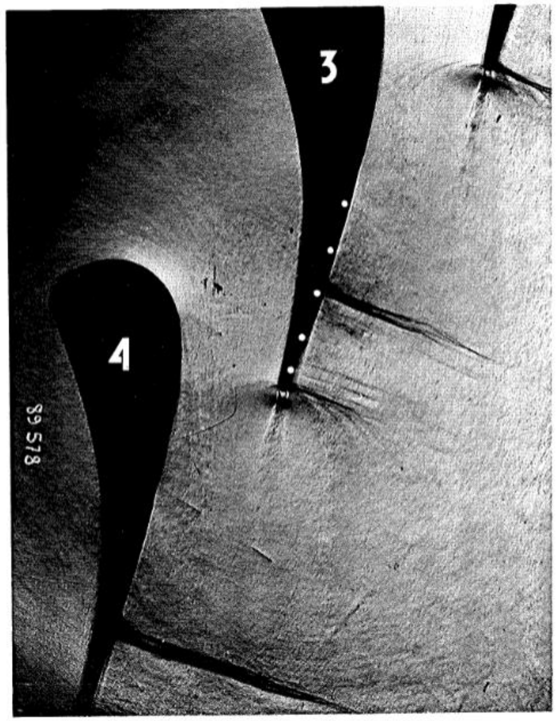
$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T(x,t)}{\partial t}$$

- 1D/2D conduction
- Semi-infinite substrate

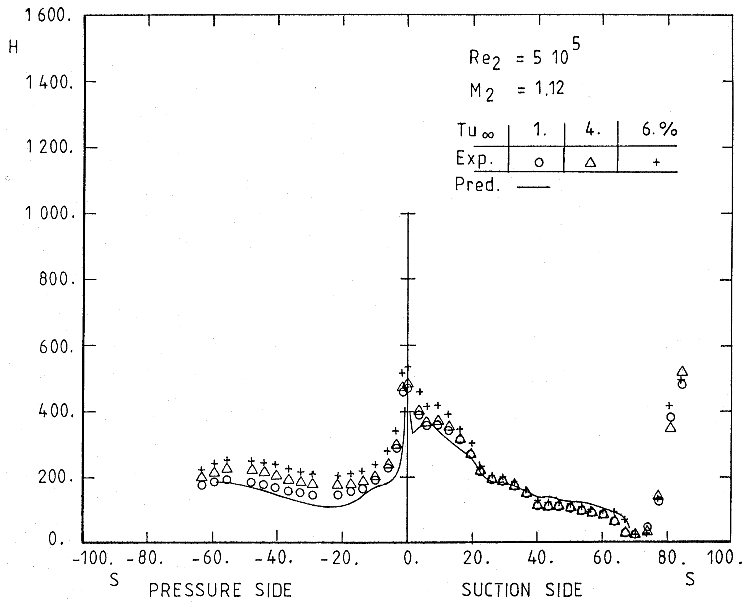
Surface heat flux : $\dot{q} = -k\left(\frac{\partial T}{\partial x}\right)_{x=0}$



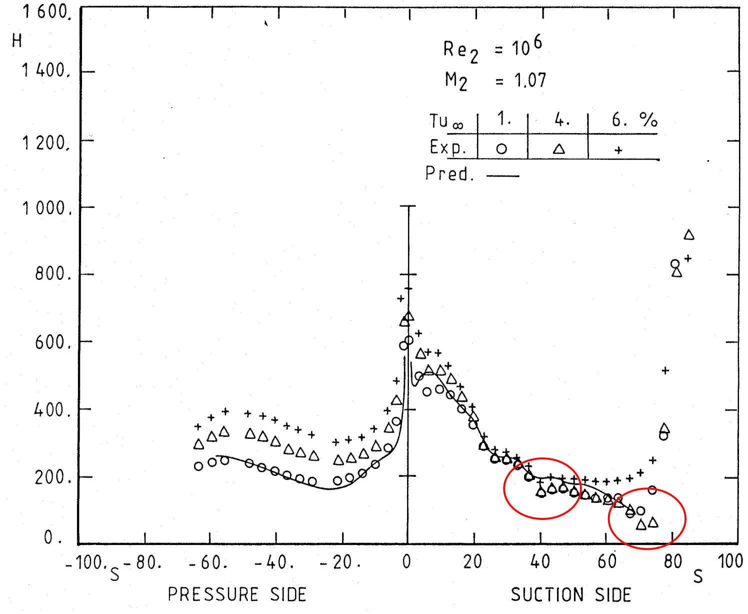
M_{is}
$M_{2,is}$ 0.875 1.02
EXP. ($Re_{2,c,is} = 10^6$)
EULER PREDICTION
S/C



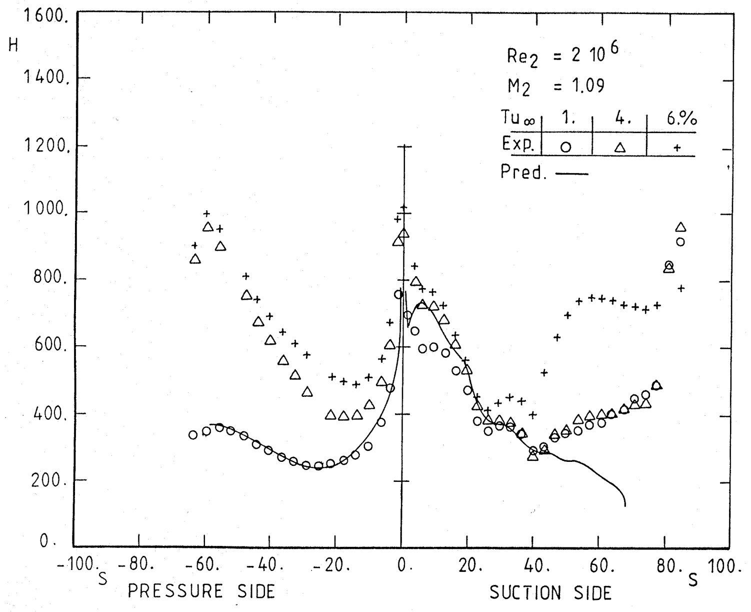
3
4
89 578



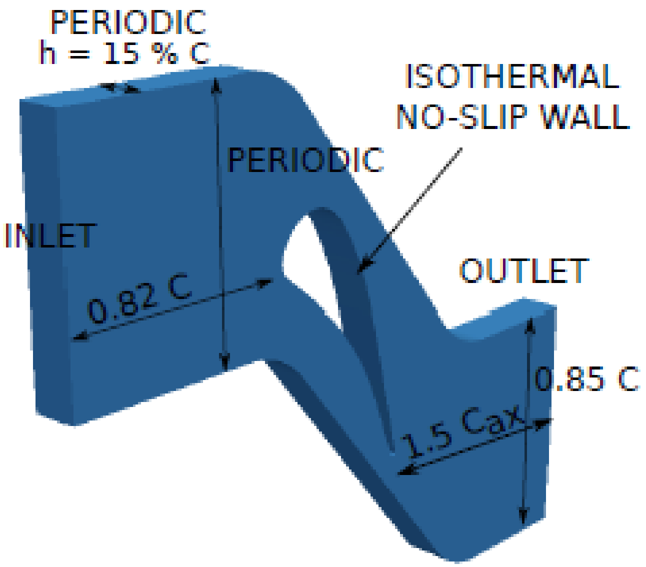
H
$Re_2 = 5\ 10^5$
$M_2 = 1.12$
Tu_∞ 1. 4. 6.%
Exp.
Pred.
S
PRESSURE SIDE
SUCTION SIDE

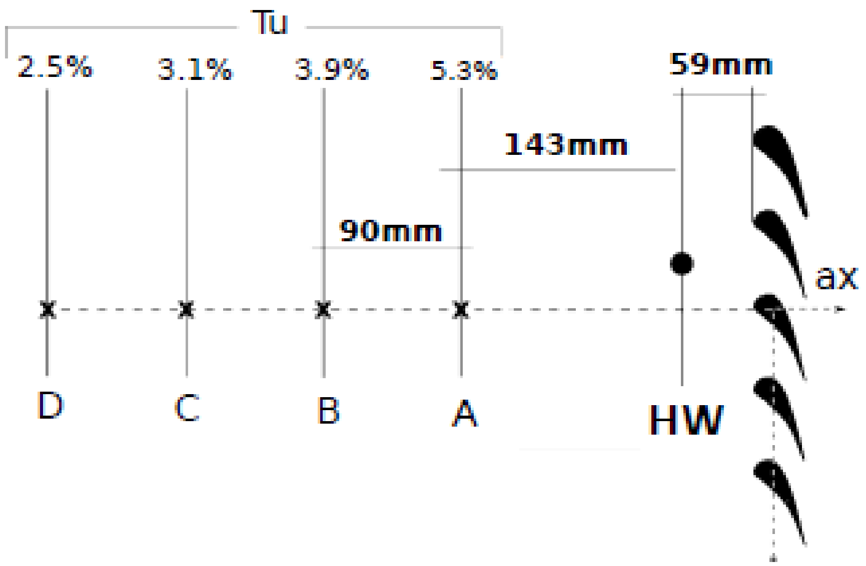


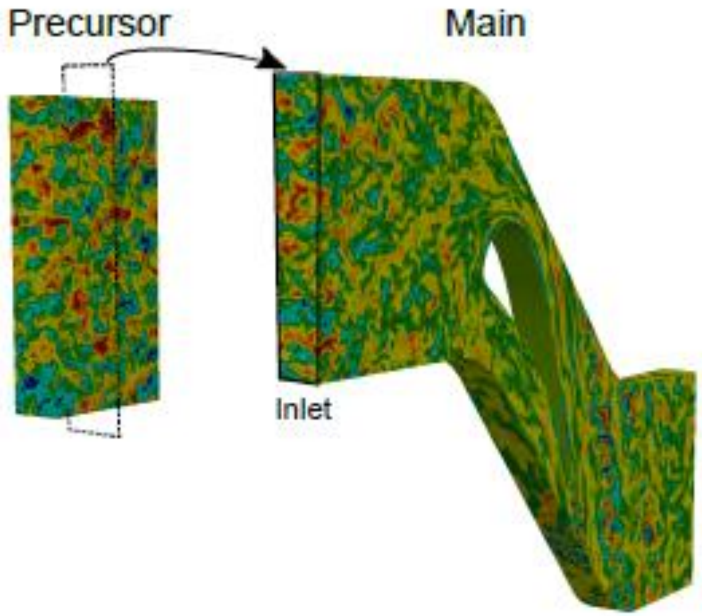
H
$Re_2 = 10^6$
$M_2 = 1.07$
Tu_∞ 1. 4. 6. %
Exp.
Pred.
S
PRESSURE SIDE
SUCTION SIDE



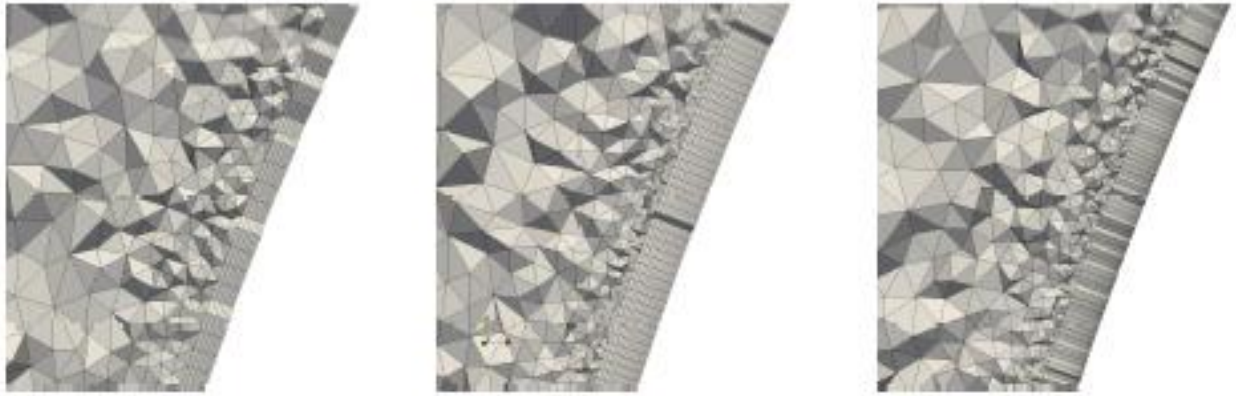
H
$Re_2 = 2\ 10^6$
$M_2 = 1.09$
Tu_∞ 1. 4. 6.%
Exp.
Pred.
S
PRESSURE SIDE
SUCTION SIDE

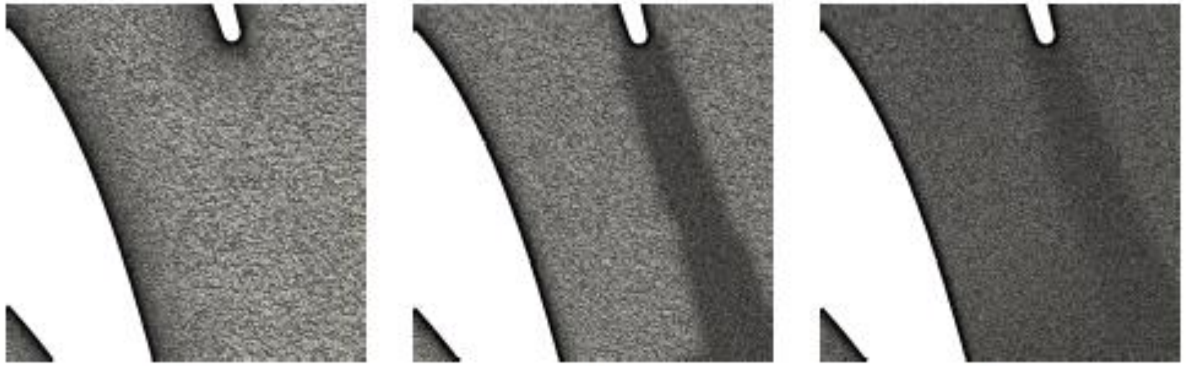

PERIODIC
h = 15 % C
ISOTHERMAL
NO-SLIP WALL
PERIODIC
INLET
OUTLET
0.82 C
0.85 C
1.5 Cax


Tu
2.5%
3.1%
3.9%
5.3%
59mm
143mm
90mm
ax
D
C
B
A
HW


Precursor
Main
Inlet

(a) (b) (c)

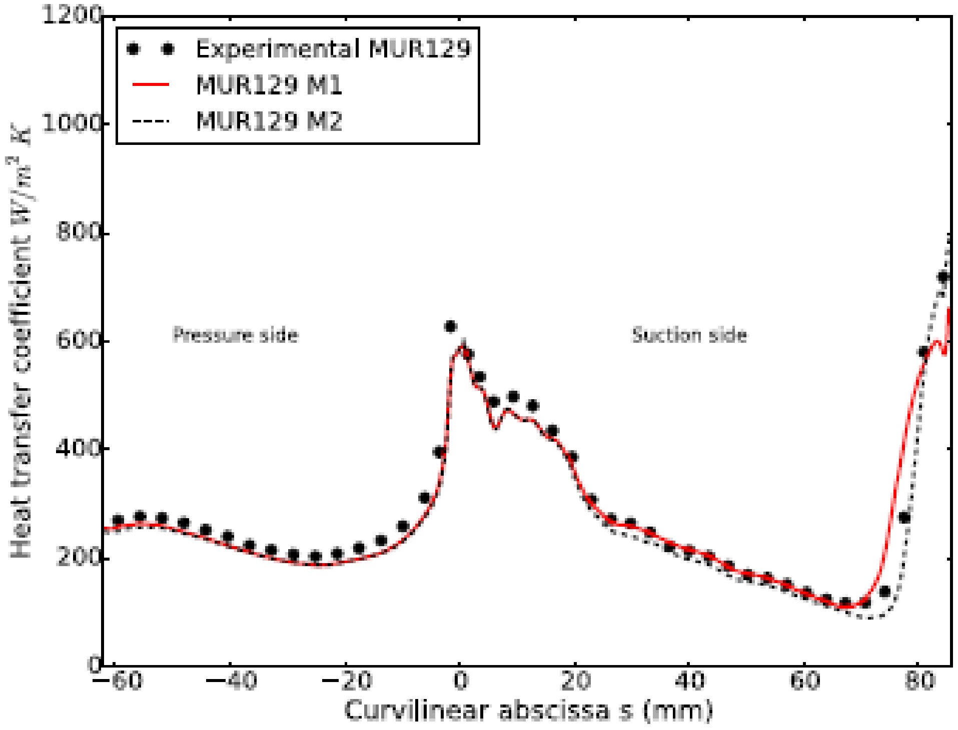


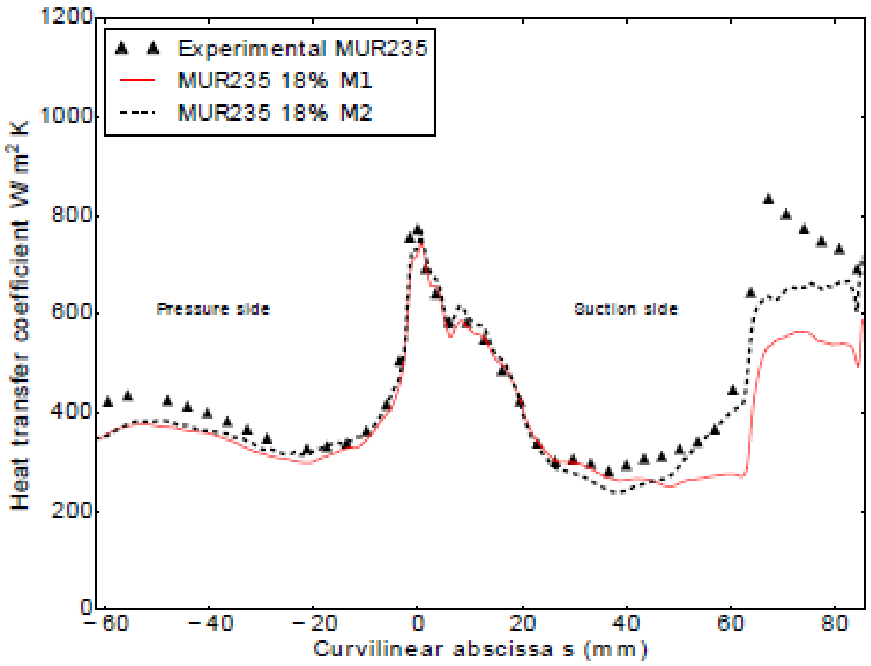


(a) (b) (c)

	M1 mesh	M2 mesh	M3 mesh
Total number of cells	65M	213M	587M
Total number of prisms	8M	89M	269M
Prims layers	5	25	15
Total number of nodes	14.4M	67.6M	193M

Luis Segui Troth (Cerfacs)





	M1 mesh	M2 mesh	M3 mesh
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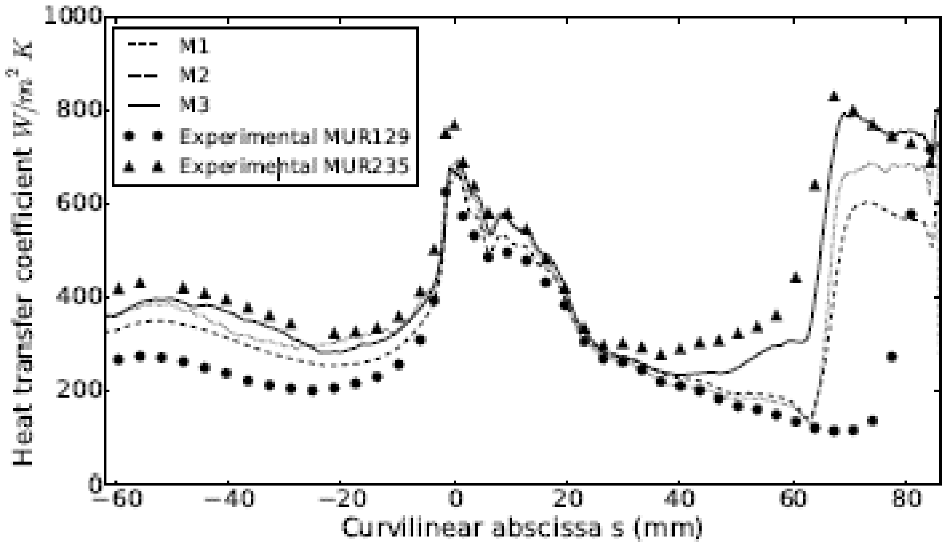

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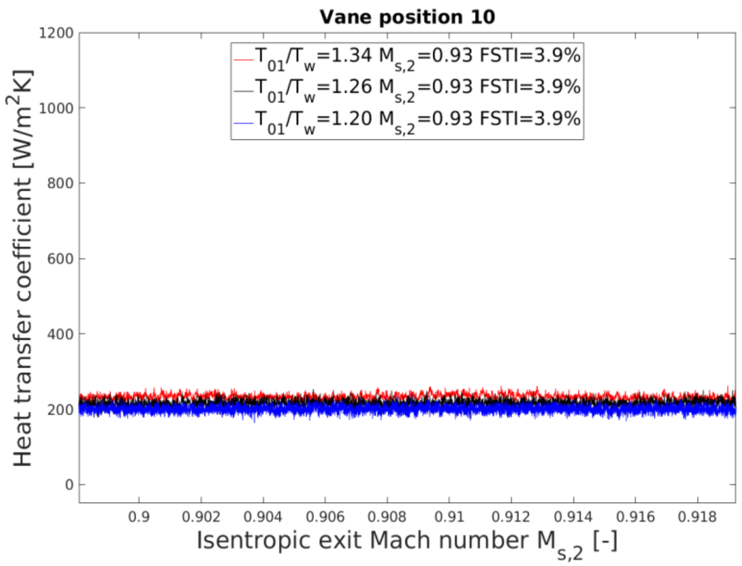
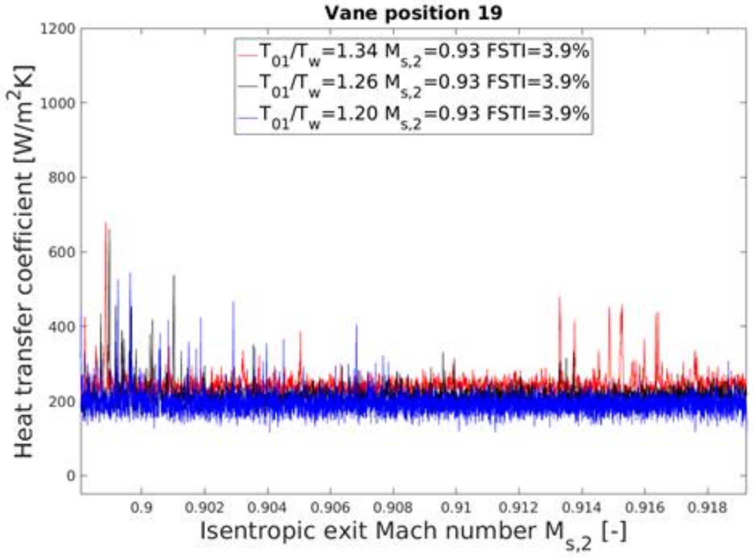
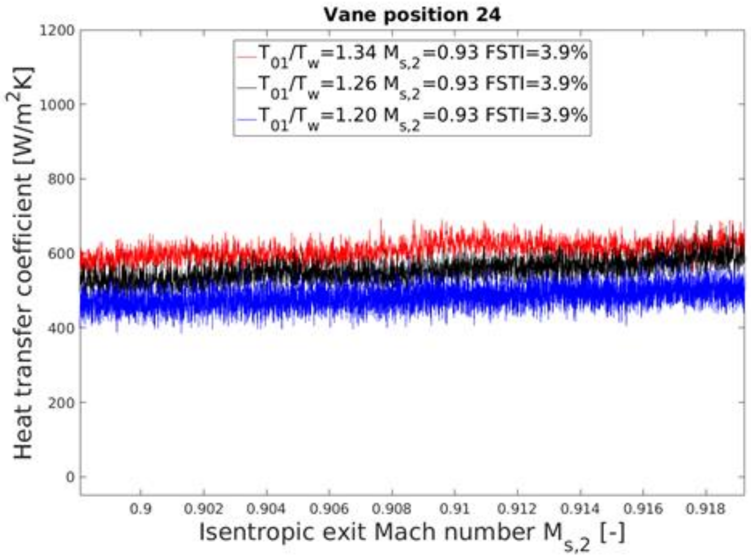

Vane position 10
T_{01}/T_w=1.34 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.26 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.20 $M_{s,2}$=0.93 FSTI=3.9%
Heat transfer coefficient [W/m²K]
Isentropic exit Mach number $M_{s,2}$ [-]

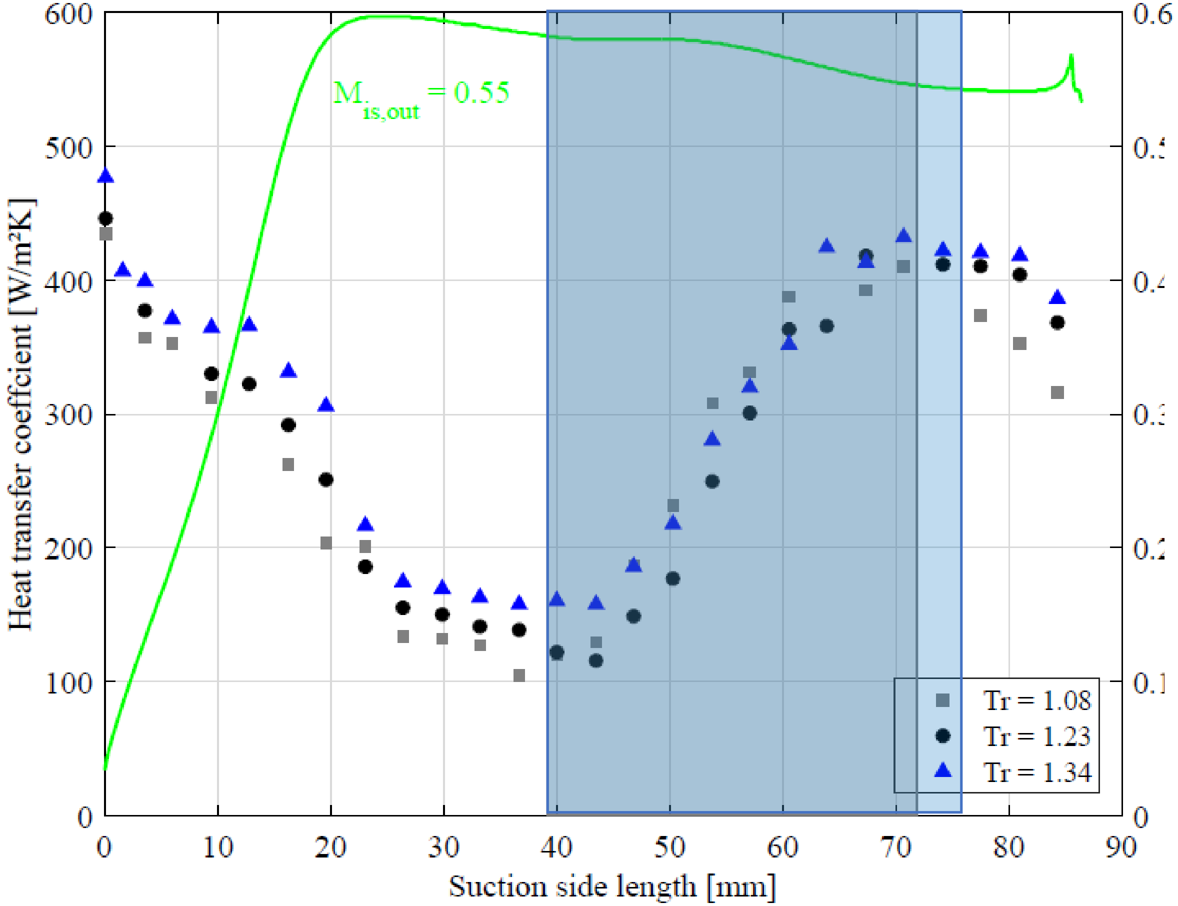

Vane position 19
T_{01}/T_w=1.34 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.26 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.20 $M_{s,2}$=0.93 FSTI=3.9%
Heat transfer coefficient [W/m²K]
Isentropic exit Mach number $M_{s,2}$ [-]

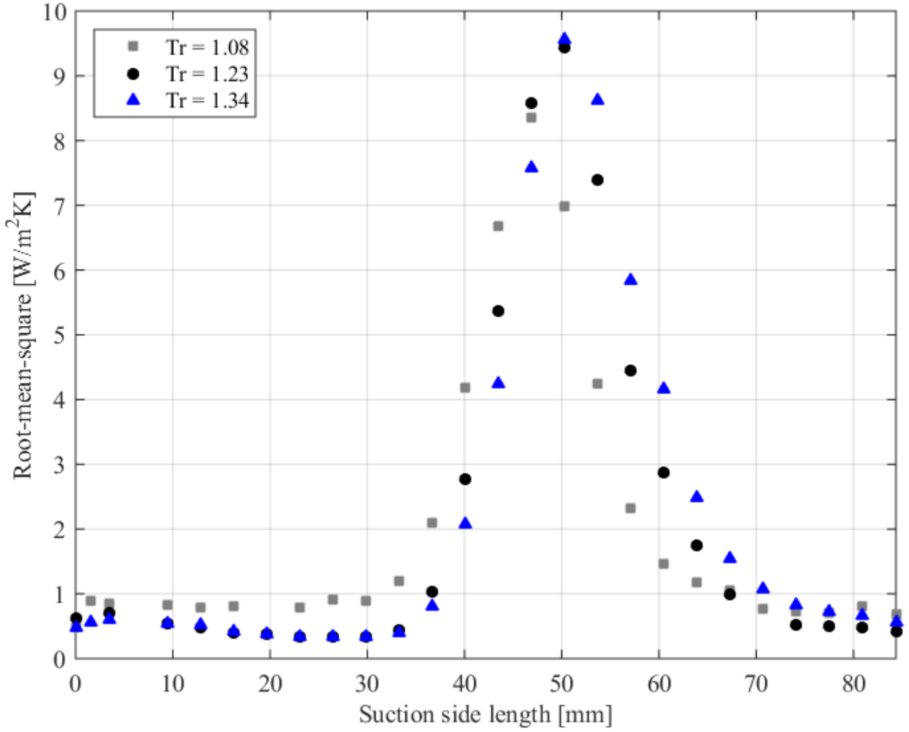

Vane position 24
T_{01}/T_w=1.34 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.26 $M_{s,2}$=0.93 FSTI=3.9%
T_{01}/T_w=1.20 $M_{s,2}$=0.93 FSTI=3.9%
Heat transfer coefficient [W/m²K]
Isentropic exit Mach number $M_{s,2}$ [-]

Effect of gas-to-wall temperature ratio on transition

Experimental information

$M_{2,is} = 0.50$ | $Re_{2,is} = 0.5 \cdot 10^6$ | $Tu_\infty = 12\%$

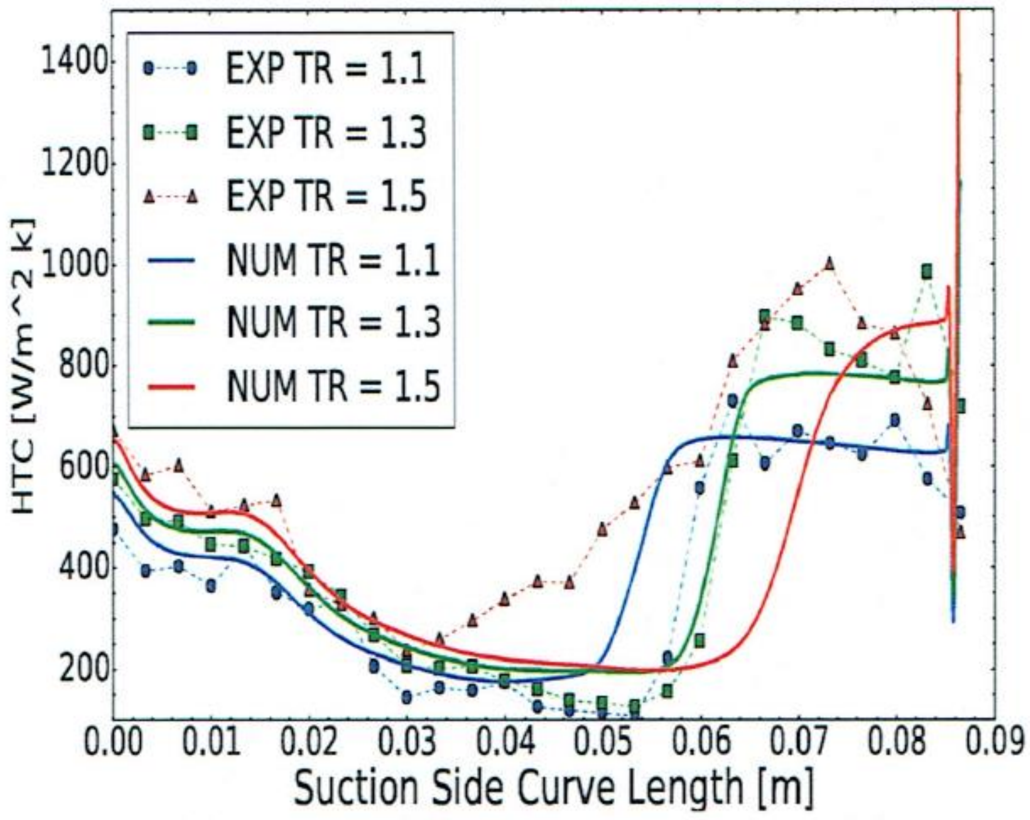


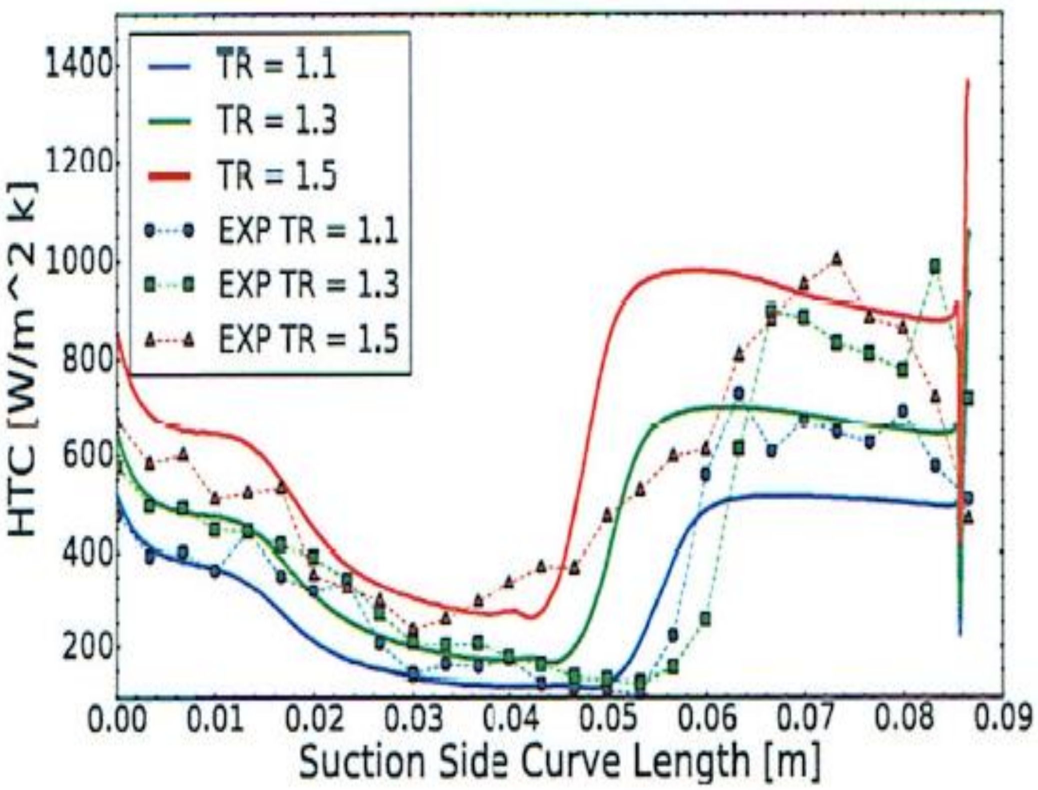


Tania Ferreira (VKI)

Effect of gas-to-wall temperature ratio on transition

Numerical information



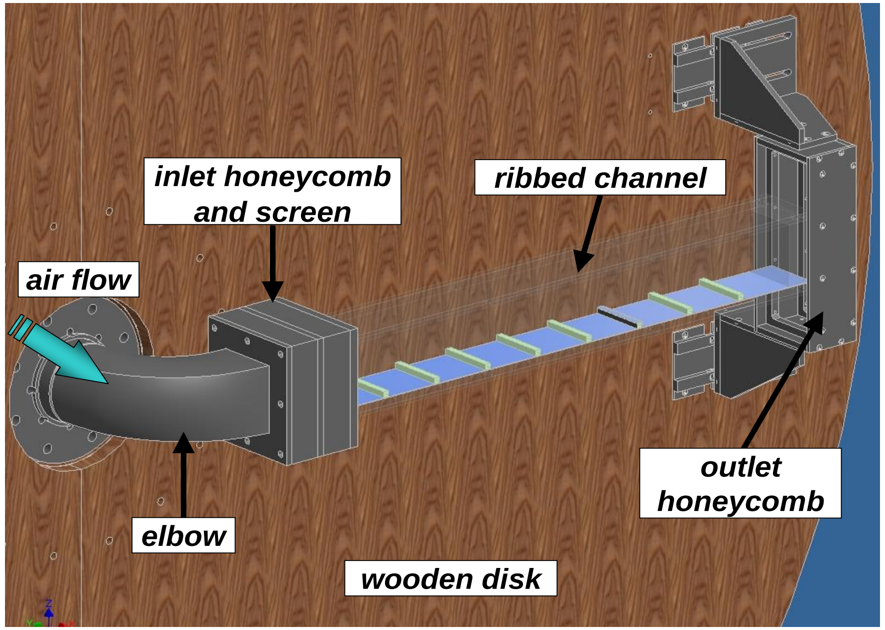


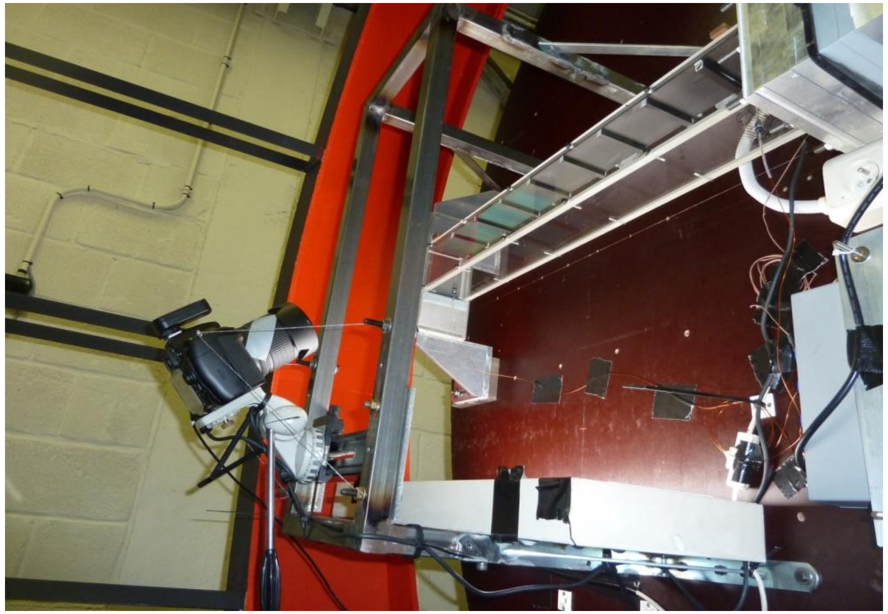
γ-Re_θ transition model

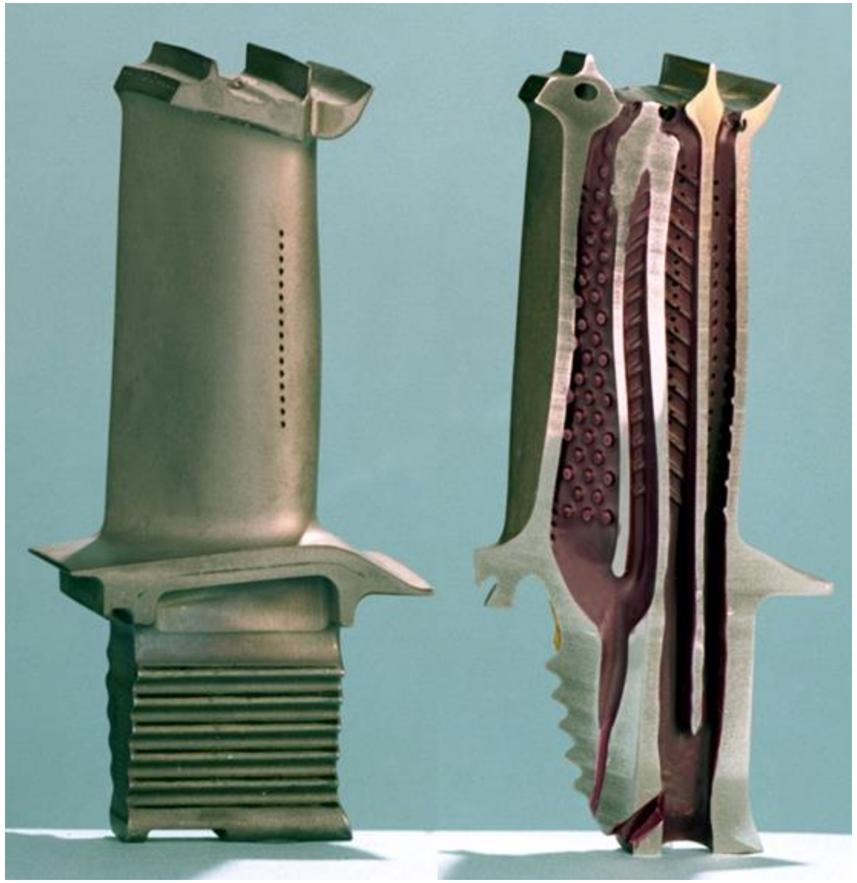
k-k_l-ω turbulence model

Riccardo Rubini (VKI)

Internal Cooling of High Pressure Turbine Blades







Similarity Analysis

$$\frac{D\boldsymbol{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\boldsymbol{u} - 2\boldsymbol{\Omega}\times\boldsymbol{u} - (\boldsymbol{\Omega}\times\boldsymbol{\Omega}\times\boldsymbol{r})$$

Assumptions:

- Rotating frame of reference
- constant viscosity
- 2D flow
- No heat transfer

projecting along x and normalizing by U_{bulk} and D_h

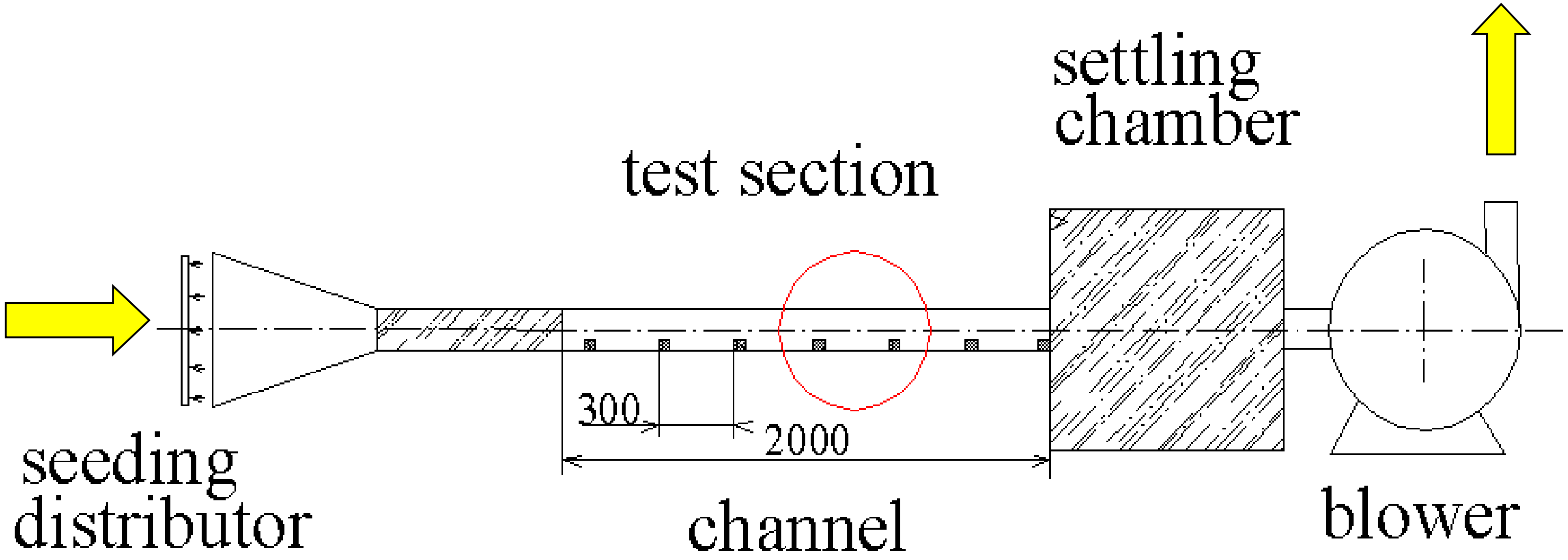
$$\frac{D\boldsymbol{u}}{Dt} = -\frac{\partial\tilde{p}}{\partial\tilde{x}} + \frac{1}{Re}\nabla^2\tilde{u} - 2\tilde{u}Ro - Bo$$

where: $Re = \frac{U_{bulk}D_h}{\nu}$

$Ro = \frac{\Omega D_h}{U_{bulk}}$

$Bo = \frac{\Delta\rho}{\rho}Ro^2\tilde{r}$ ⇨ $\frac{Gr}{Re^2}$ substituting g with $\Omega^2 r$

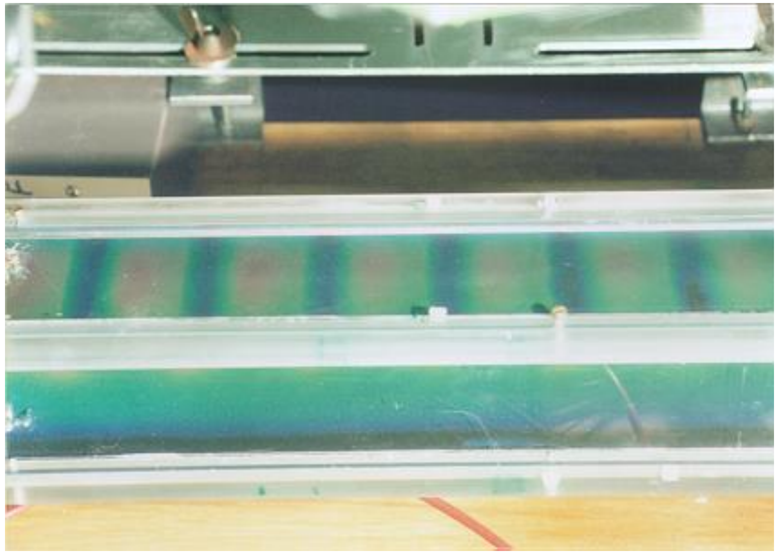
Geometrical Definition of the Test Section

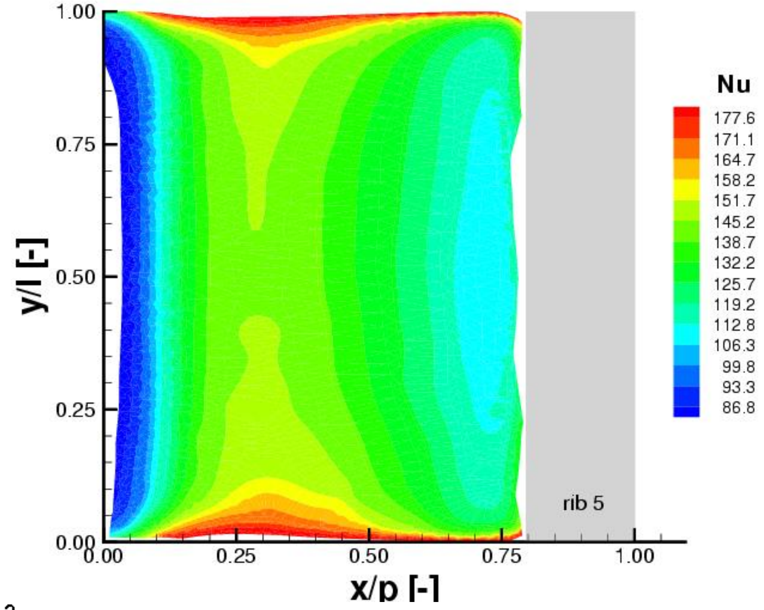


Geometrical and flow similarity conditions

Rib height : 30 mm	Re=40000	Uo = 6 m/s
Test section : 100 x 100 mm^2	Pr = 0.7 (air)	$T_{flow} = T_{wall} = 20\ ^oC$

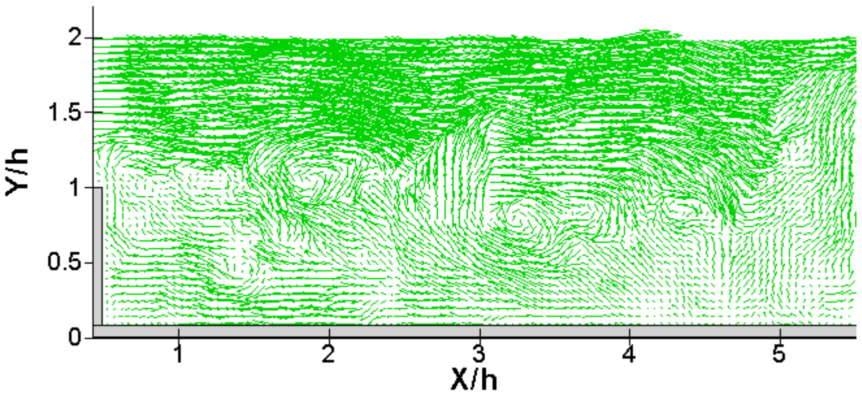
Internal Cooling

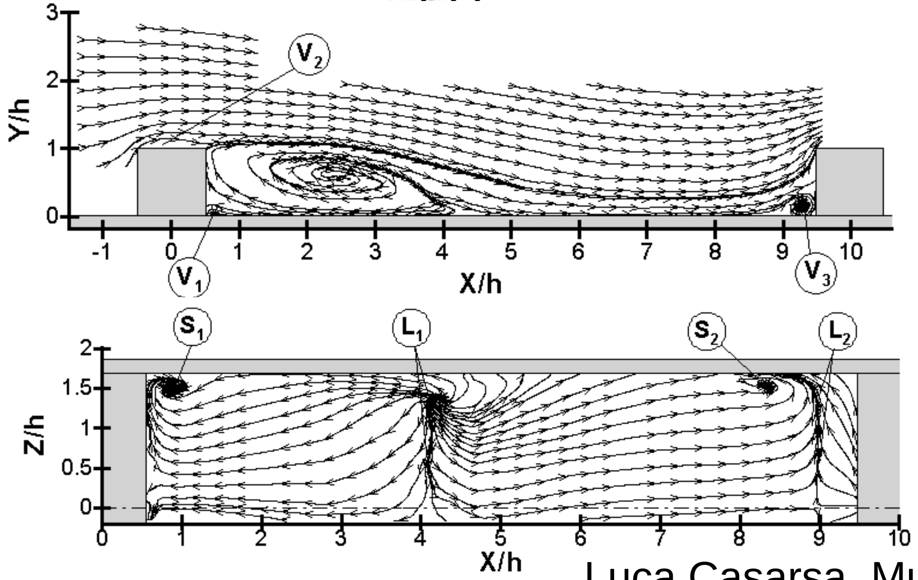




↑ Heat Transfer (L.C.)

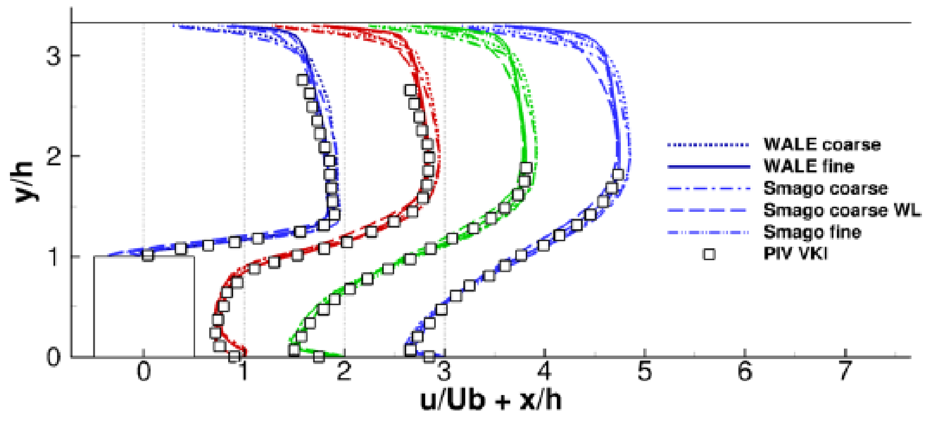
↓ Aerodynamics (P.I.V)

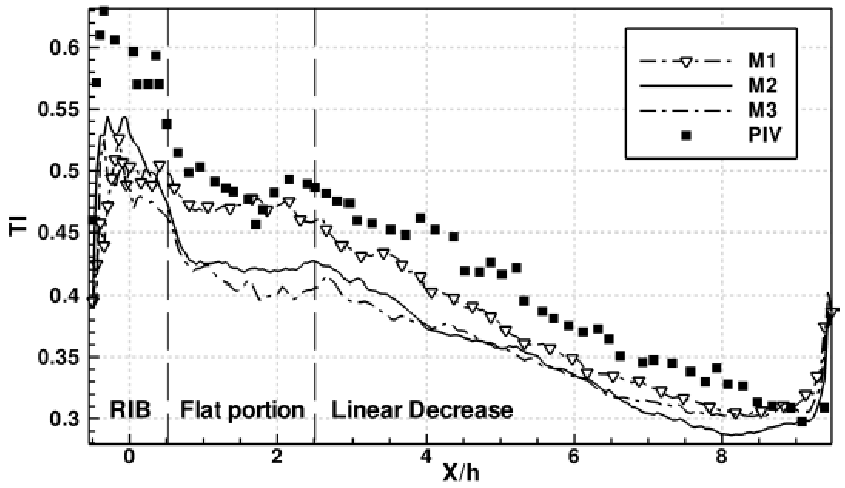


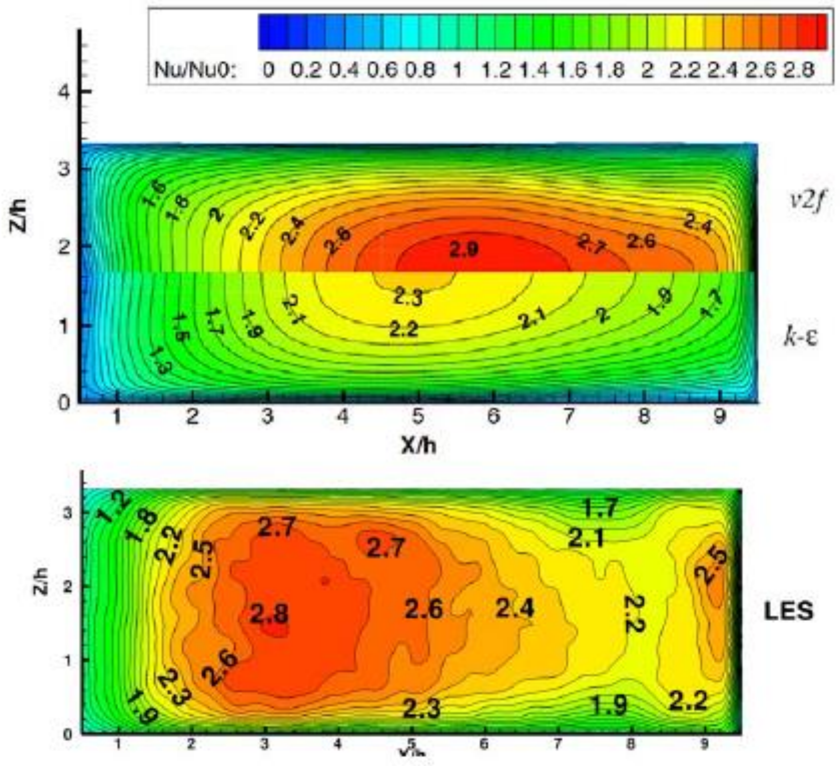


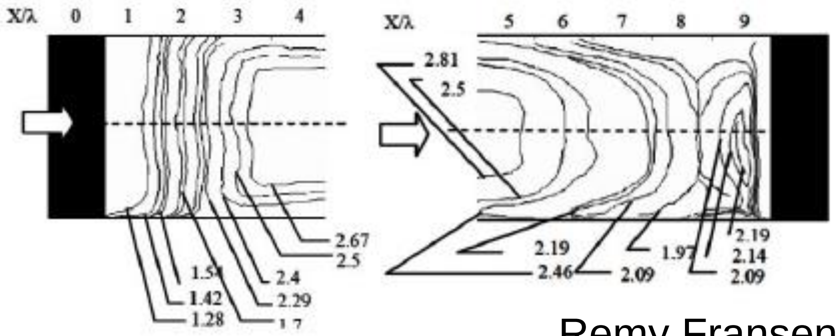
Luca Casarsa, Murat Çakan (VKI)

Internal Cooling Channels (state of the art - CFD)



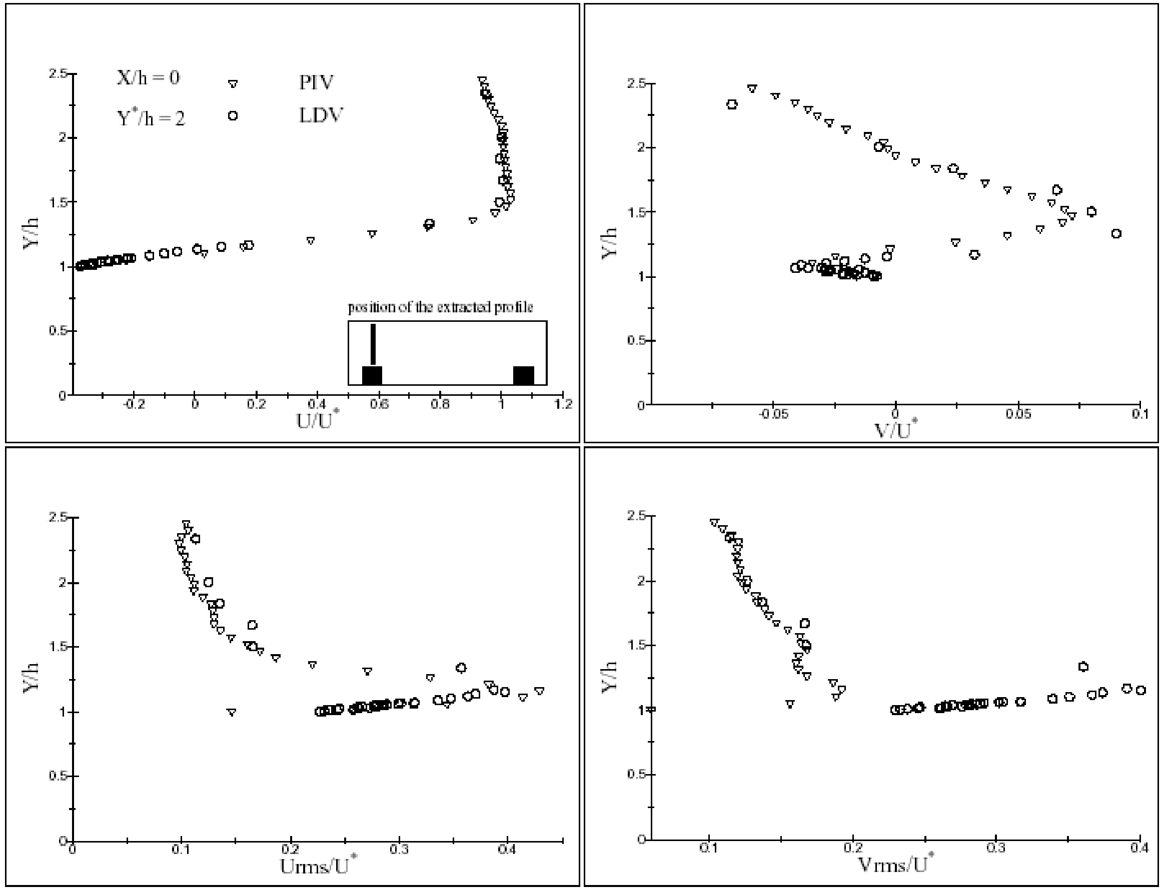


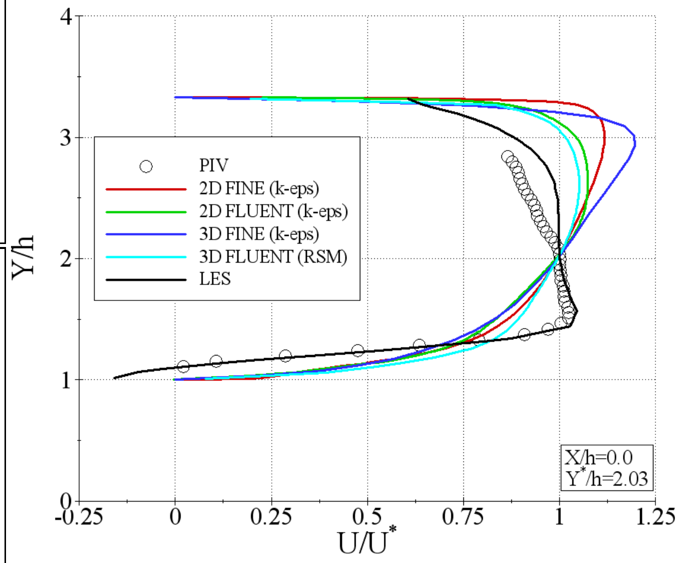




Remy Fransen (Cerfacs)

COMPARISON WITH LDV AND CFD

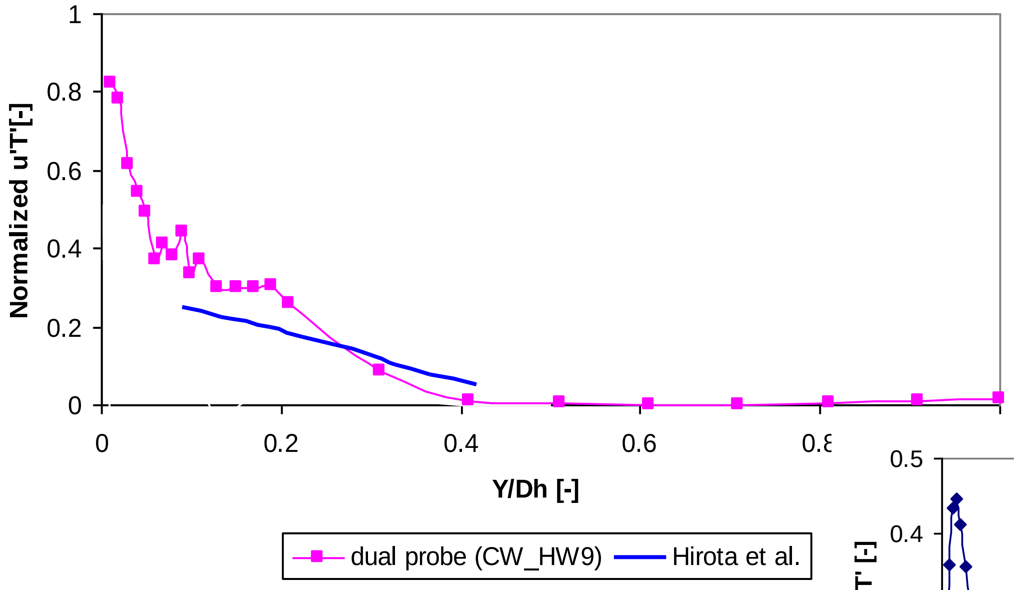


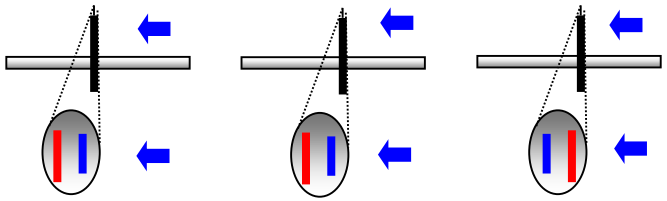


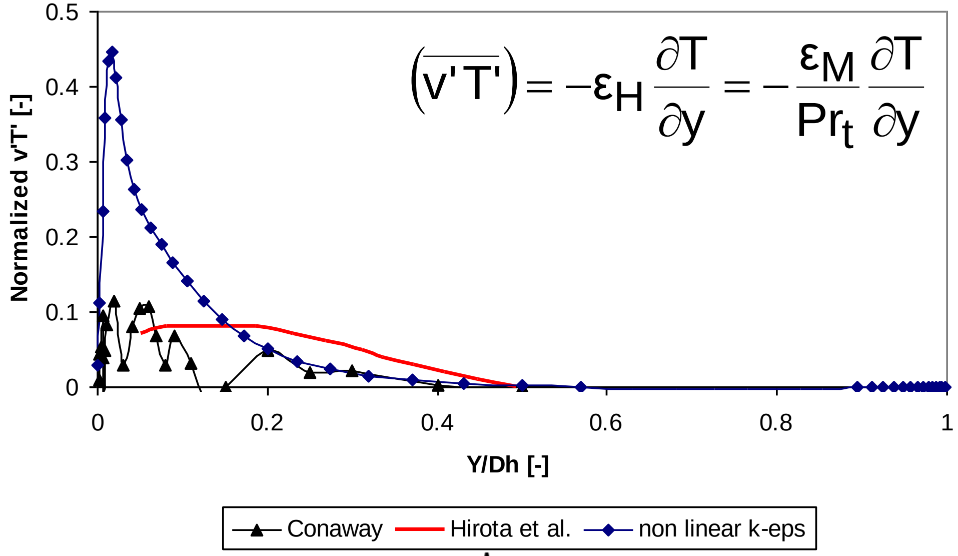
Luca Casarsa(VKI)

von Karman Institute

INPUT FROM LDV, HOT AND COLD WIRES

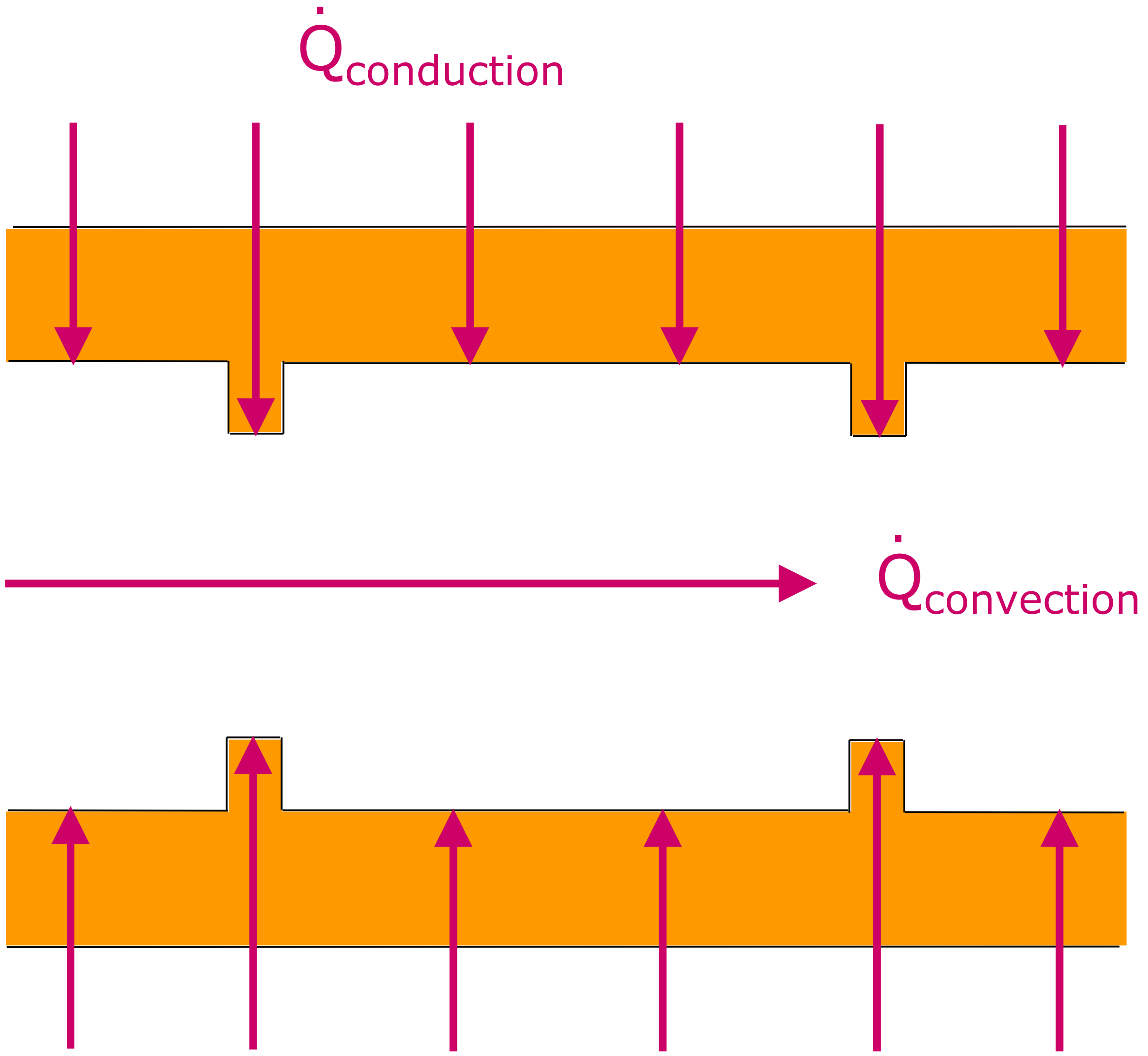


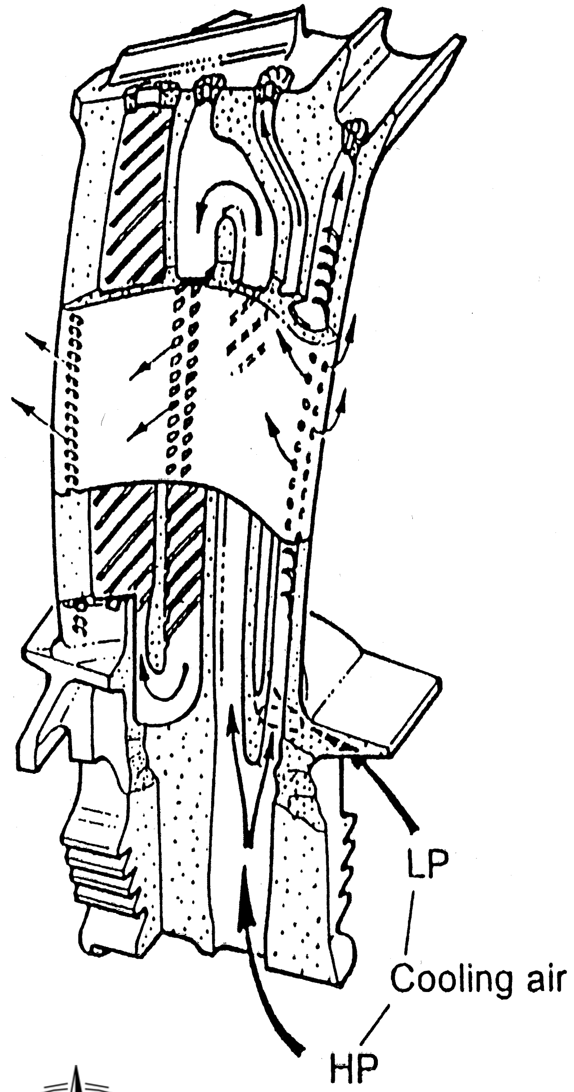




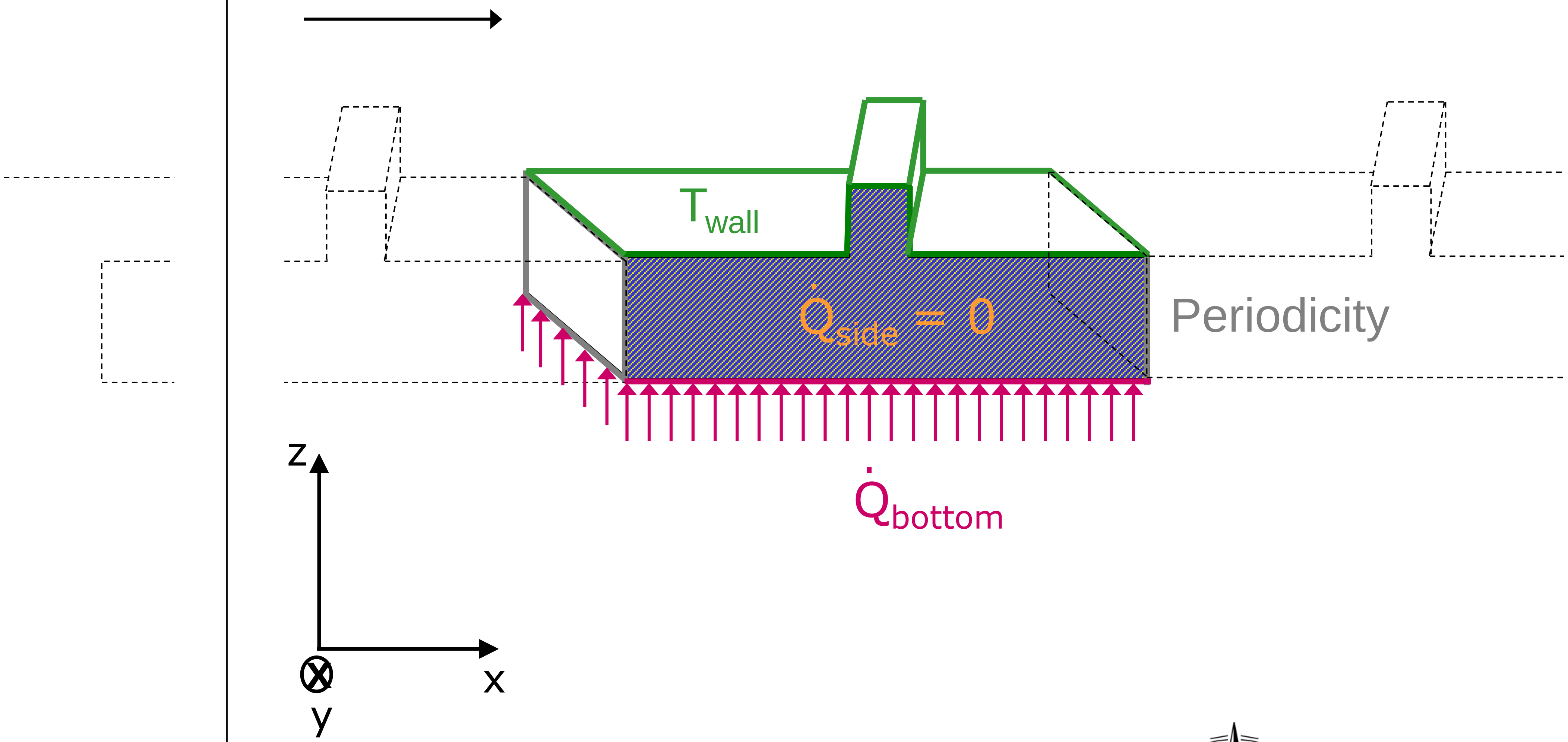
$$\left(\overline{v'T'}\right) = -\varepsilon_H \frac{\partial T}{\partial y} = -\frac{\varepsilon_M}{Pr_t}\frac{\partial T}{\partial y}$$

CONJUGATE PROBLEM

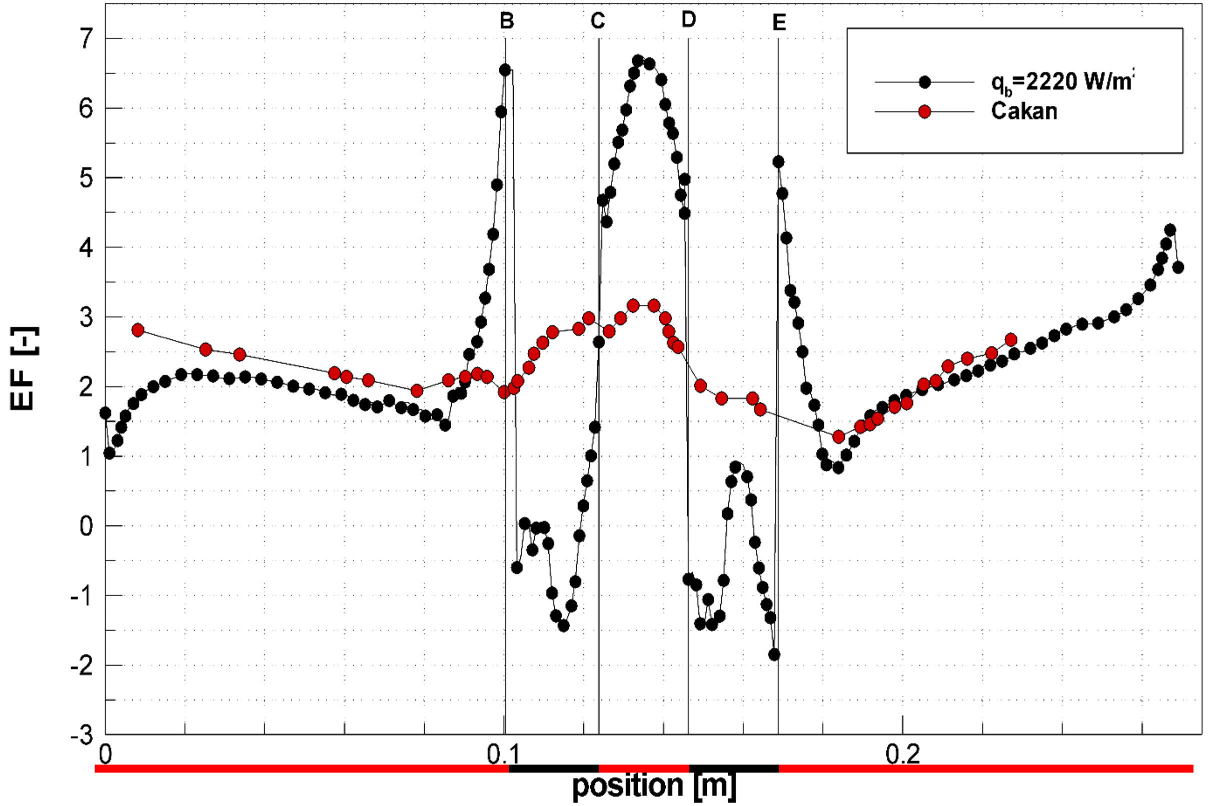


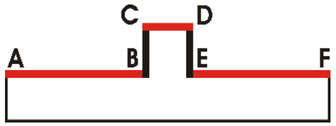


BOUNDARY CONDITIONS



CONJUGATE PROBLEM : RESULTS

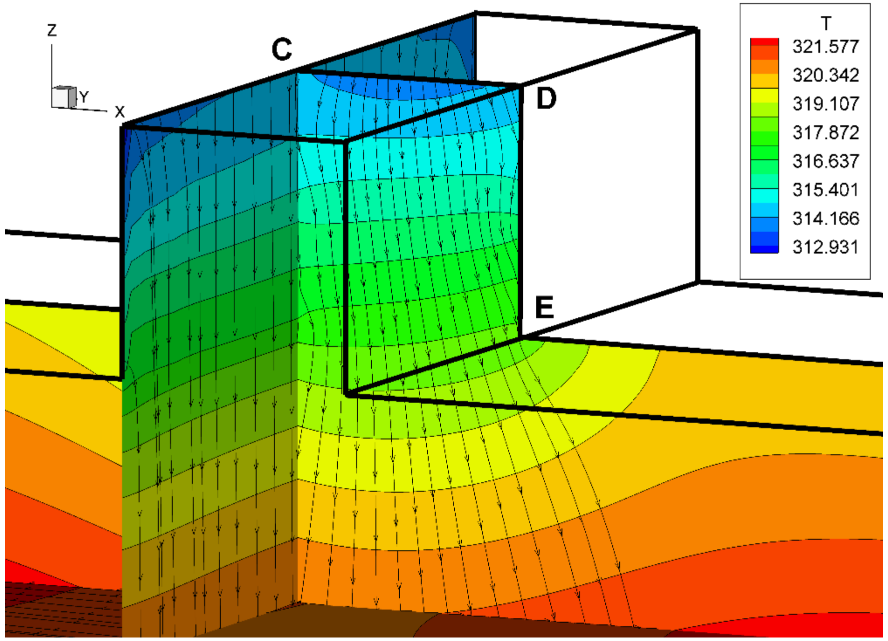


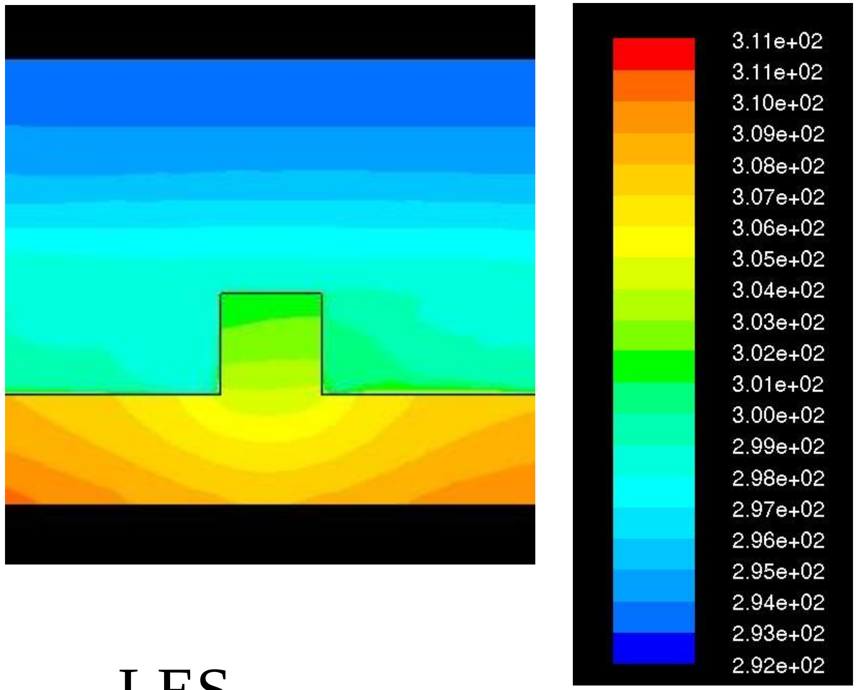


BOUNDARY TYPE	$\overline{EF}$	$\left|\Delta\overline{EF}\right|$ %
Constant heat flux bottom	1.7864	37.87%
Constant heat flux top [12]	2.4630	

$$\overline{EF} = \frac{\int_{wp} EF \cdot ds}{wp}$$

CONJUGATE PROBLEM : CFD ?





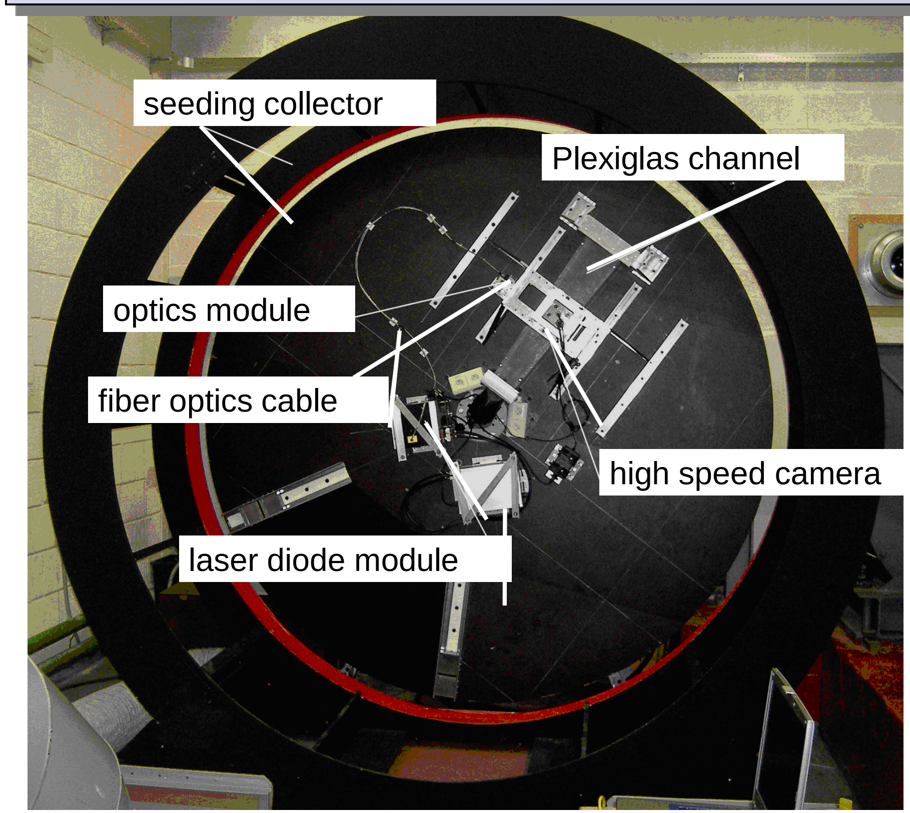
Based on . . . measurements . . . LES

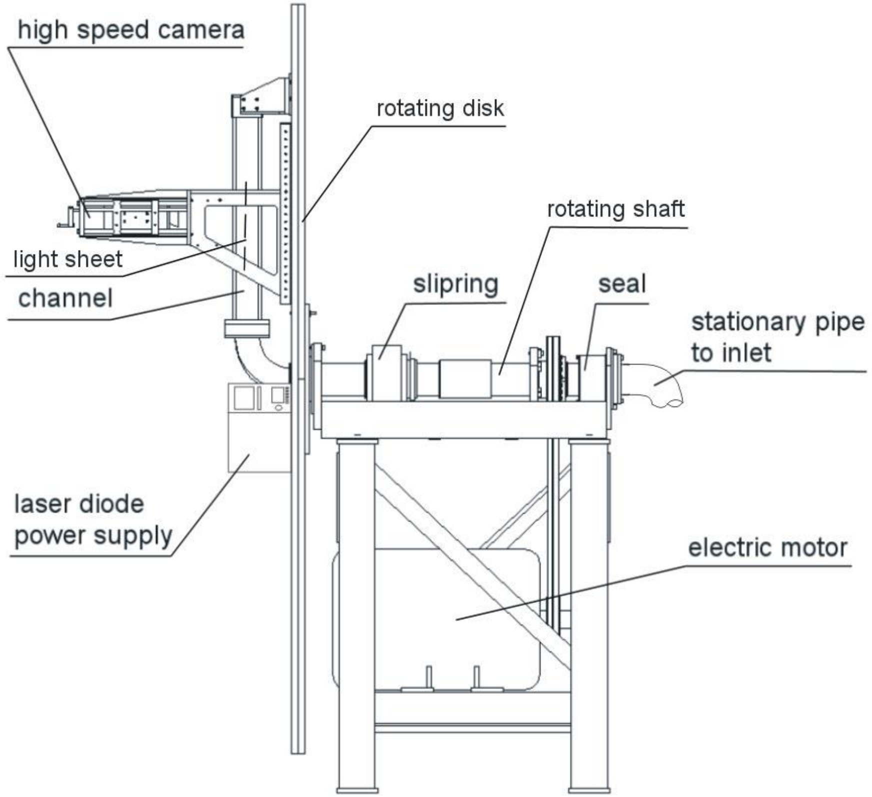
Rotating Facility RC-1

- 2,5 m wooden disk driven by DC motor up to 160 rpm
- 25 W air-cooled continuous laser diode
- 200 µm fiber cable + compact optics module
- 800 x 600, 4.8 kHz CMOS camera

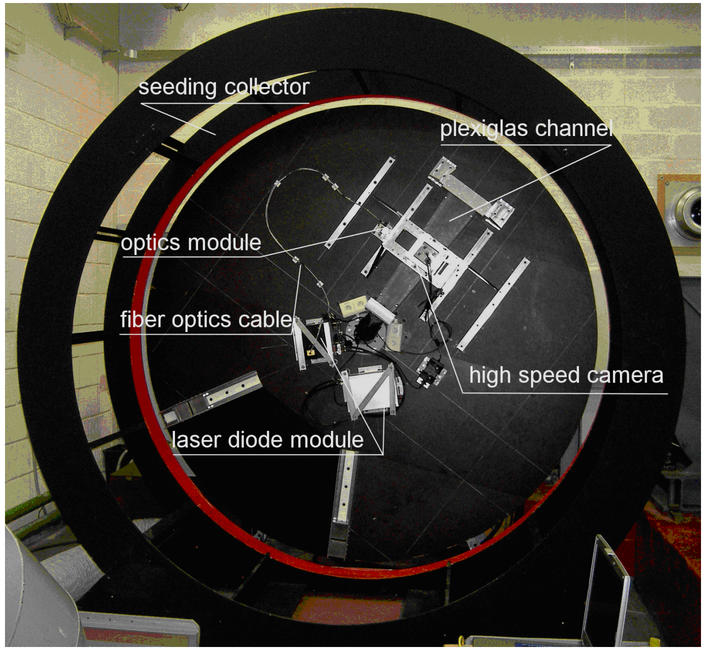
} PIV system mounted on the disk

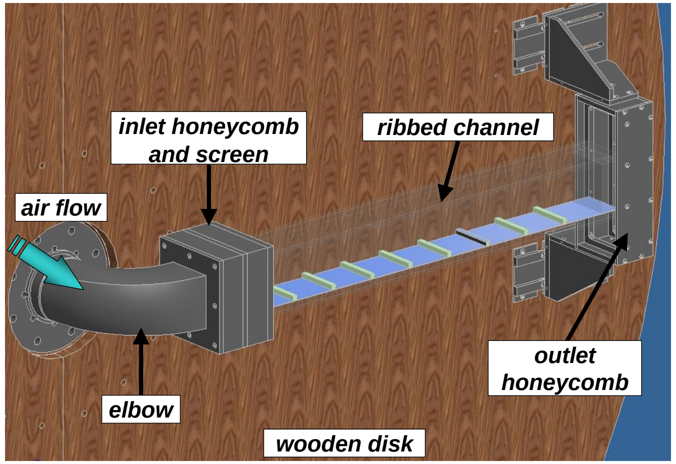
- Same accuracy and resolution as in a non-rotating rig

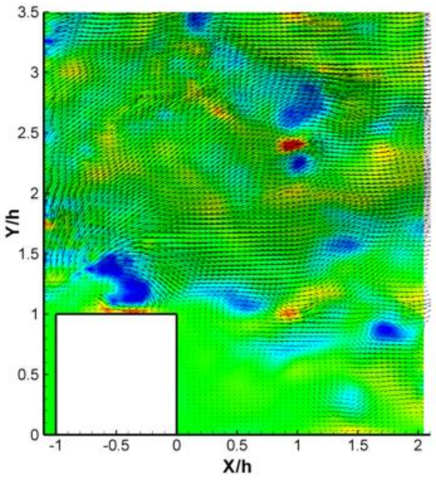




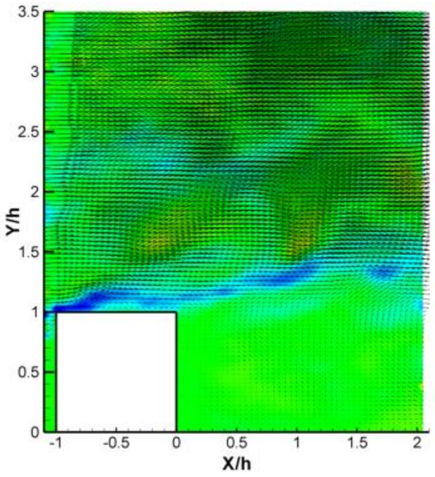
Rotating Channels – State of the Art



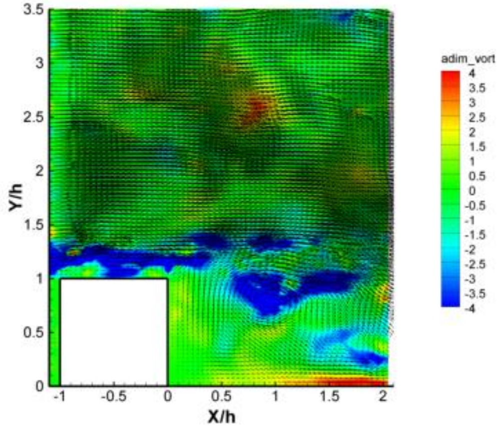




No Rotation



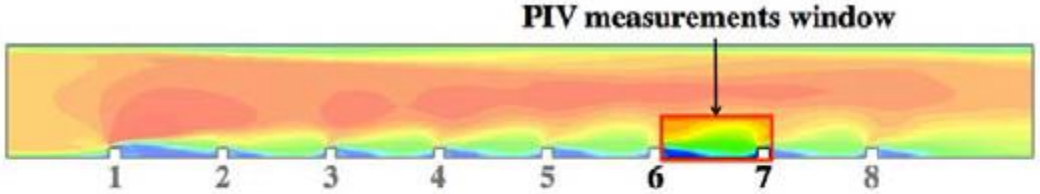
Stabilizing Rotation

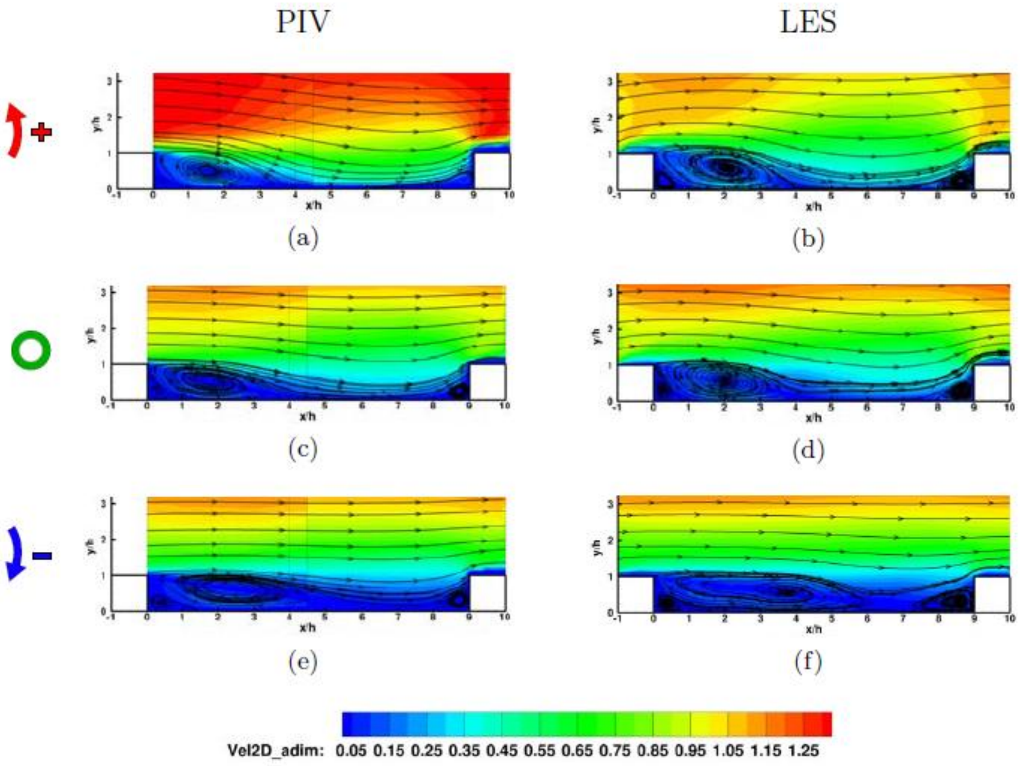


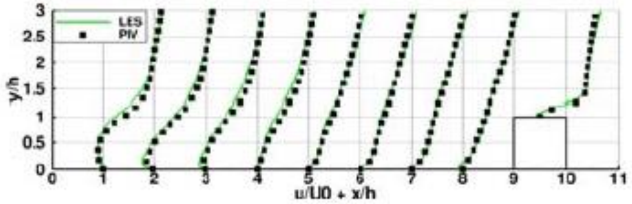
Destabilizing Rotation

Larger possibilities of exploitation

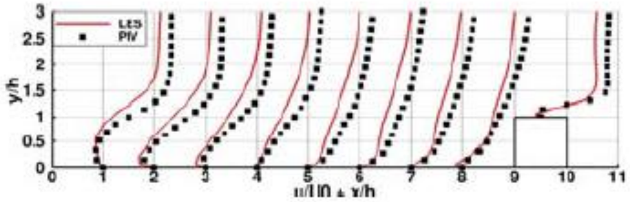
Filippo Coletti (VKI)



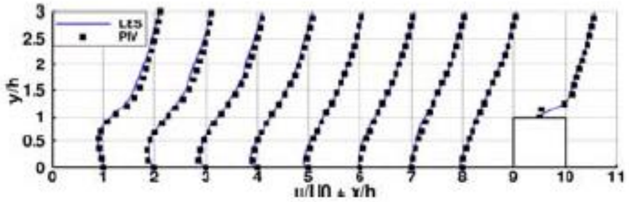




(a)



(b)

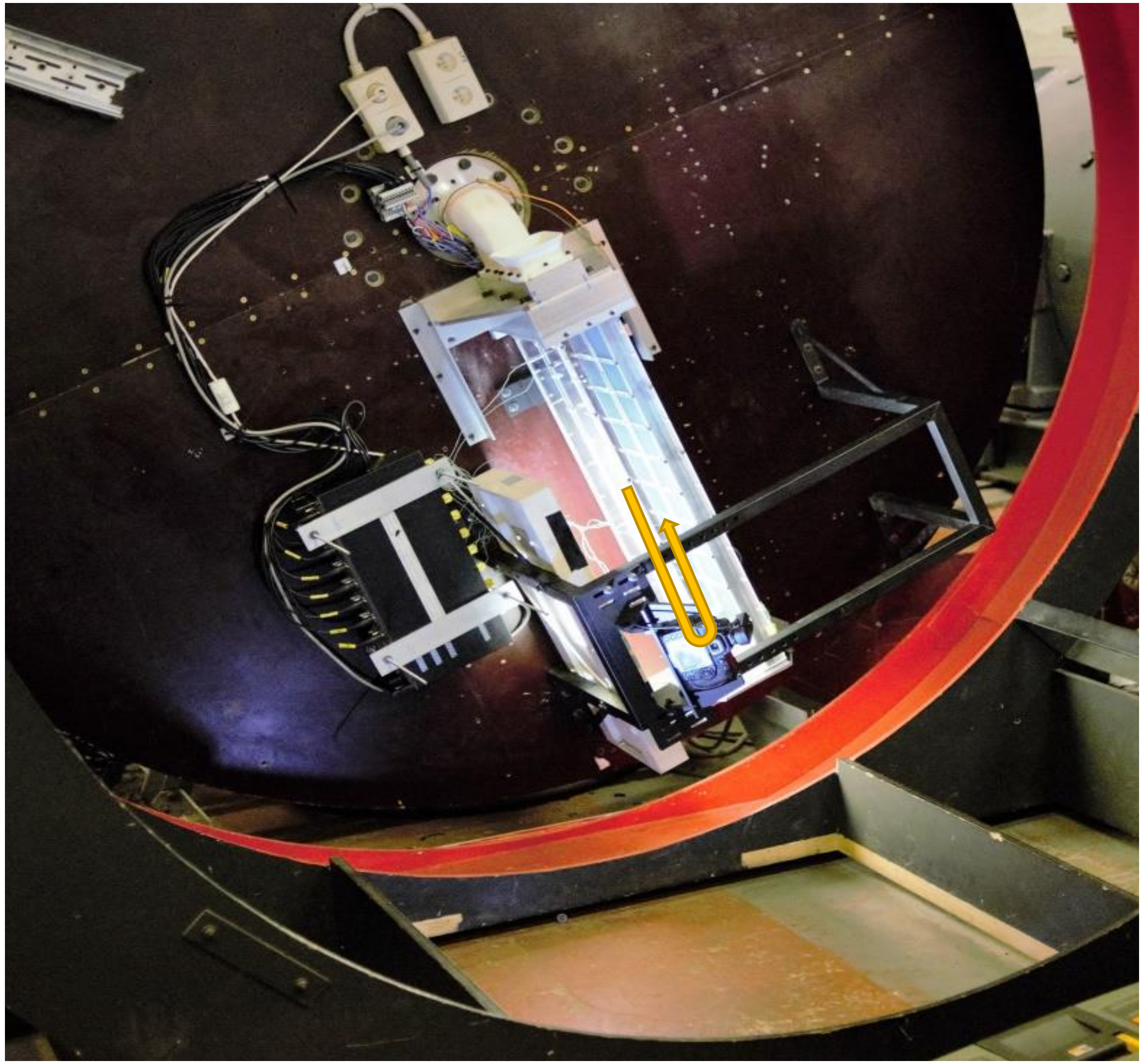


(c)

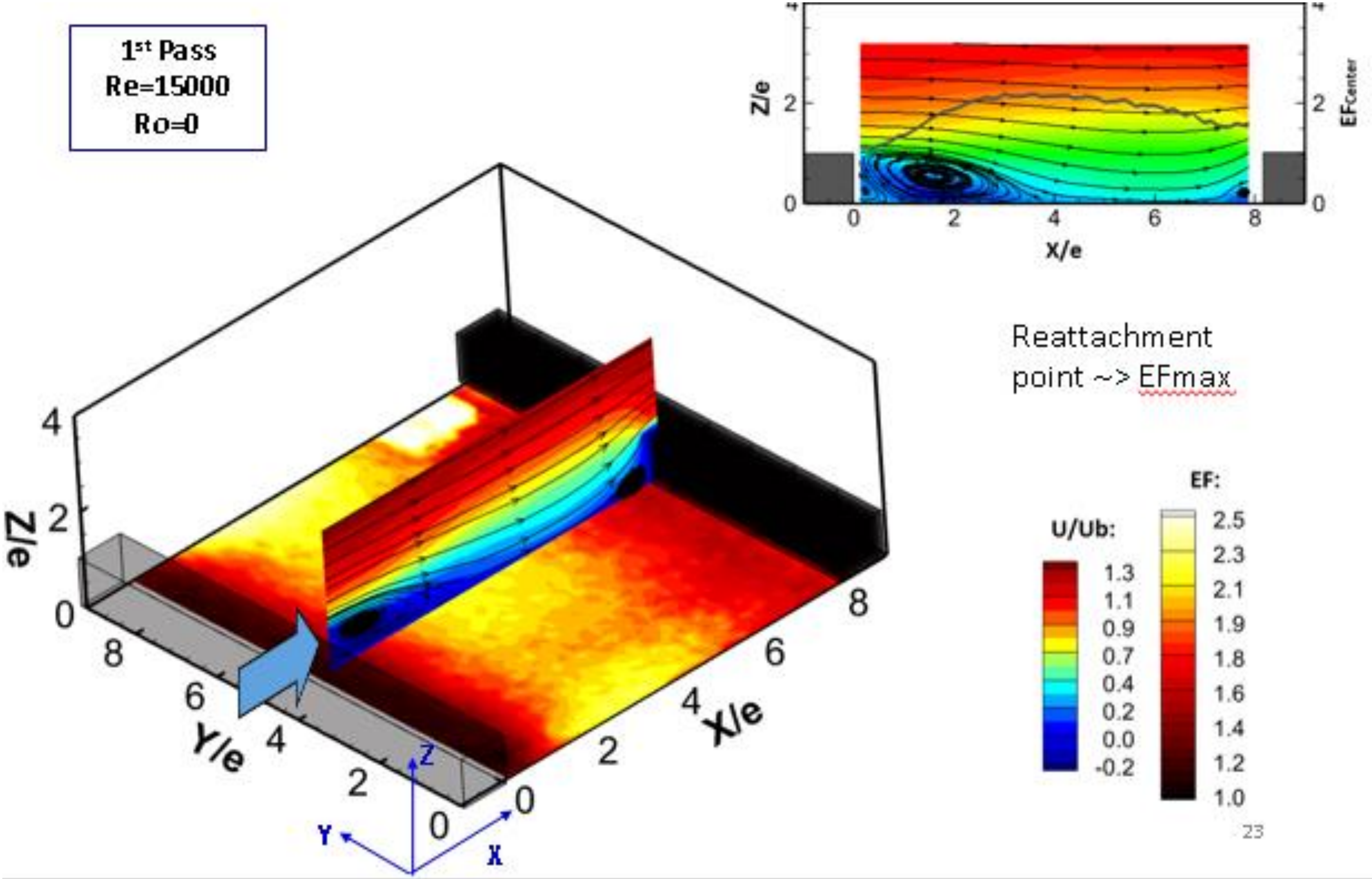
Comparison of LES (lines) and PIV (symbols) mean streamwise velocity profiles in the channel symmetry plane
between the 6th and the 7th ribs:
non-rotating case (a), destabilizing rotation (b) and stabilizing rotation (c)

Filippo Coletti(VKI), Remy Fransen (Cerfacs)

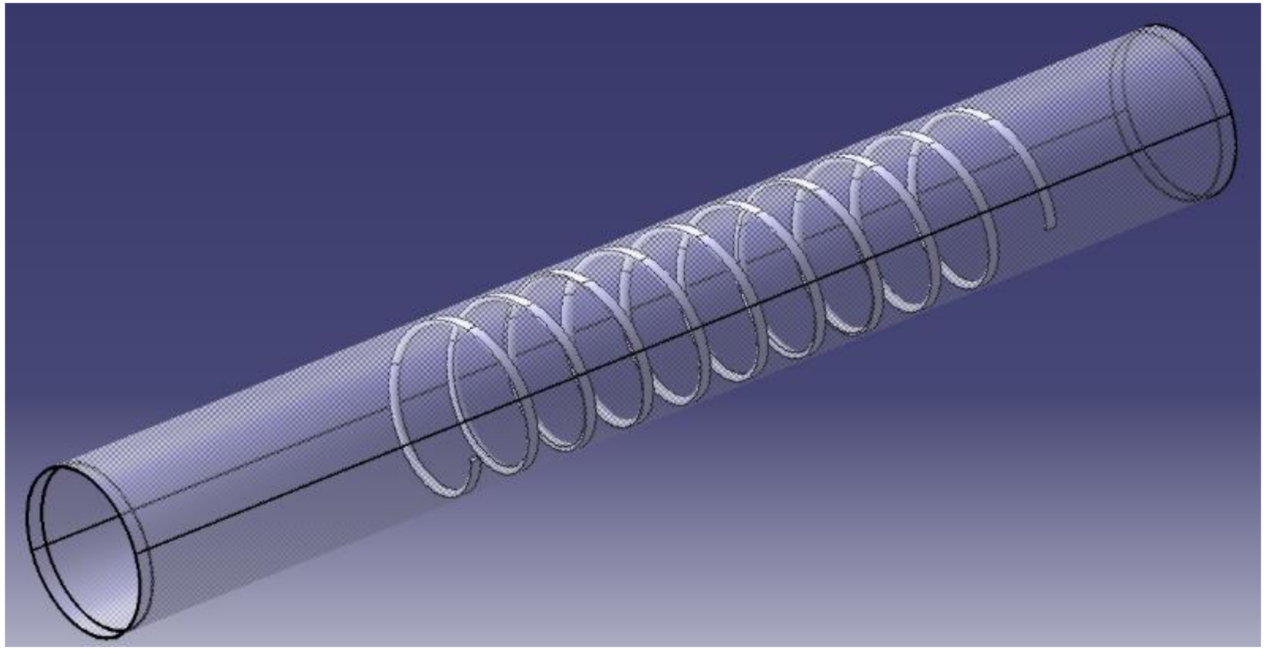
Two-Pass Rotating Duct

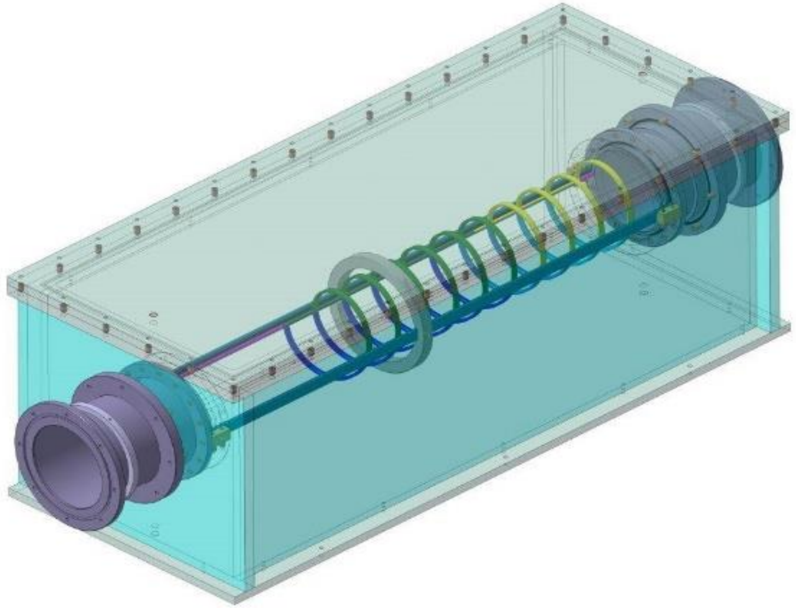


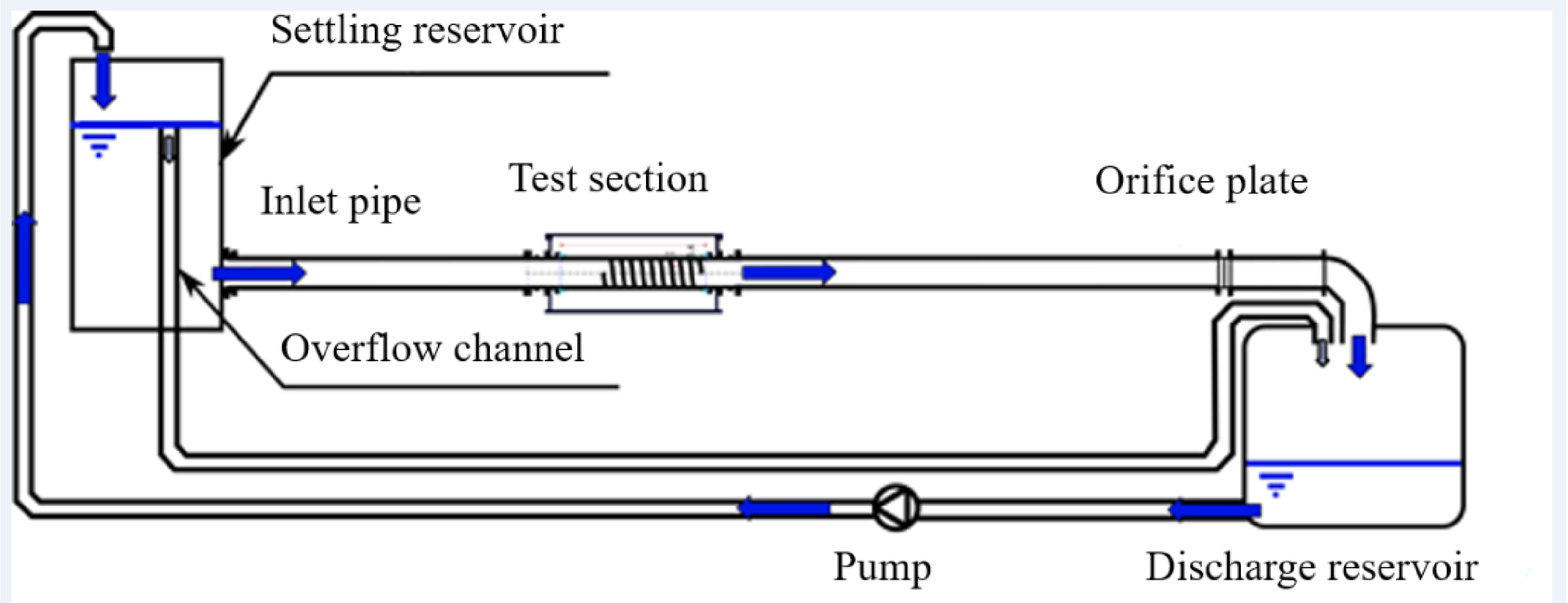
Two-Pass Rotating Duct

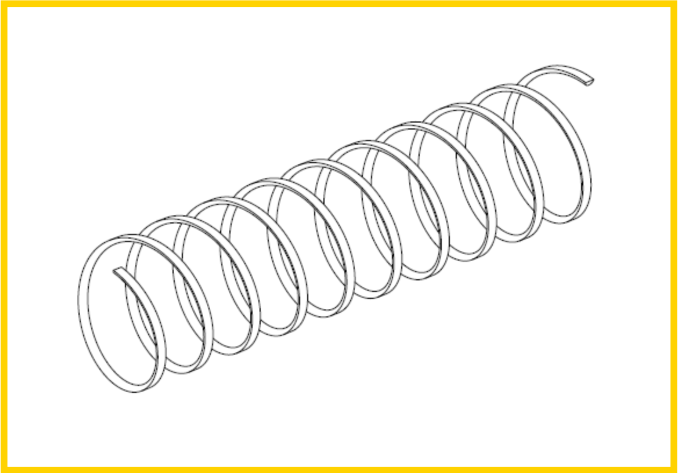


Helically corrugated tubes



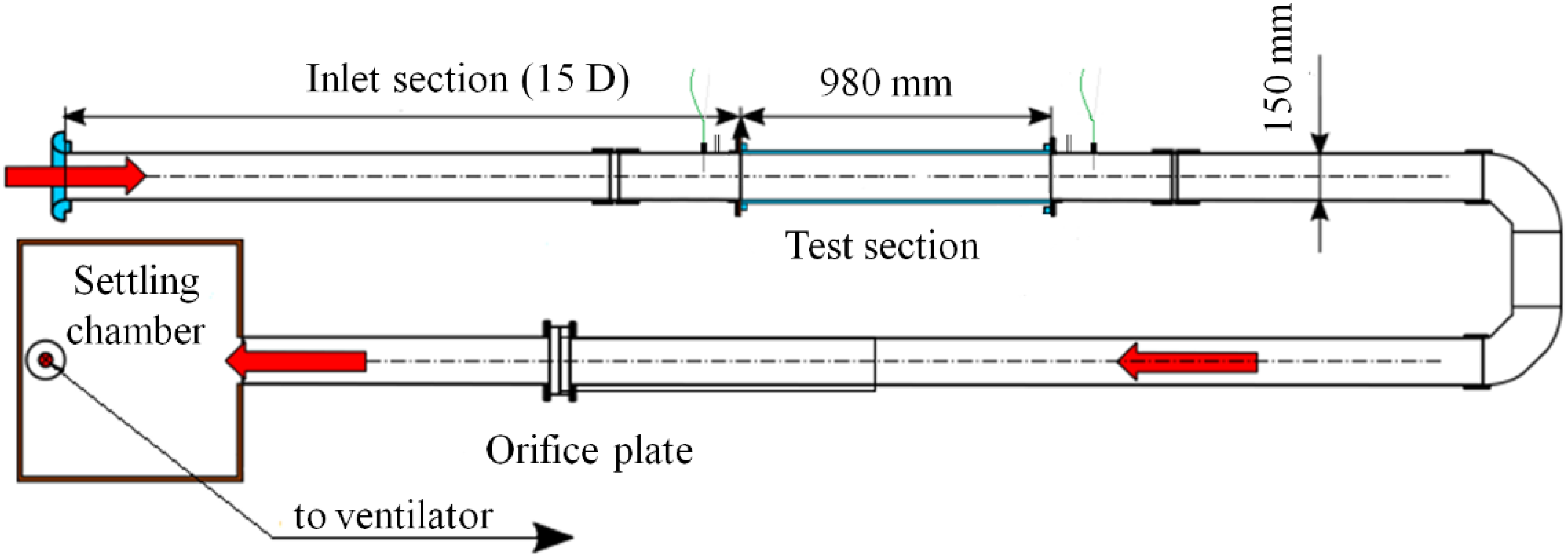


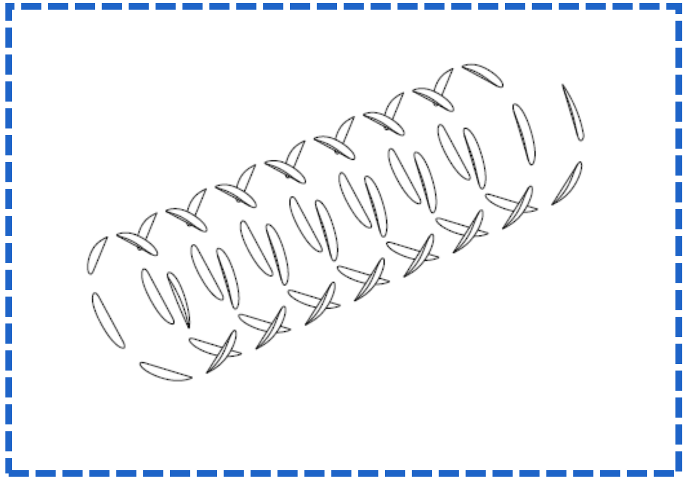




$\Delta p_{exp} / \Delta p_0 = 6.25$

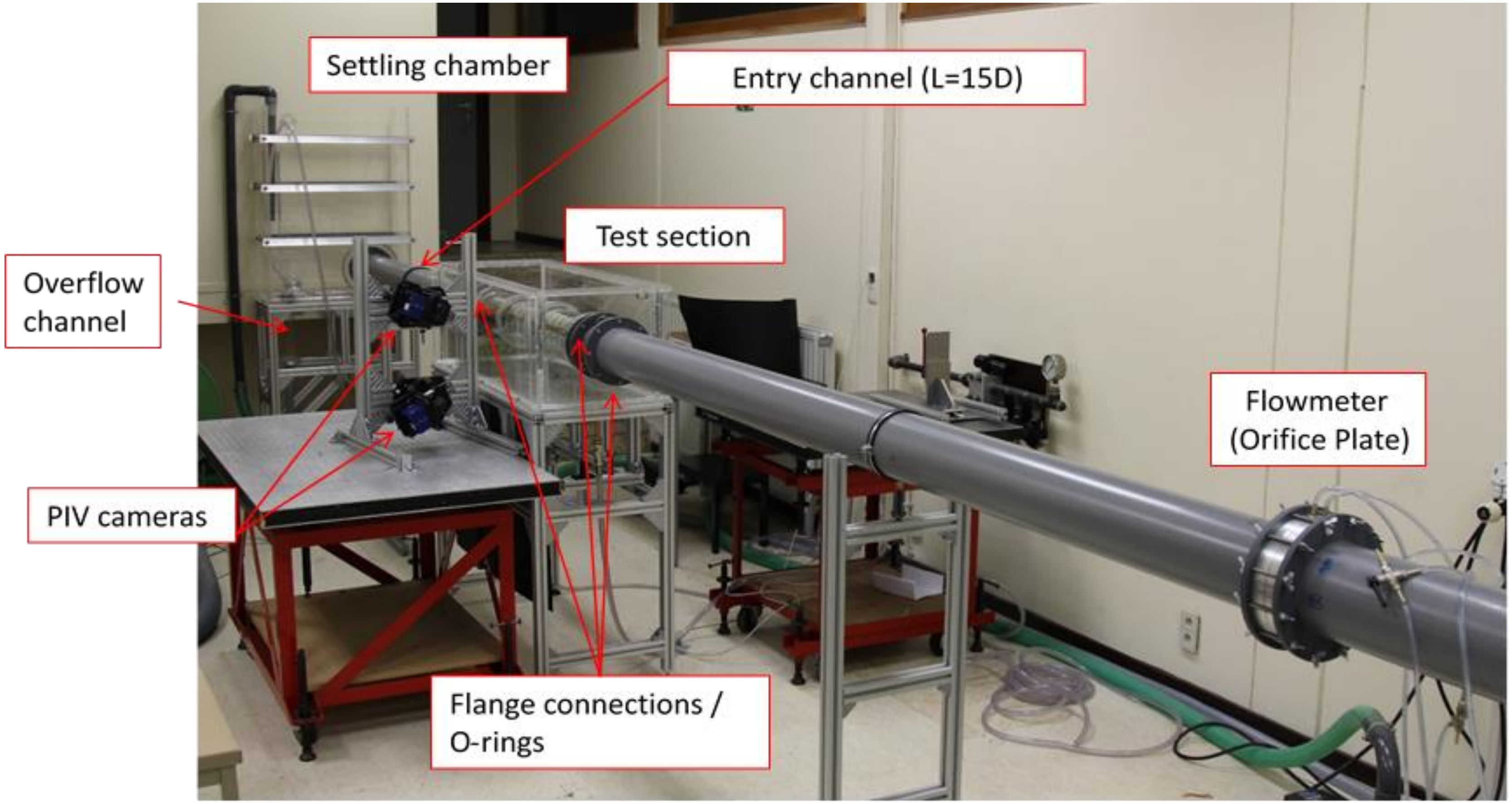
$\Delta p_{num} / \Delta p_0 = 6.68$

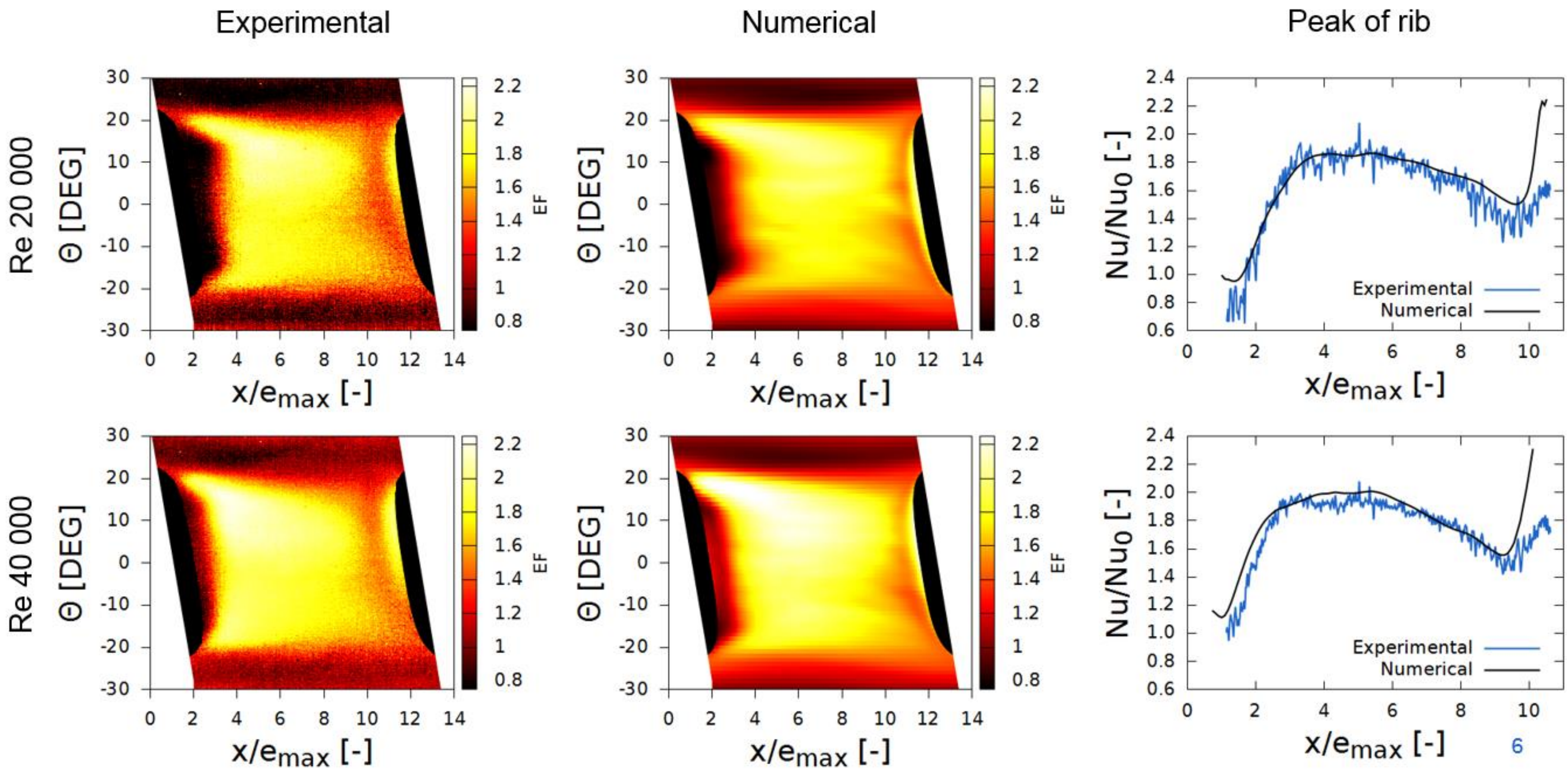




$\Delta p_{exp} / \Delta p_0 = 3.57$

$\Delta p_{num} / \Delta p_0 = 3.67$


Settling chamber
Entry channel (L=15D)
Test section
Overflow channel
PIV cameras
Flange connections / O-rings
Flowmeter (Orifice Plate)



Marco Virgilio (VKI), Jens Dedeyne (RUG)

Conclusions (my humble vision)

- Measurements and computations are <u>complementary</u>
  - Validation of numerical simulations (Expe -> CFD)
  - Setup of an experiment (CFD -> Expe)

- Experiments are expensive (people, time, level of similarity, space and time resolution)
- Simulations (still) need assumptions
  - RANS: turbulence and transition modelling
  - LES: subgrid scale modelling
  - DNS: not affordable (yet) for industrial flows
  - Thermal urbulence modelling

- Absolute needs:
  - Uncertainty analysis (<u>for both</u>)
  - Complete and detailed boundary conditions definition/description (turbulence …)
  - New approaches to be invented, designed, validated
  - Ideally done (if possible) in very close contact