Performances aero-thermiques de grilles d’aubes de turbines HP et aérodynamiques de turbines BP en conditions representatives de fonctionnement moteur

Institut von Karman de Dynamique des Fluides
Département “Turbomachines et Propulsion”
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High-Pressure Gas Turbine Nozzle Blades

LS 89 – Uncooled nozzle guide vane

$Re_{2,is,c}$: 5.5 10^5 – 2 10^6
Tu_∞ : 1 % - 6 % -> 25 %
$M_{2,is}$: subsonic – transonic
Gas/wall temp ratio : 1.1 – 1.5

Aero and heat flux data (uniform temperature wall BC)

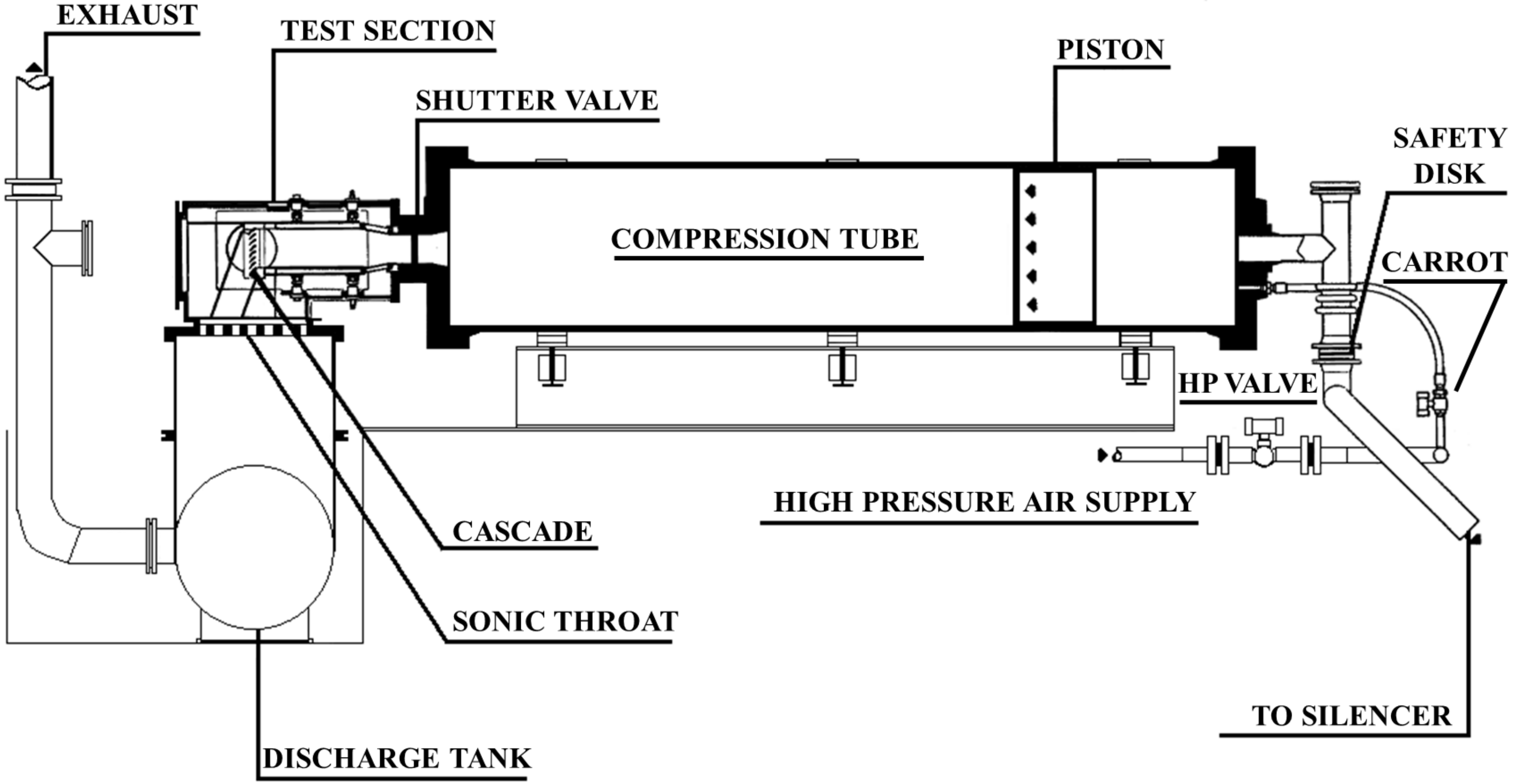
LS 94 – Film cooled version of LS 89

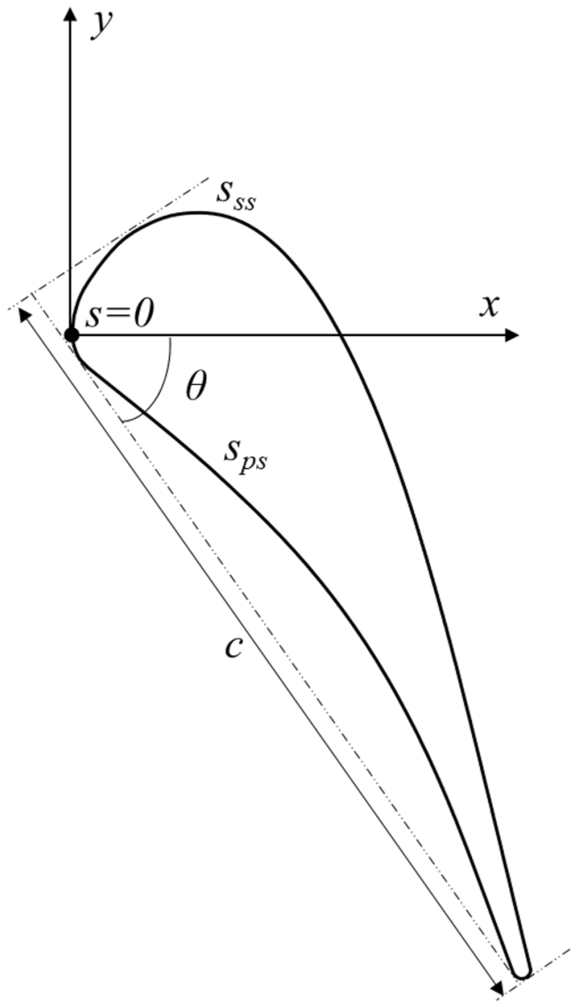
Suction/Pressure side film cooling
Similar boundary conditions

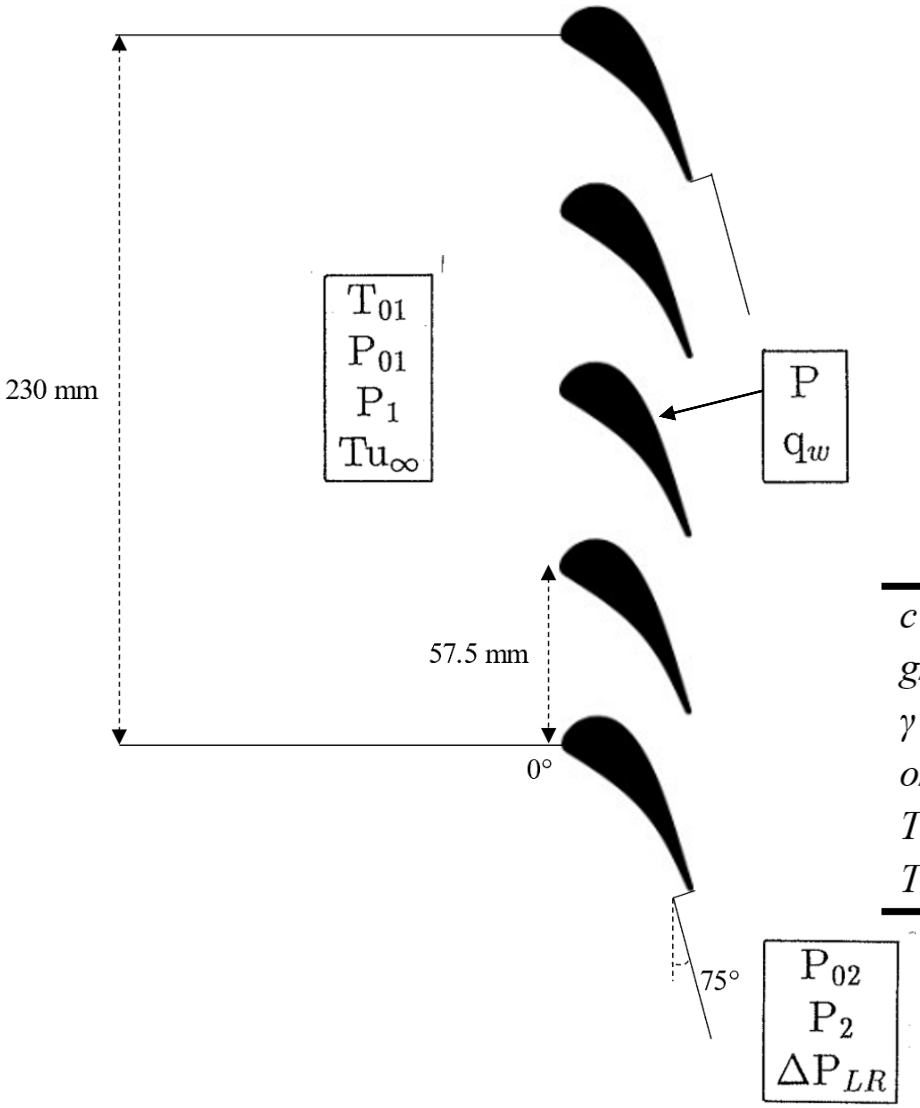
Aero and heat flux data (uniform temperature wall BC)

Steady inlet and exit boundary conditions

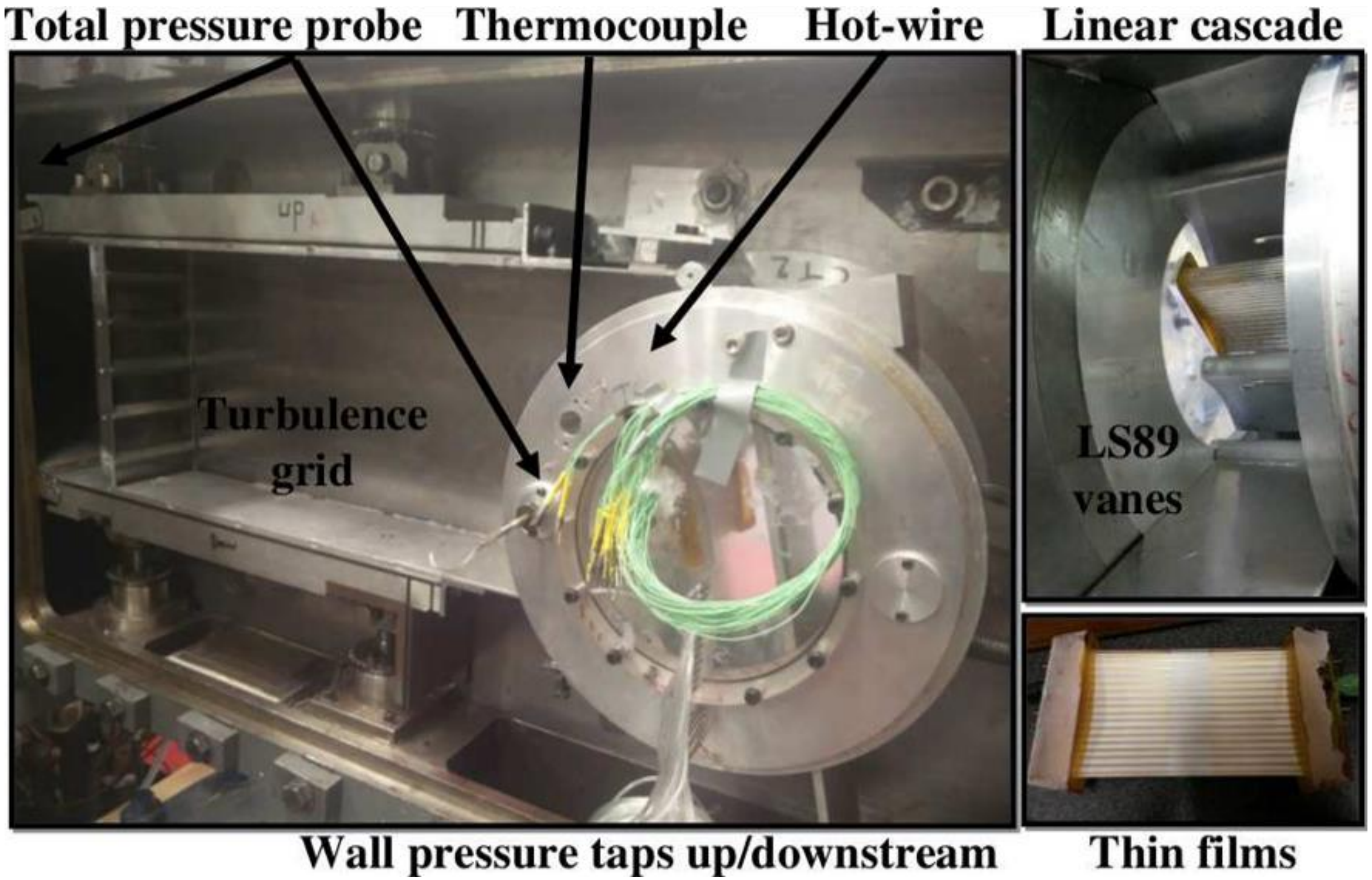
LS 89

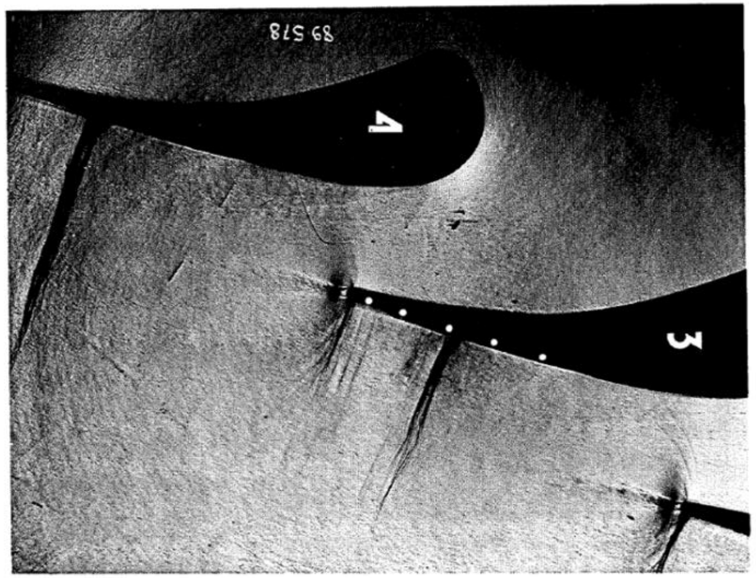

EXHAUST
TEST SECTION
SHUTTER VALVE
PISTON
SAFETY DISK
COMPRESSION TUBE
CARROT
HP VALVE
HIGH PRESSURE AIR SUPPLY
CASCADE
SONIC THROAT
TO SILENCER
DISCHARGE TANK

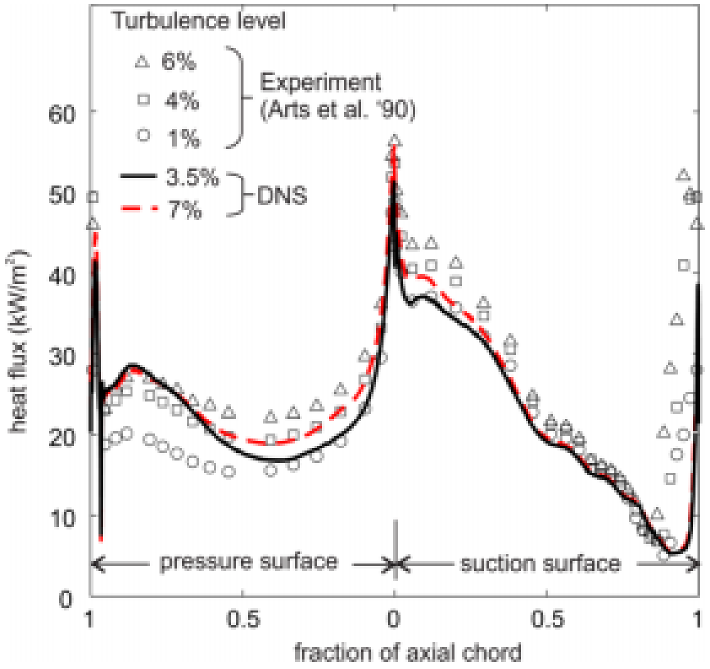




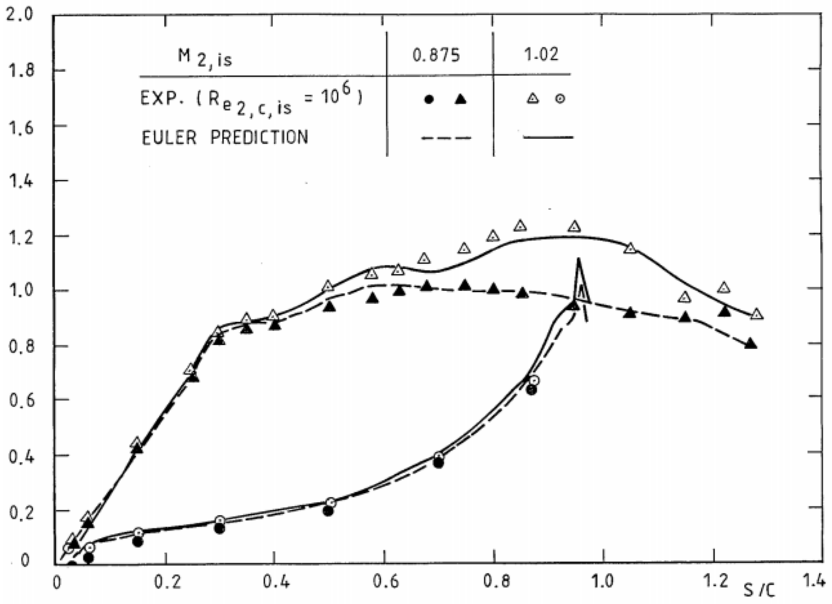
c	: 67.647 mm
g/c	: 0.850
γ	: 55.0 deg (from axial direction)
o/c	: 0.2207
T_{LE}/c	: 0.061 (evaluated around stagnation point)
T_{TE}/c	: 0.0105


Total pressure probe
Thermocouple
Hot-wire
Linear cascade
Turbulence grid
LS89 vanes
Wall pressure taps up/downstream
Thin films

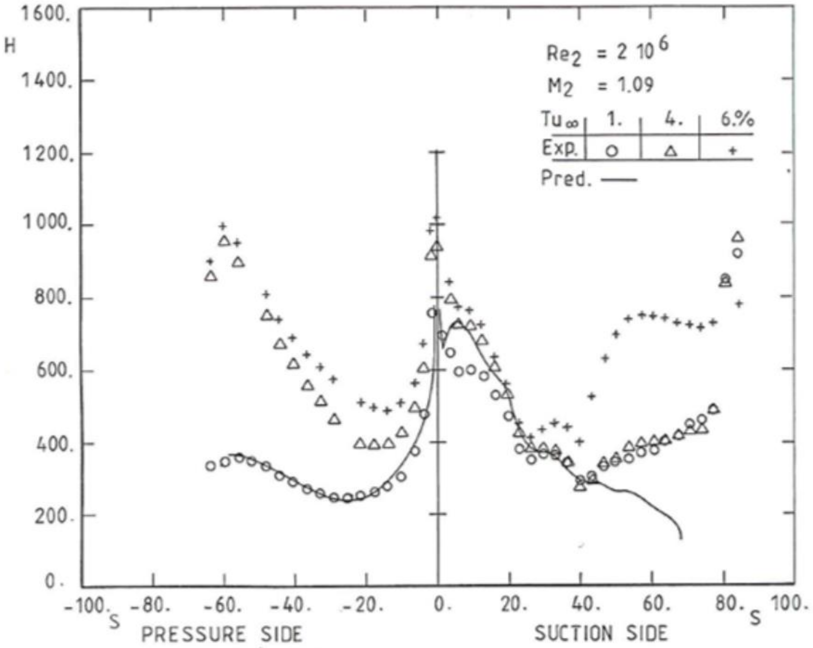




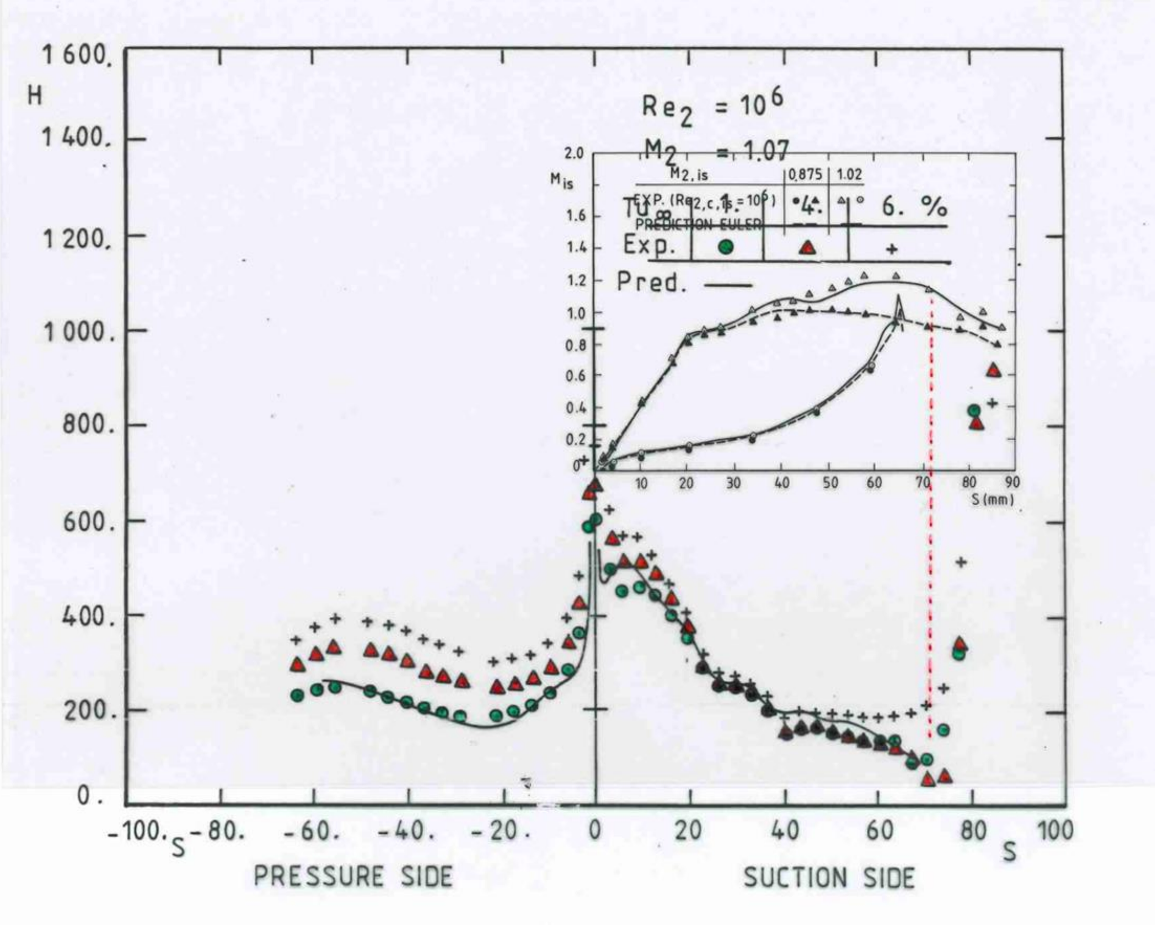
Turbulence level
6%
4%
1%
Experiment
(Arts et al. '90)
3.5%
7%
DNS
heat flux (kW/m²)
0
10
20
30
40
50
60
pressure surface
suction surface
1
0.5
0
0.5
1
fraction of axial chord



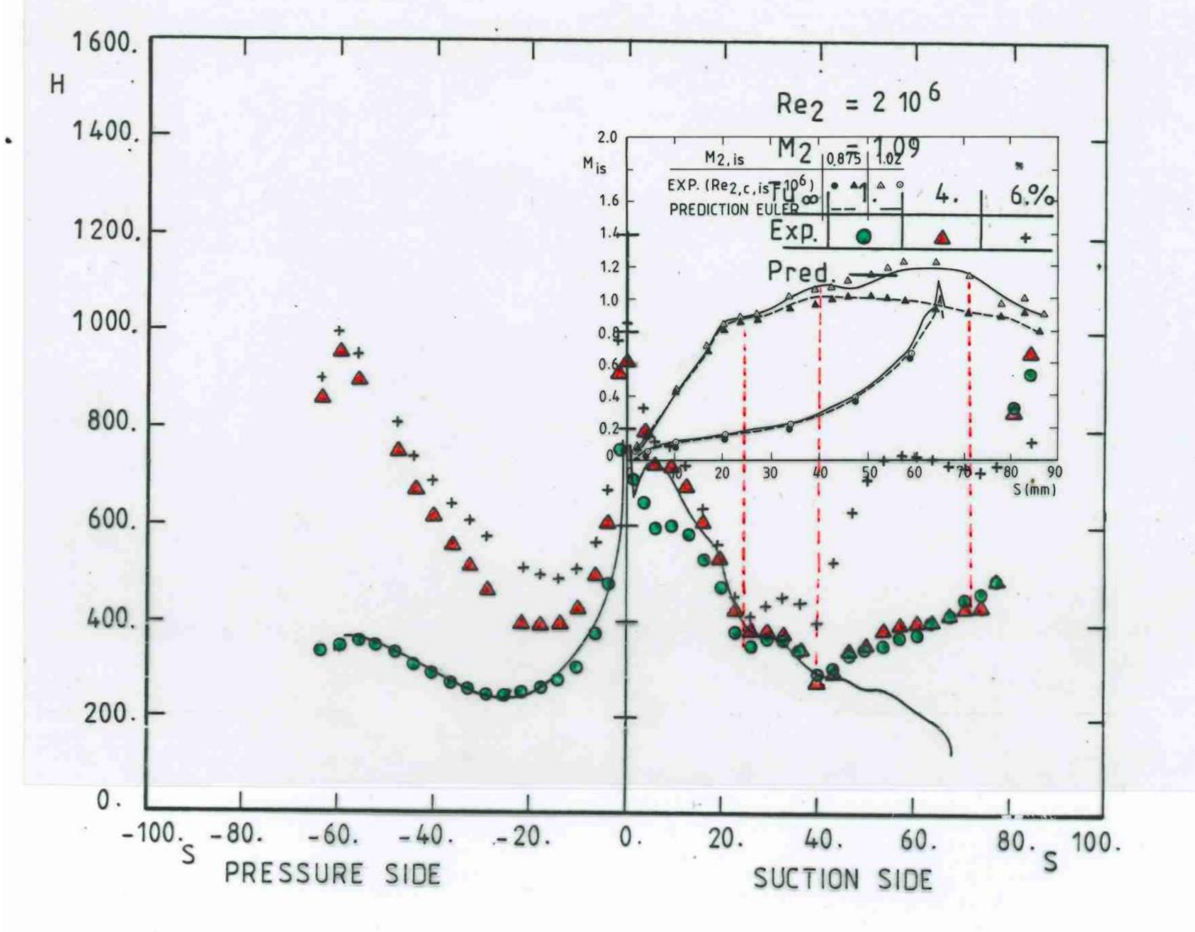
M 2, is
0.875
1.02
EXP. (Re 2, c, is = 10^6)
EULER PREDICTION
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
S/C



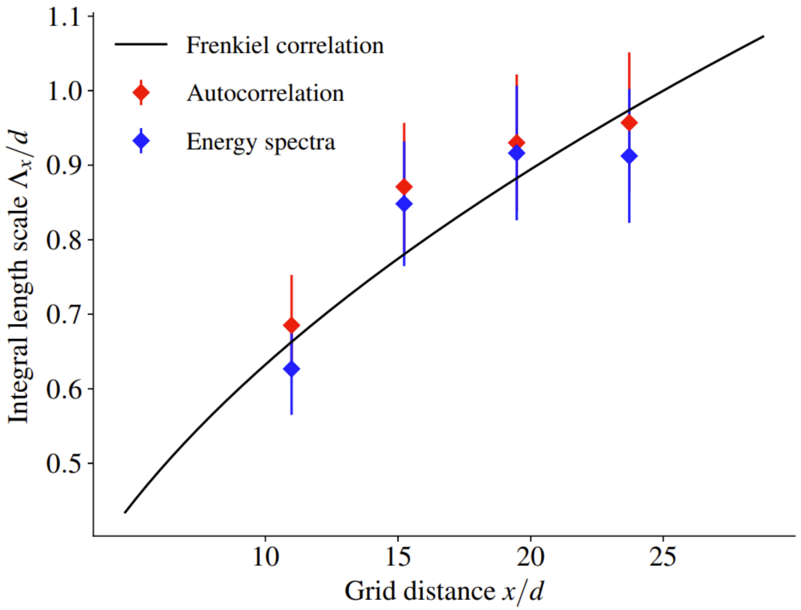
H
Re2 = 2 10^6
M2 = 1.09
Tu∞ 1. 4. 6.%
Exp.
Pred.
1600.
1400.
1200.
1000.
800.
600.
400.
200.
0.
-100.
-80.
-60.
-40.
-20.
0.
20.
40.
60.
80.
100.
S
PRESSURE SIDE
SUCTION SIDE



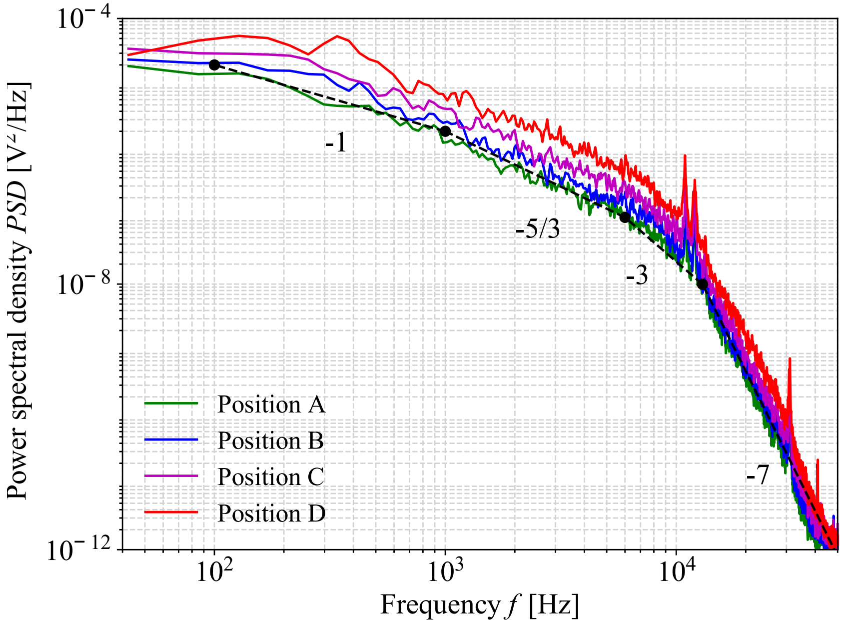
Re2 = 10^6
M2 = 1.07
Tu∞ 1. 4. 6. %
Exp.
Pred.
M2,is 0,875 1.02
EXP. (Re2,c,is = 10^6)
PREDICTION EULER
Mis
S (mm)
H
PRESSURE SIDE
SUCTION SIDE
S

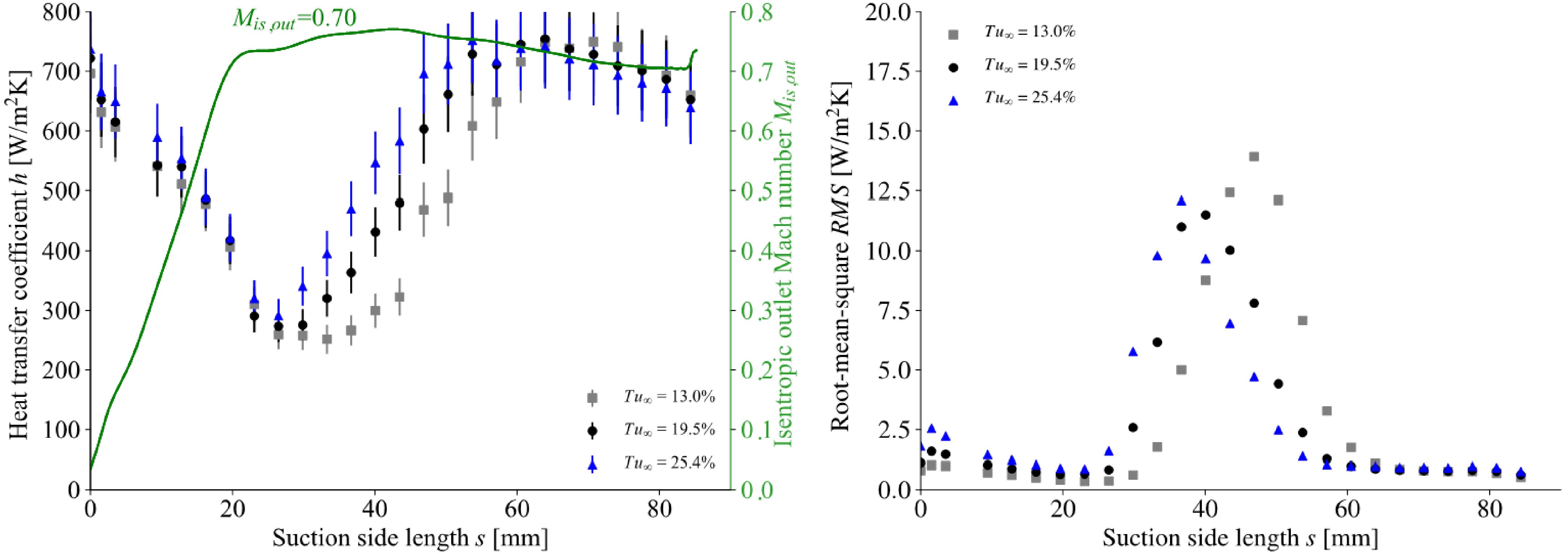


Re2 = 2 10^6
M2 = 1.09
Tu∞ 1. 4. 6.%
Exp.
Pred.
M2,is 0,875 1.02
EXP. (Re2,c,is = 10^6)
PREDICTION EULER
Mis
S (mm)
H
PRESSURE SIDE
SUCTION SIDE
S



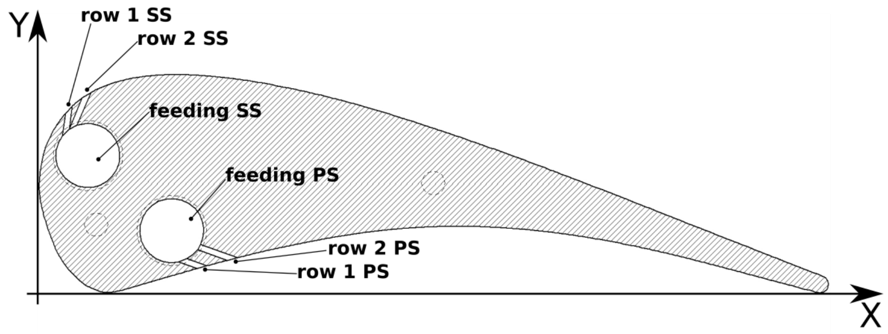
Grid	Square	Diamond
Position	Turbulence intensity [%]	
A	8.80	13.0
B	9.80	13.4
C	12.3	18.0
D	15.8	24.7





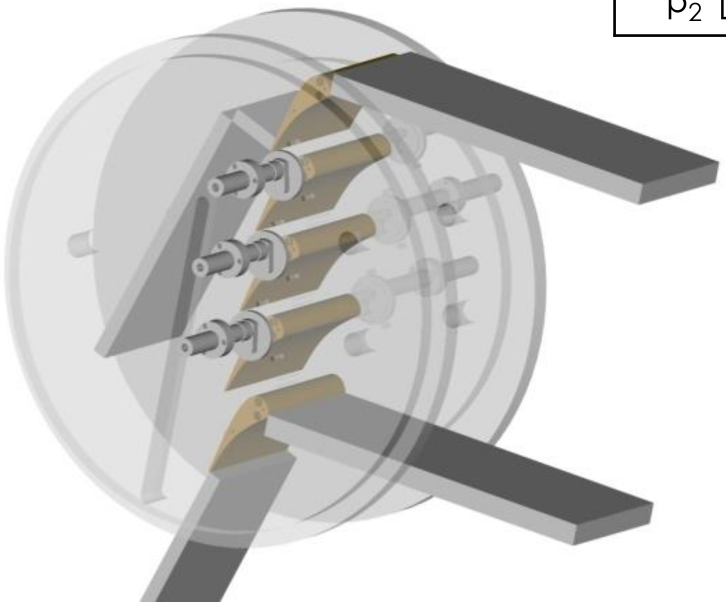
$M_{is,out}$=0.70
Heat transfer coefficient h [W/m^{2}K]
Isentropic outlet Mach number $M_{is,out}$
Suction side length s [mm]
Tu_∞ = 13.0%
Tu_∞ = 19.5%
Tu_∞ = 25.4%
Root-mean-square RMS [W/m^{2}K]
Suction side length s [mm]
Tu_∞ = 13.0%
Tu_∞ = 19.5%
Tu_∞ = 25.4%

LS 94

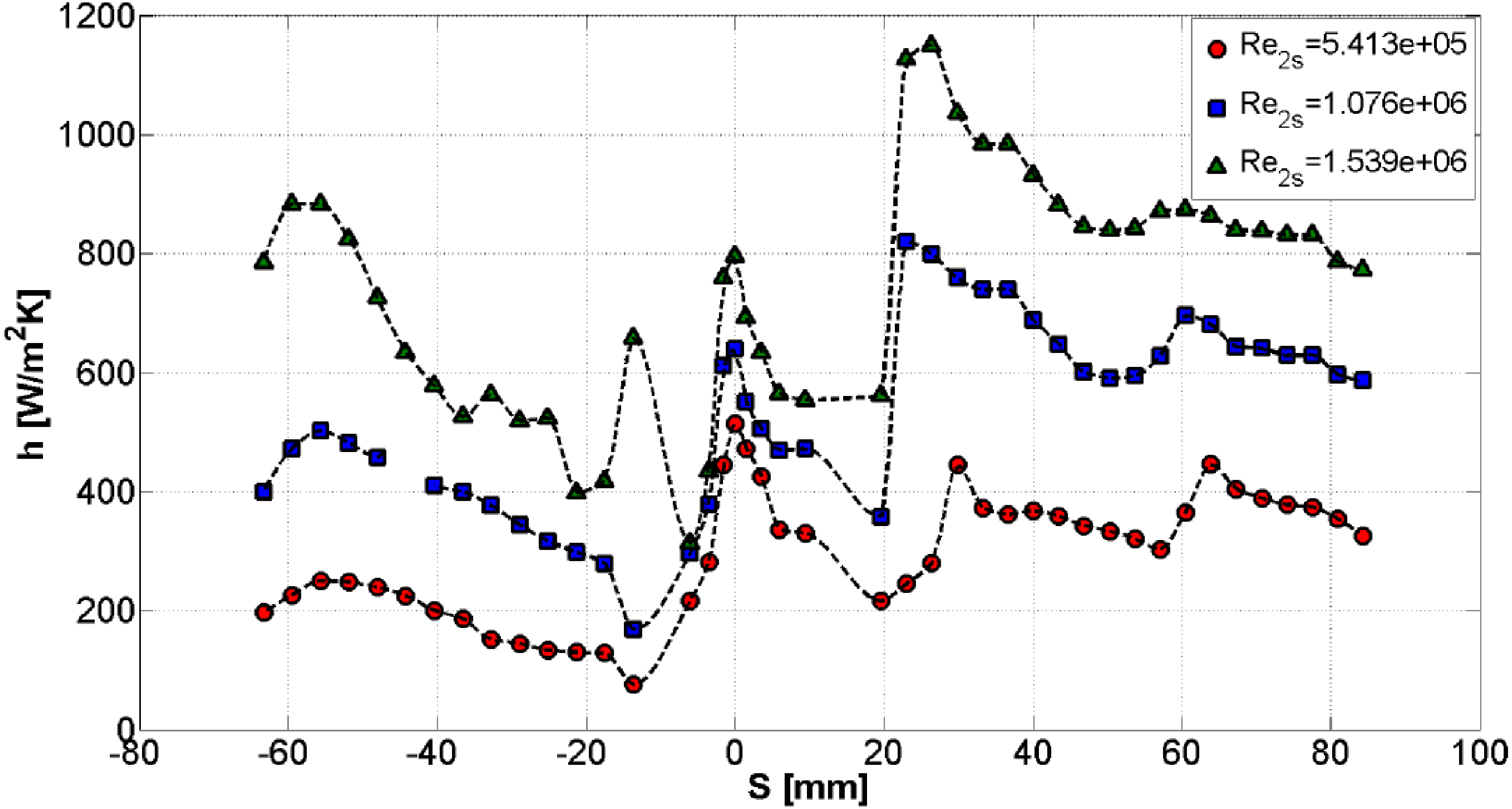


5 blades linear cascade	
c [mm]	67.47
h [mm]	100
g/c	0.85
γ [°]	55
o/c	0.2207
β_2 [°]	≈75

Cooling Geometry	PS Two // rows	SS Two rows
Diameter [mm] Cylindrical Holes	0.5	0.5
Inclination [°]	35 - //	35

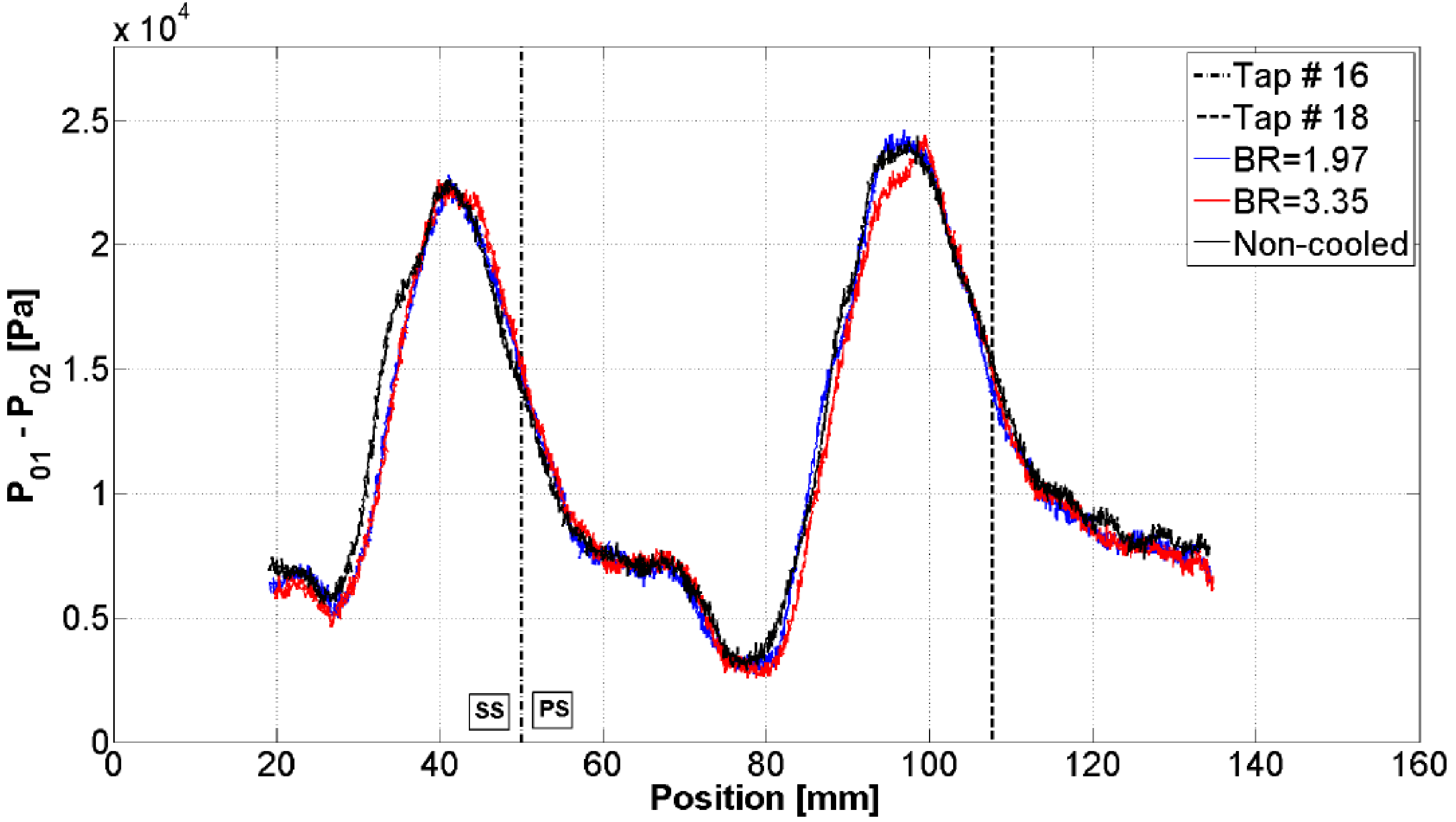


Convective heat-transfer coefficient distribution



Ma_{2s}=0.9 – Tu=1%

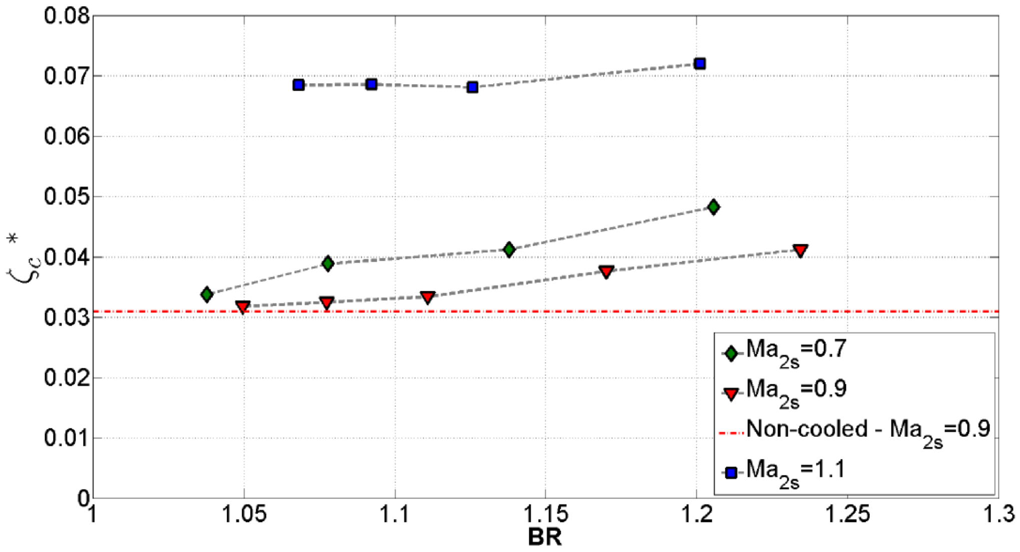
δh = ± 6.8%



Ma_{2s}=1.1 - Re_{2s}=1.5 M – Tu=1%

Mass-averaged loss coefficient / Area-averaged flow angle

$\delta\zeta^{*}_{c} = \pm\, 0.0025$

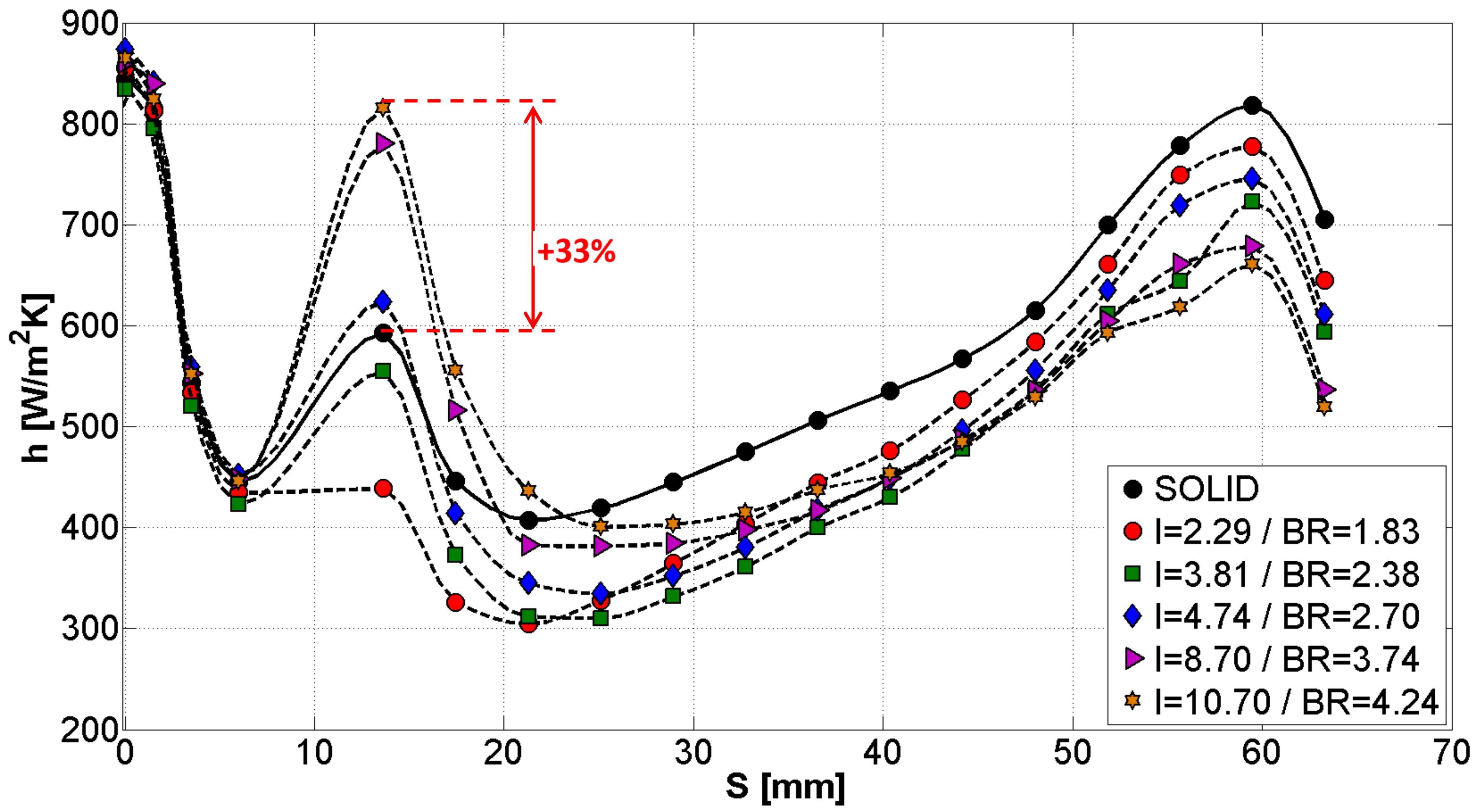


Re_{2s}=1.5 M
Tu=1%

$\delta\beta 2 < 0.16$ [°]

$$\zeta_c^{*} = 1 - \frac{\left[1-\left(\frac{\overline{P_2}}{\overline{P_{02}}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)_m}\right]\cdot\left[\dot{m}^{*}_{\infty}T_{01} + \dot{m}_c T_{0c}\right]}{\dot{m}^{*}_{\infty}T_{01}\cdot\left[1-\left(\frac{\overline{P_2}}{P_{01}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)_g}\right] + \dot{m}_c T_{0c}\left[1-\left(\frac{\overline{P_2}}{P_{0c}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)_c}\right]}$$

Convective heat-transfer coefficient



Ma_{2s}=1.1 Re_{2s}=1.5 M
Tu=5.3%

$\delta h = \pm 6.8\%$

T106 – T2

Low-Pressure Gas Turbine Blades

T106 – Design by MTU aero-engines and tested at DLR, Cambridge U., VKI …

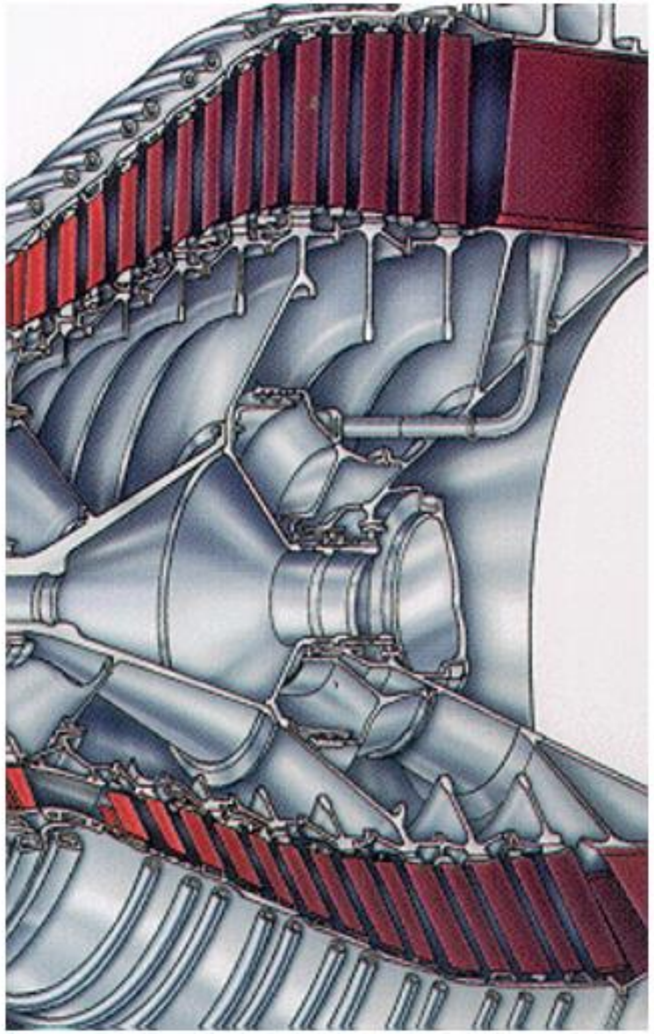
$Re_{2,is,c}$: 8.0 10^4 – 2.5 10^5
Tu_∞ : 1 % - 4 %
$M_{2,is}$: ~ 0.6 (transonic exit should come soon)

Aero data (uniform temperature wall BC)

T2 – Design by VKI (higher pitch-to-chord ratio – UTAT programme)

Similar boundary conditions and measurements

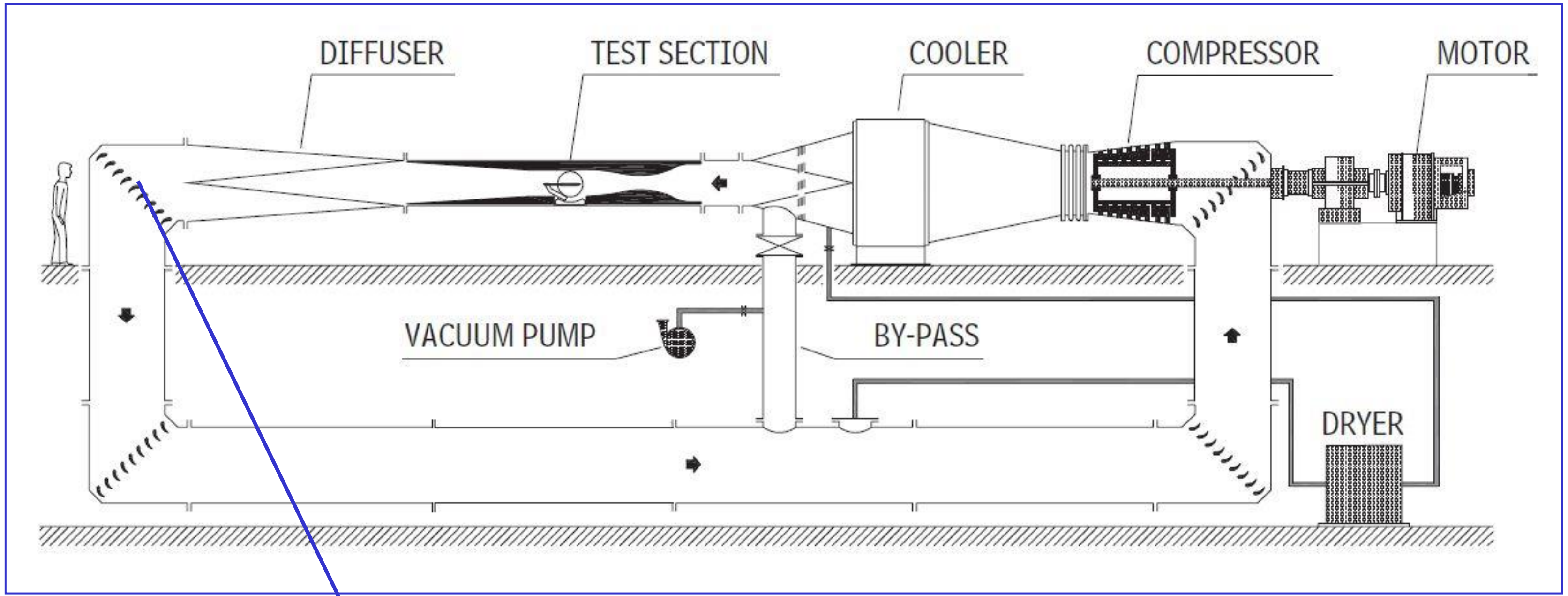
<u>Steady and periodic</u> inlet and <u>steady</u> exit boundary conditions

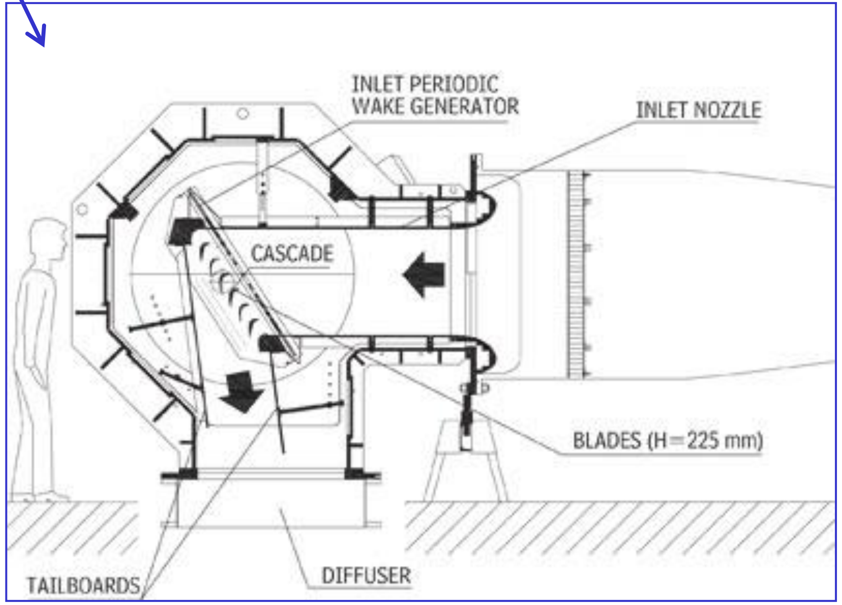


- High aspect ratio ⇨ **2D behavior**
- Re ~ 10^5 ⇨ **Laminar flow**
- Large # of blades ⇨ **Heavy**

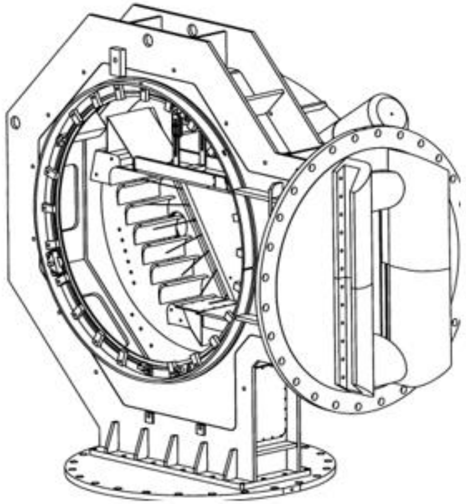
Reduction of the blade number

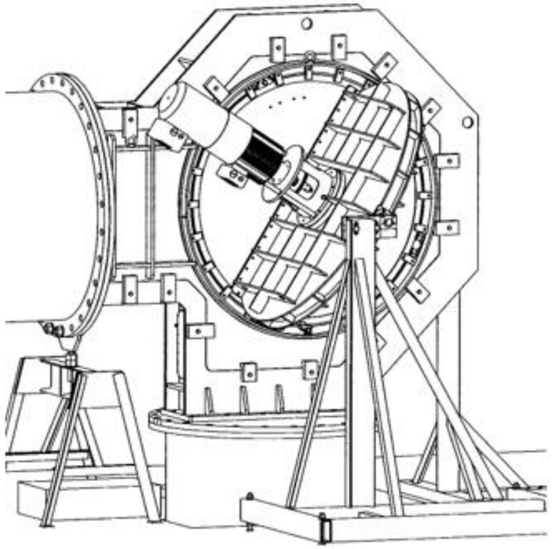
- Decrease of **Weight** and **Costs**
- Risks of **Laminar Separation** as g/c ↗

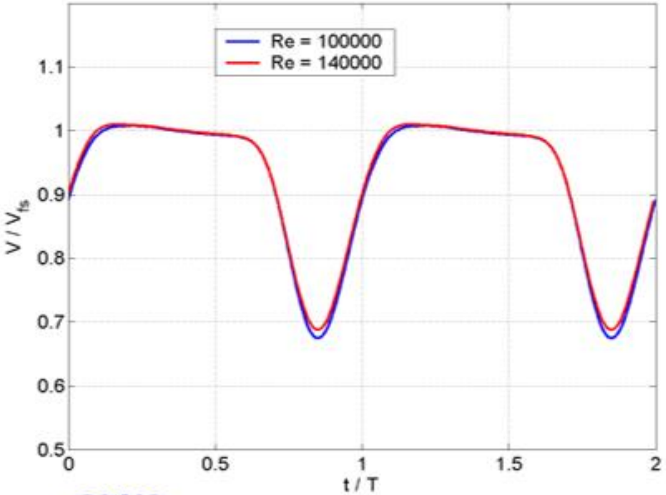

DIFFUSER
TEST SECTION
COOLER
COMPRESSOR
MOTOR
VACUUM PUMP
BY-PASS
DRYER


INLET PERIODIC
WAKE GENERATOR
INLET NOZZLE
CASCADE
BLADES (H=225 mm)
TAILBOARDS
DIFFUSER

HIGH SPEED PERIODIC INLET WAKES GENERATOR

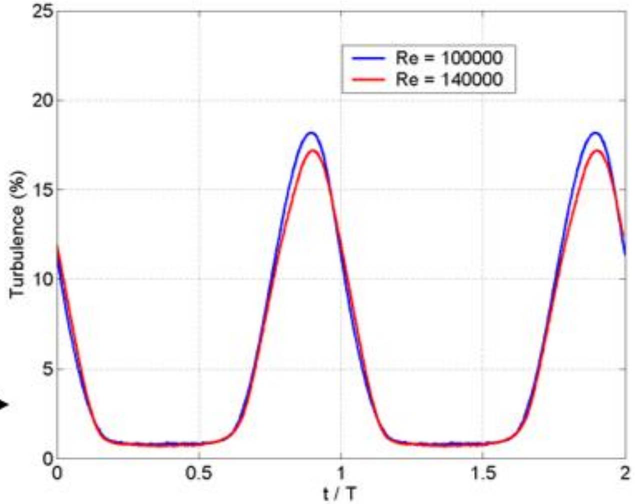




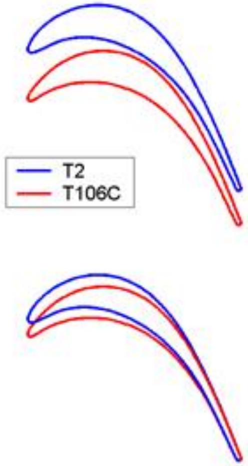


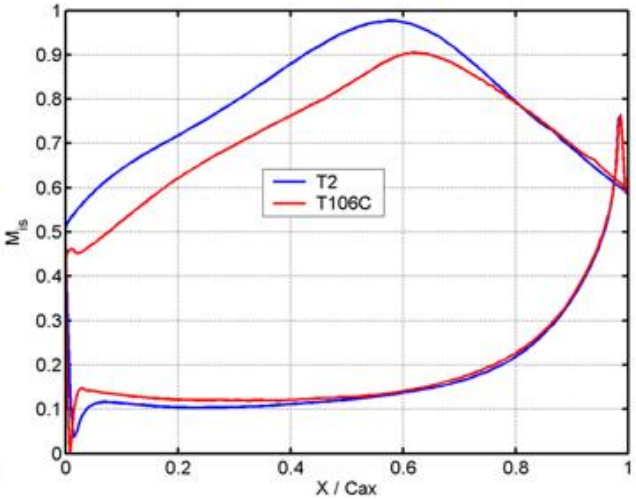
Inlet velocity profile

Inlet turbulence profile

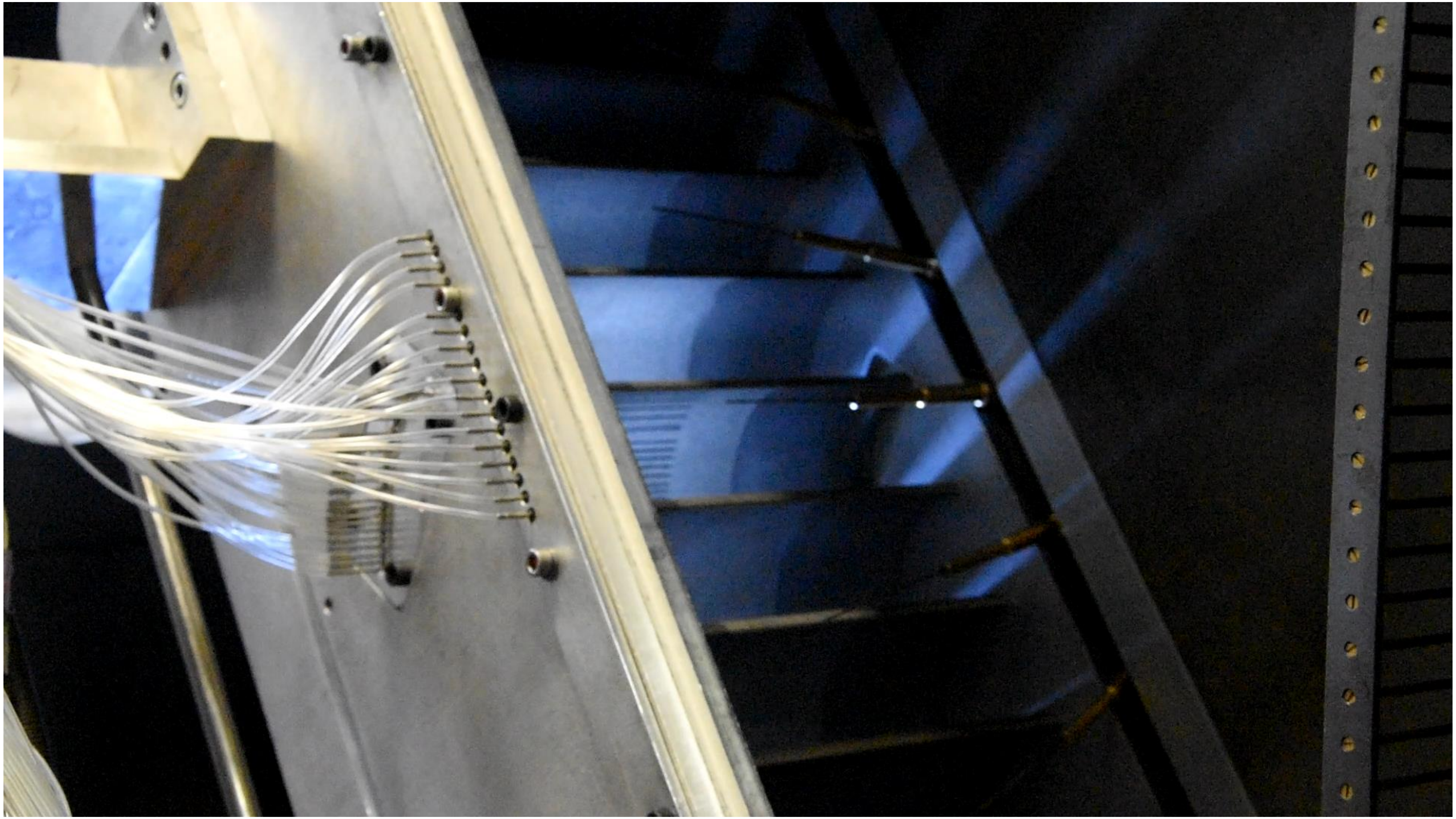


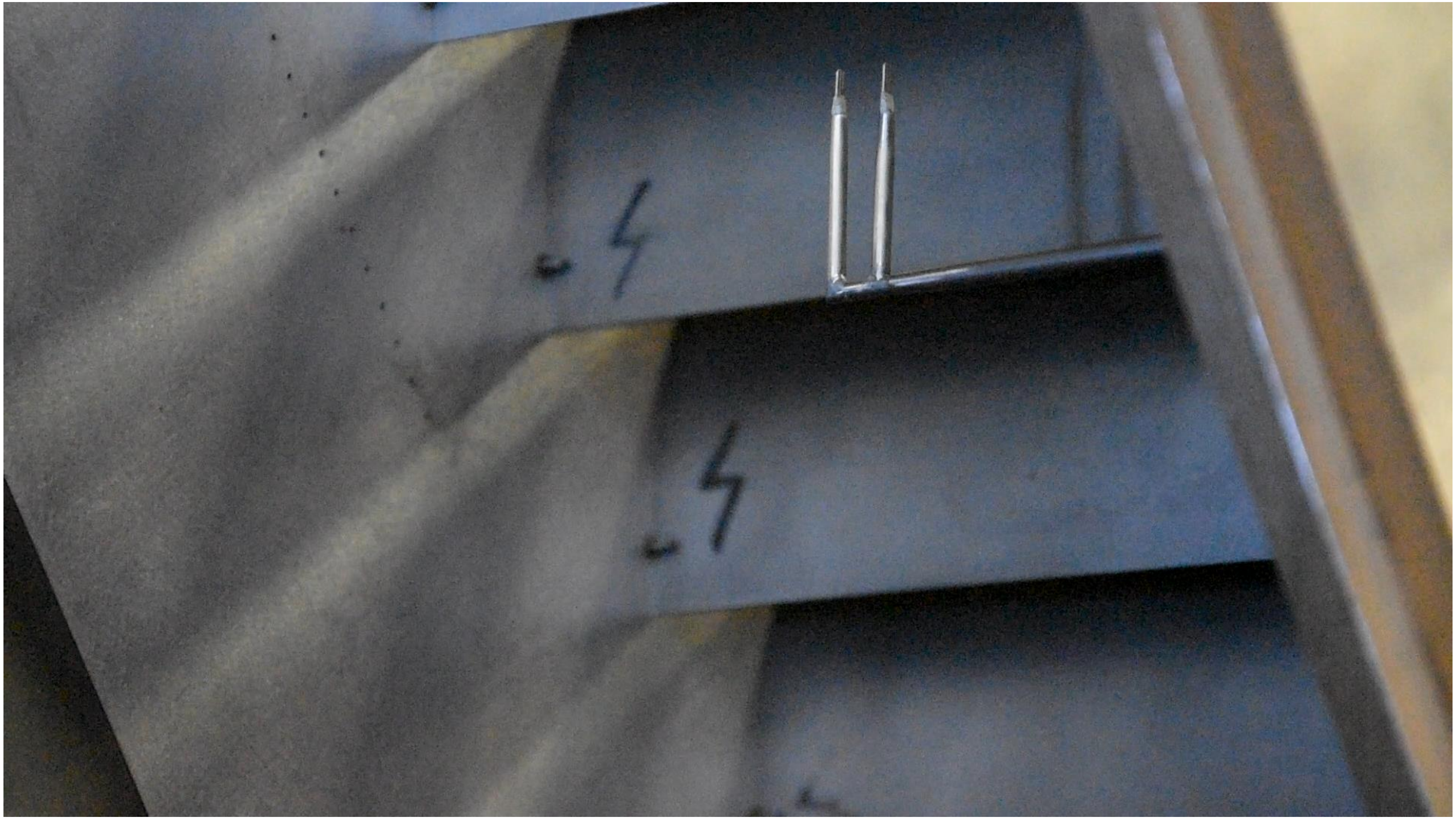
GEOMETRIES - INSTRUMENTATION



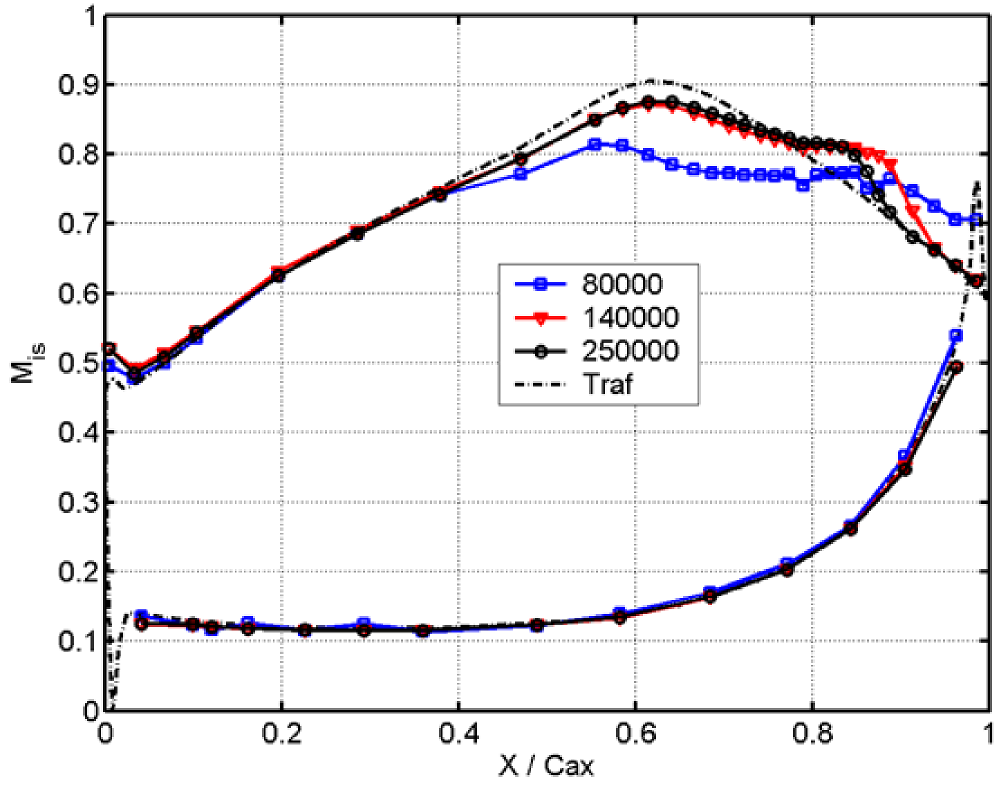


	T106C	T2
Chord length (mm)	93.01	96.35
Blade height (mm)	225.0	225.0
Aspect ratio	2.4	2.34
Pitch-to-chord ratio	0.95	1.05
Throat (mm)	43.38	50.99
Stagger angle (deg)	30.71	33.53
Arc cos (throat/pitch) (deg)	60.58	59.74
Inlet flow angle	32.7	32.7
Exit Mach number	0.65	0.65

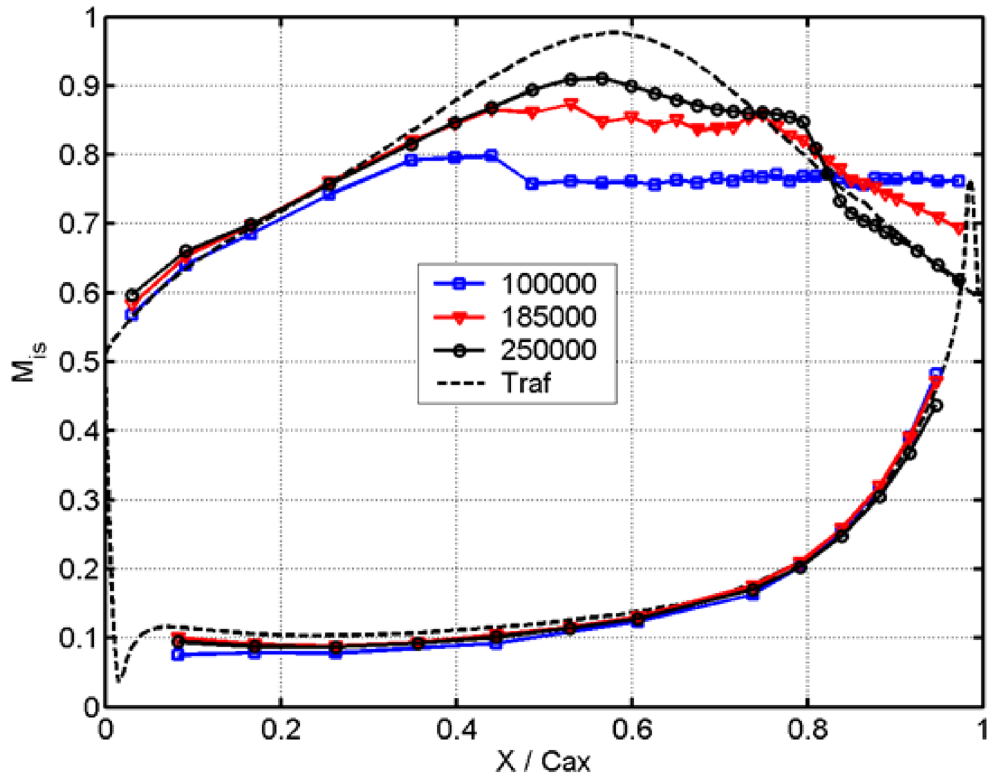




STEADY STATE INLET FLOW
BLADE ISENTROPIC MACH NUMBER DISTRIBUTION

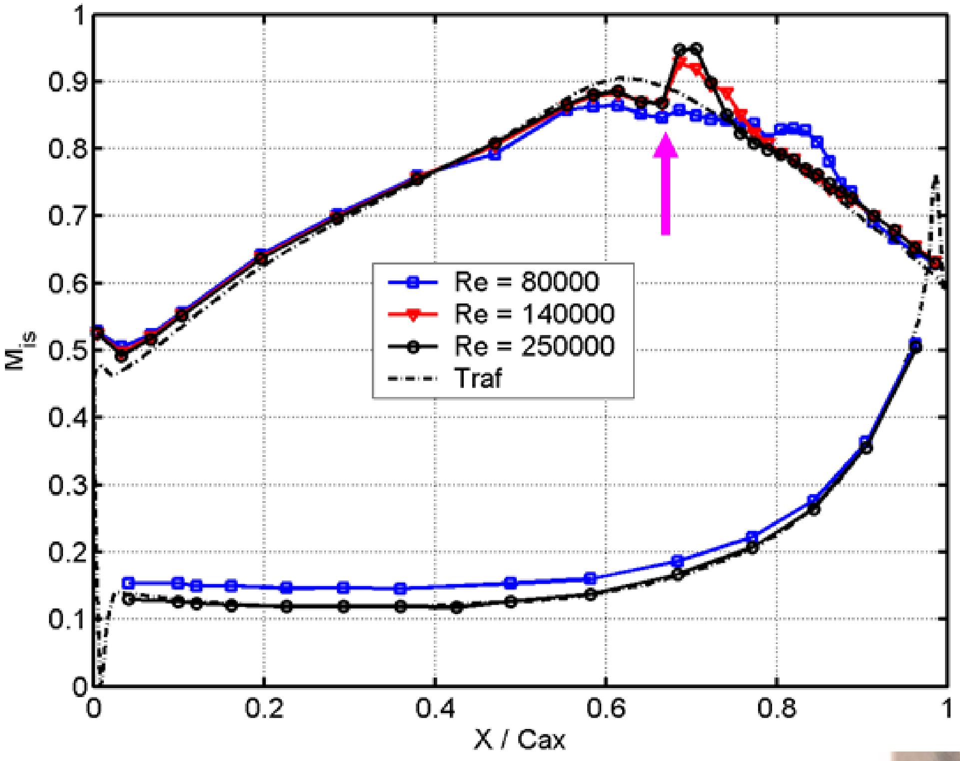


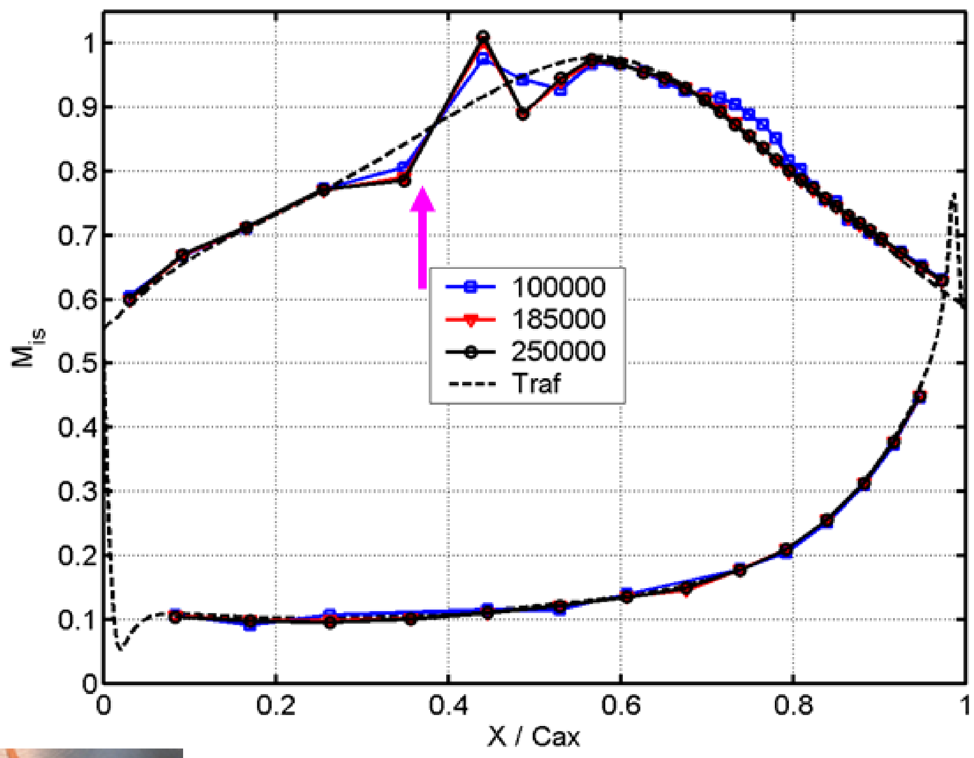
T106-C Cascade
Smooth suction side



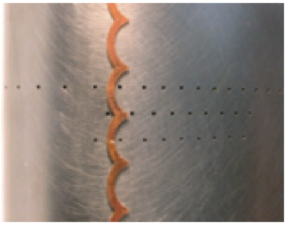
T2 Cascade
Smooth suction side

STEADY STATE INLET FLOW
BLADE ISENTROPIC MACH NUMBER DISTRIBUTION



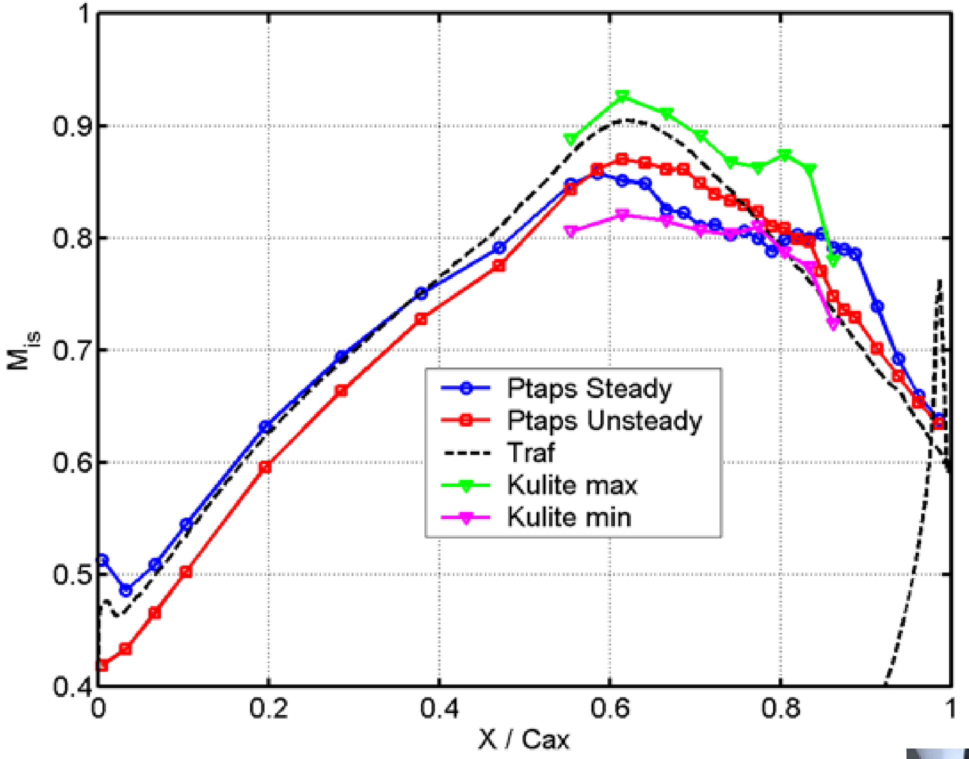


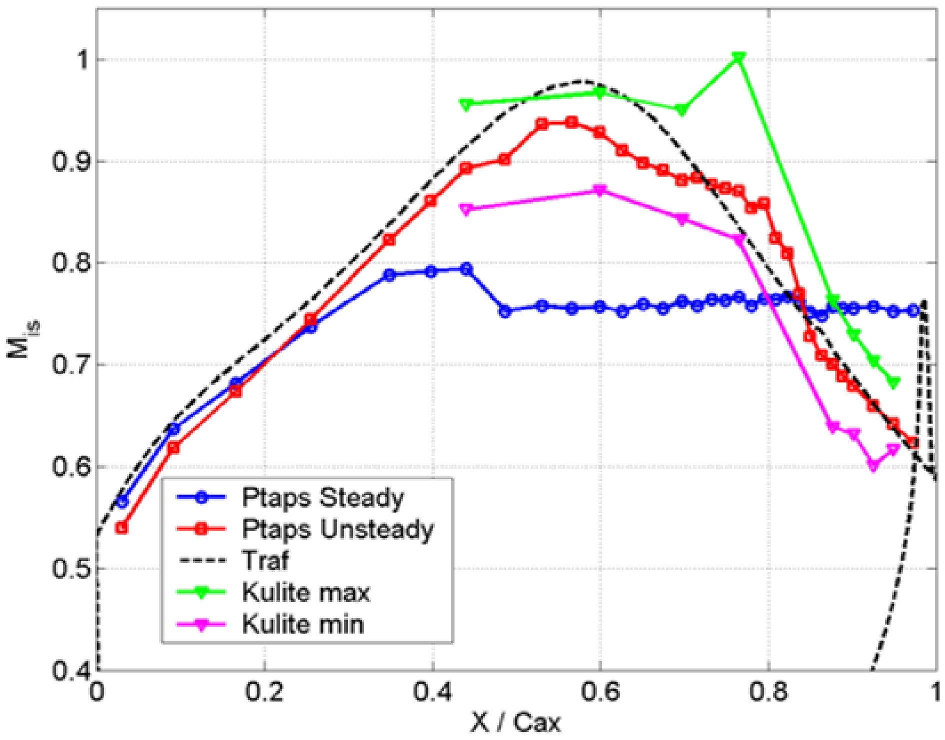
T106-C Cascade
Local roughness on suction side



T2 Cascade
Local roughness on suction side

PERIODIC INLET WAKES
BLADE ISENTROPIC MACH NUMBER DISTRIBUTION

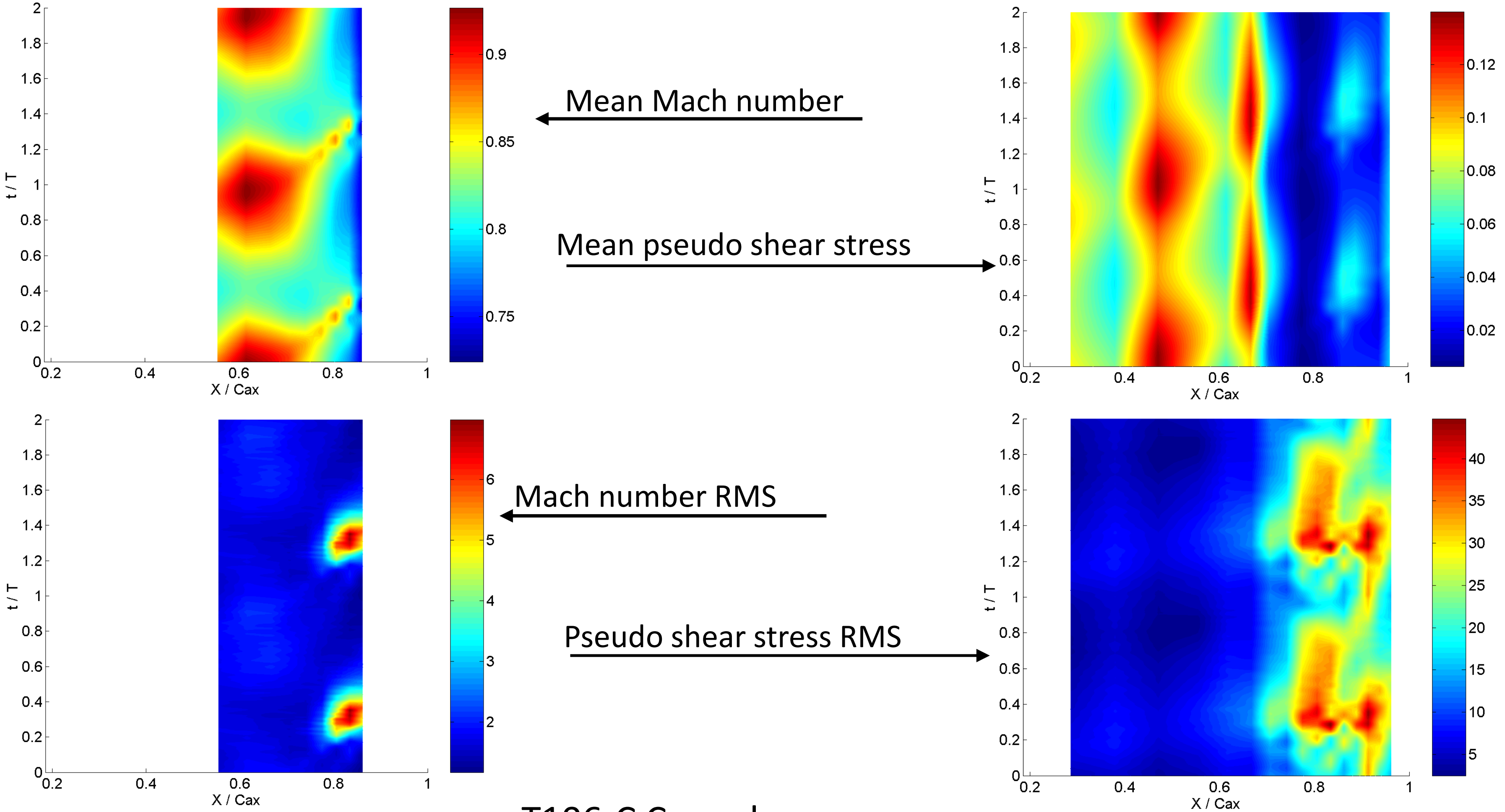




T106-C Cascade
Smooth suction side

T2 Cascade
Smooth suction side

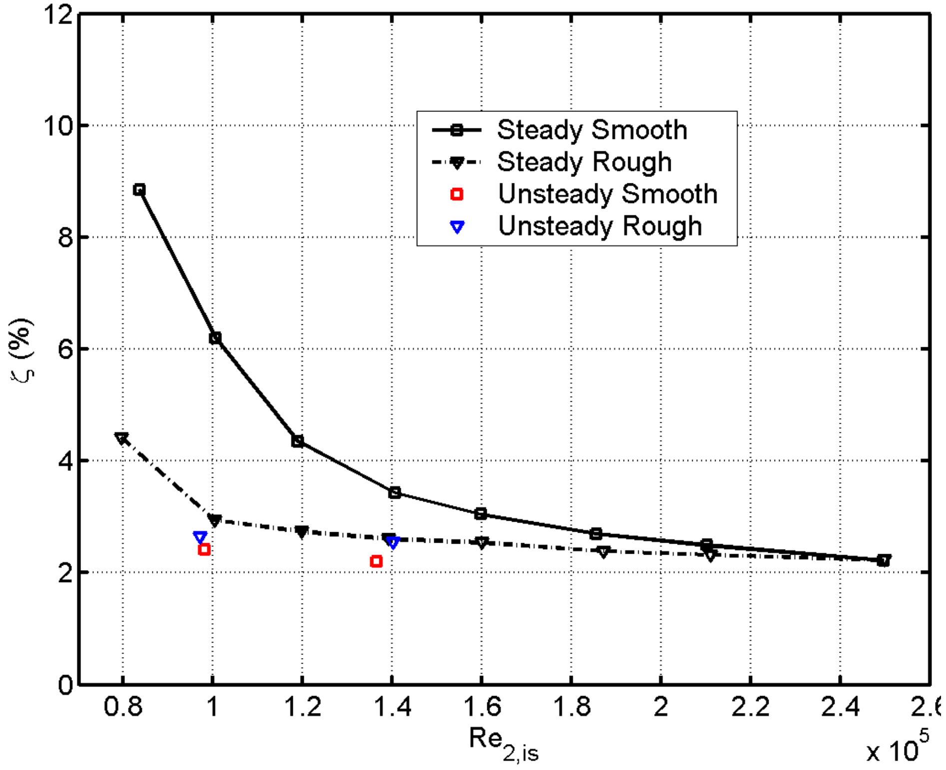
PERIODIC INLET WAKES – TIME/SPACE DIAGRAMS



T106-C Cascade

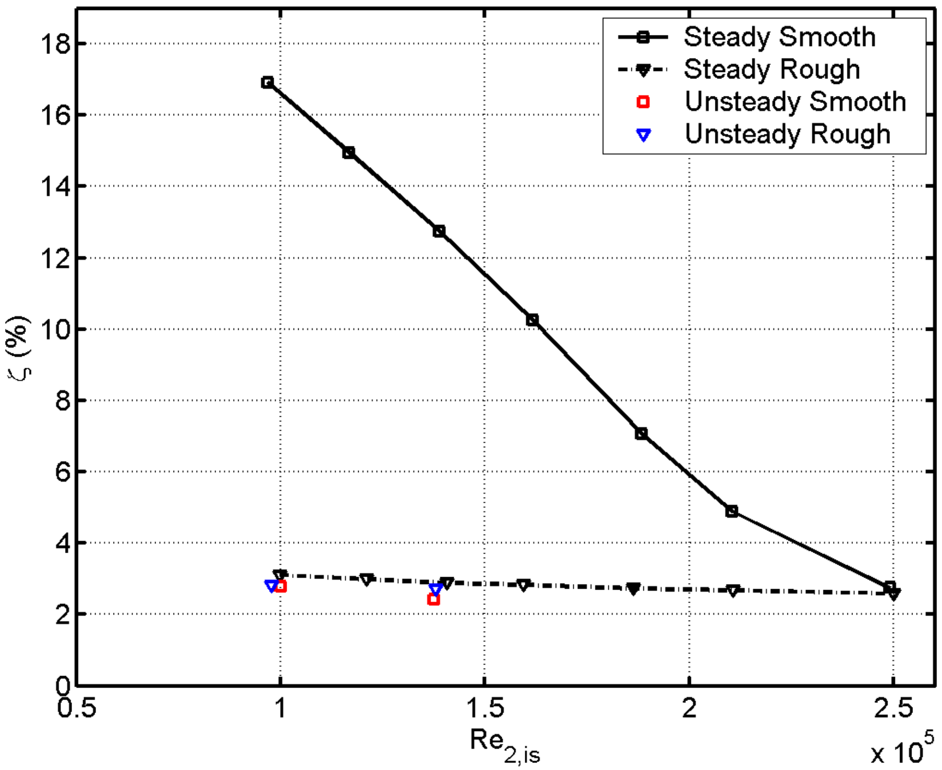
Smooth suction side

EXIT KINETIC ENERGY LOSS COEFFICIENT

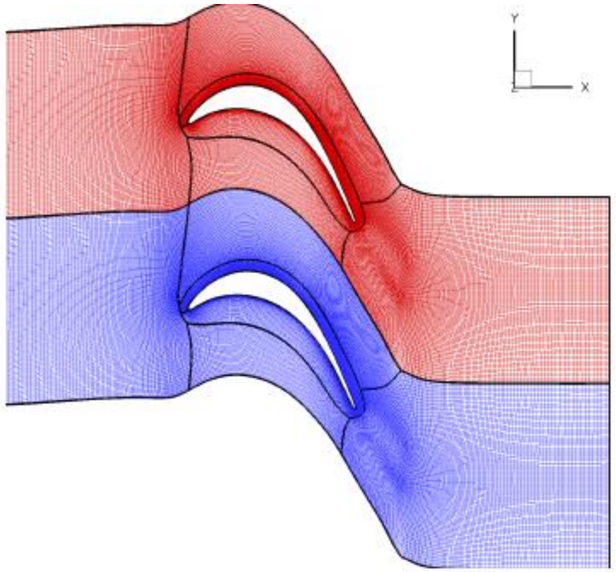


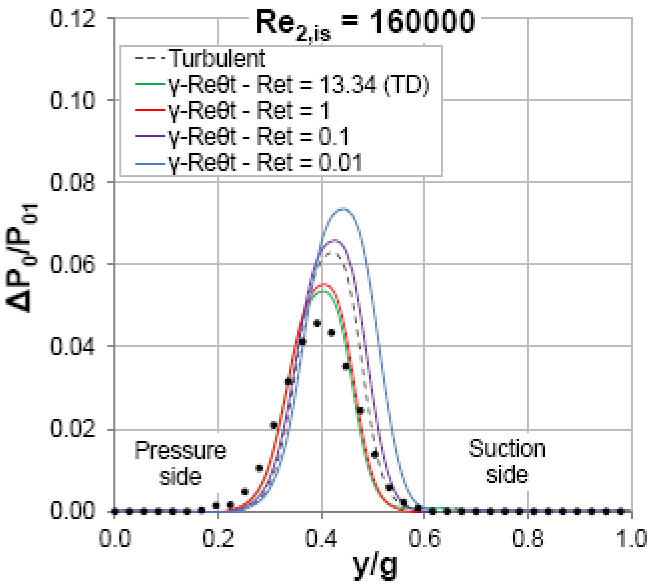
T106-C Cascade

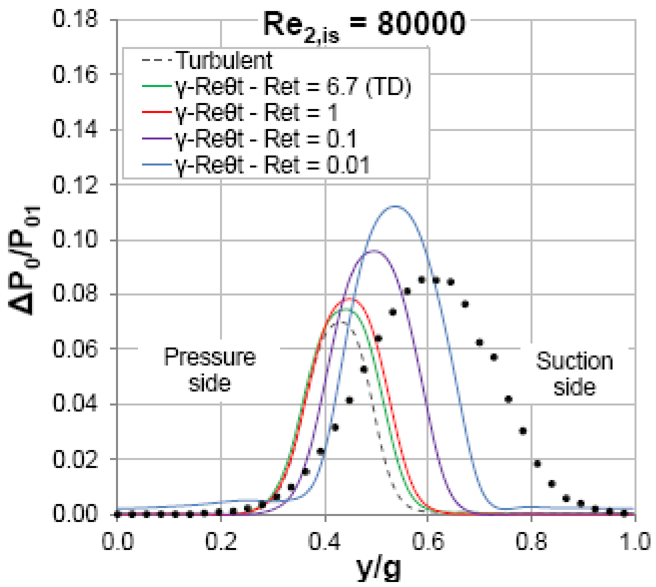
$$\zeta = 1 - \frac{1-\left(\dfrac{\overline{P_2}}{\overline{P_{02}}}\right)^{\frac{\gamma-1}{\gamma}}}{1-\left(\dfrac{\overline{P_2}}{P_{01}}\right)^{\frac{\gamma-1}{\gamma}}}$$

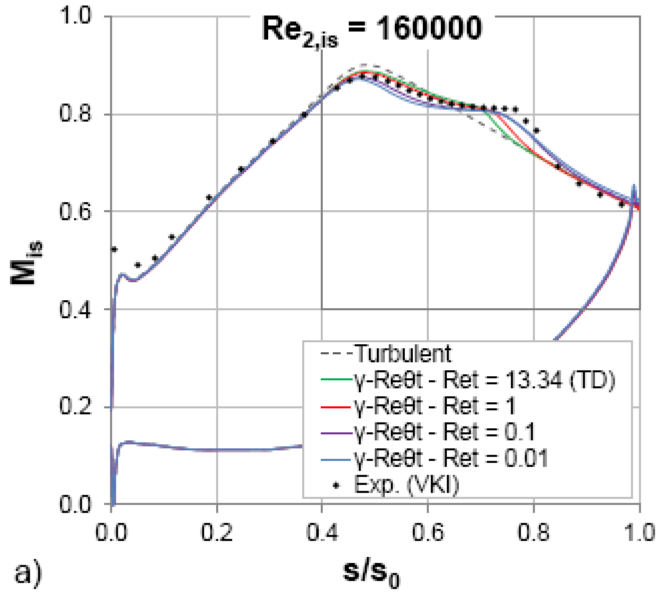


T2 Cascade

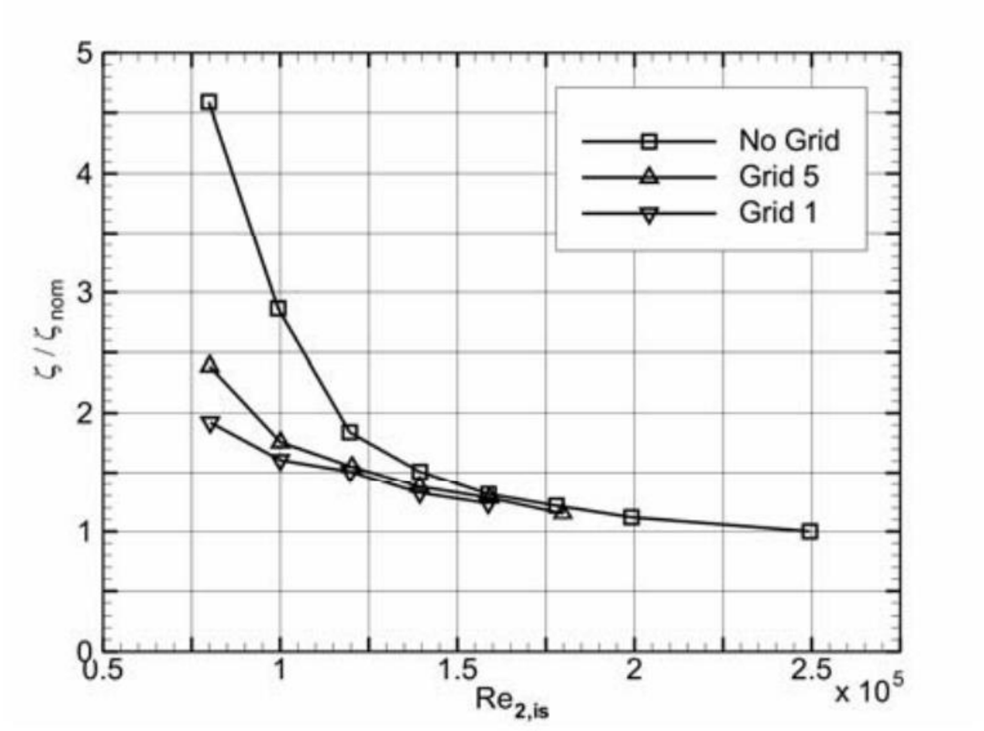

Y
X

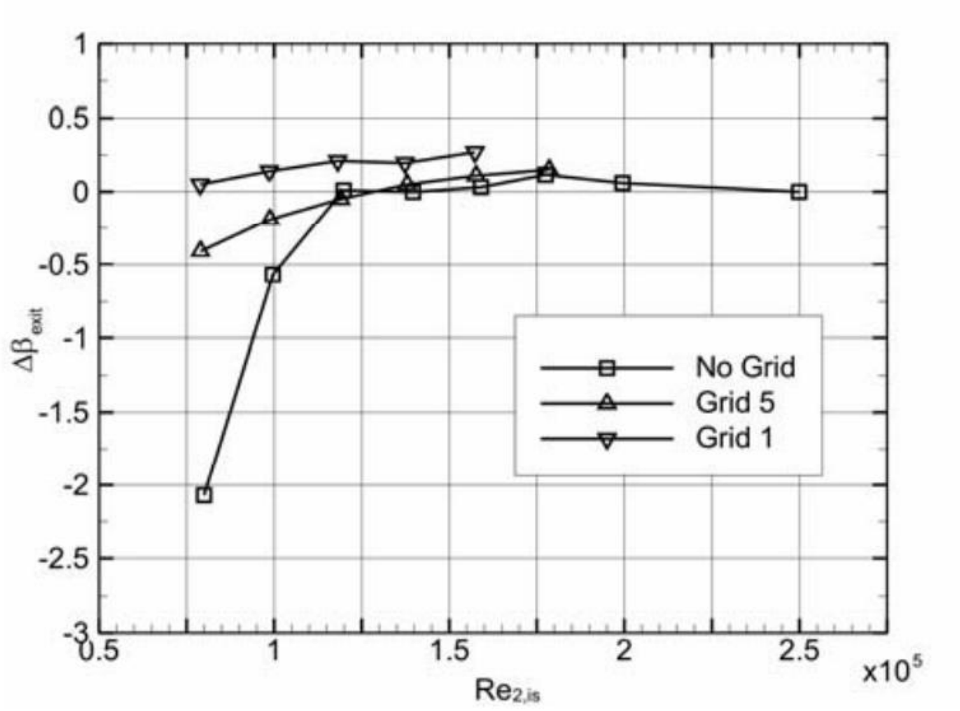

Re2,is = 160000
Turbulent
γ-Reθt - Ret = 13.34 (TD)
γ-Reθt - Ret = 1
γ-Reθt - Ret = 0.1
γ-Reθt - Ret = 0.01
ΔP0/P01
Pressure side
Suction side
y/g
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.0
0.2
0.4
0.6
0.8
1.0


Re2,is = 80000
Turbulent
γ-Reθt - Ret = 6.7 (TD)
γ-Reθt - Ret = 1
γ-Reθt - Ret = 0.1
γ-Reθt - Ret = 0.01
ΔP0/P01
Pressure side
Suction side
y/g
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14
0.16
0.18
0.0
0.2
0.4
0.6
0.8
1.0


Re2,is = 160000
Turbulent
γ-Reθt - Ret = 13.34 (TD)
γ-Reθt - Ret = 1
γ-Reθt - Ret = 0.1
γ-Reθt - Ret = 0.01
Exp. (VKI)
Mis
s/s0
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0

a)





No Grid   Tu : 0.8 %   Integral length scale : 0.005 m

Grid 5   Tu : 1.8 %   Integral length scale : 0.012 m

Grid 1   Tu : 3.2 %

Conclusions – Summary

Validation is a “must” – in both directions

Geometries and experimental data are available

Application to RANS – URANS – LES …