XV Research & Development in Power Engineering Conference

Overview of Turbine Flow Losses and Efficiency

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Overview of Turbine Flow Losses and Efficiency

1. Steam, gas, ORC turbines efficiency (opportunities to improve efficiency)

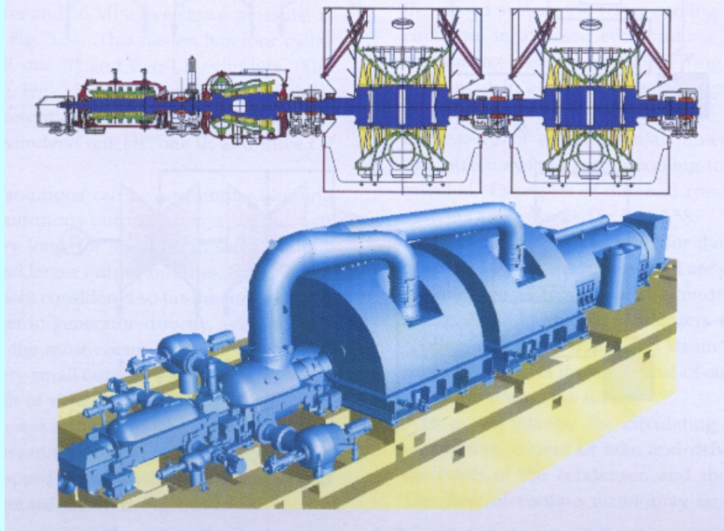
2. Turbine flow loss mechanisms and design correlations

3. Useful CFD results

   - Secondary, tip/shroud leakage flows and interactions,
   - Highly loaded cascades,
   - Stator/rotor interactions,
   - Partial admission control stage, adaptive stage.

4. Summary (ways to improve turbine efficiency).

STEAM TURBINES – Thermal, Fossil fuel / Nuclear

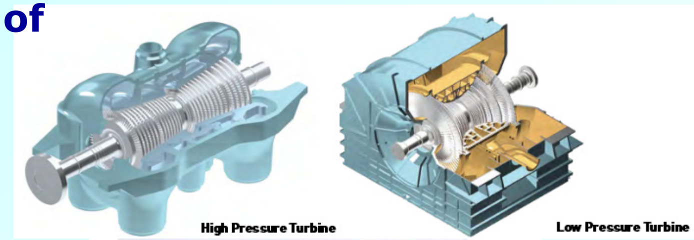


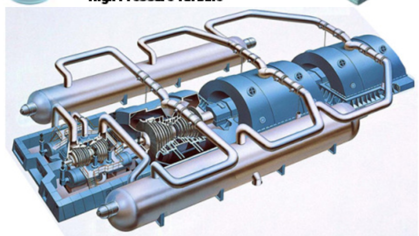
Scheme and view of 26K480 turbine (supercritical)

- **HP, IP TURBINES – fully 3D blading, flow efficiency very high, little room for efficiency improvements**

- **LP CYLINDERS – high span-wise gradients of reaction, wet steam flow, some room for efficiency improvements with the use of improved CFD modelling in the wet steam region,**

Source: Steam and Gas Turbines with examples of Alstom technology, ed. K.Kosowski





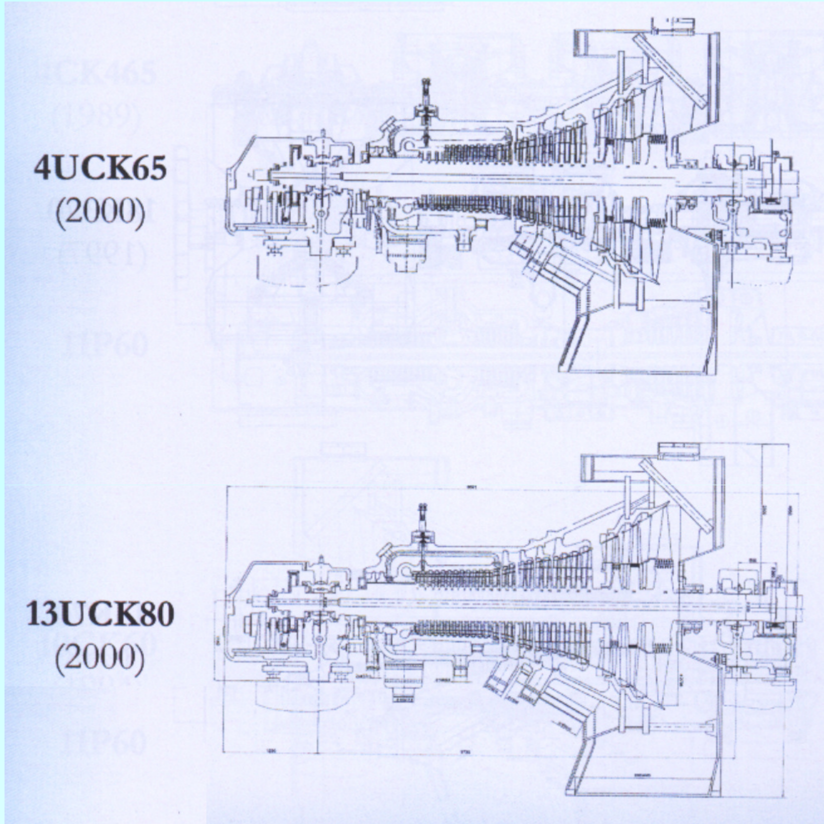
Source: Mitsubishi Power

For Nuclear Power Plants (1,251 MW)

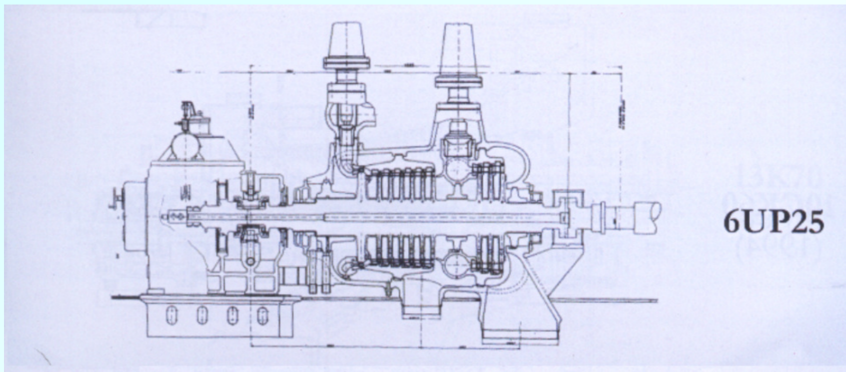
STEAM TURBINES – cogeneration

- **HP, LP blading – flow efficiency can be improved by 3D blade stacking**

- **variable load conditions – control stage / adaptive stage aerodynamics becomes important to make use of the available pressure drop**



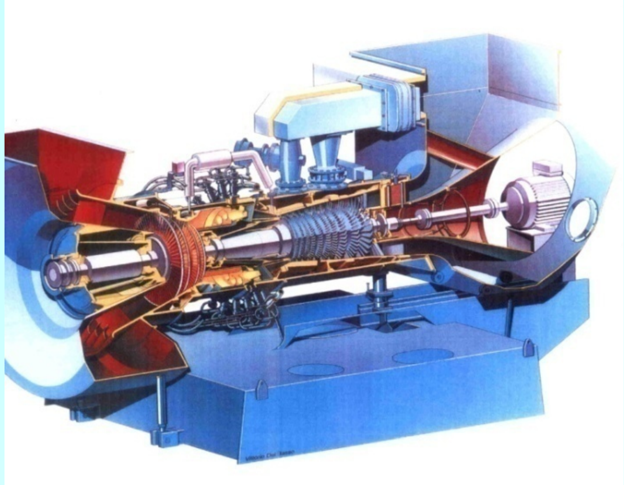
U-extraction
C-heating
P-backpressure
K-condensing

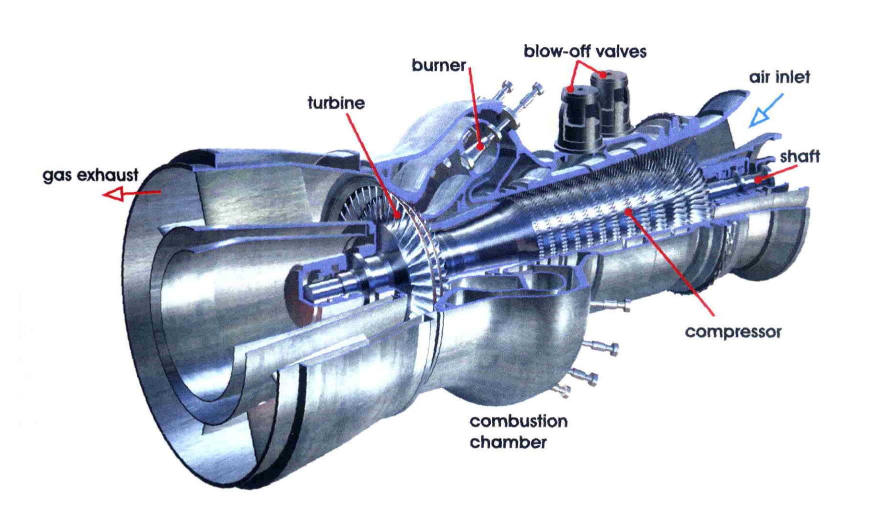


Source: Steam and Gas Turbines with examples of Alstom technology, ed. K.Kosowski

GAS TURBINES

- **GT – turbine flow efficiency high, except for UHL turbines**
  - **compressor flow aerodynamics – still to be mastered**
  - **blade cooling – compromise between flow and heat transfer efficiency**





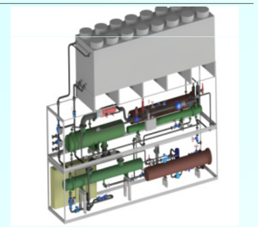
GT8C gas turbine (Alstom)

Source: Steam and Gas Turbines with examples of Alstom technology, ed. K.Kosowski

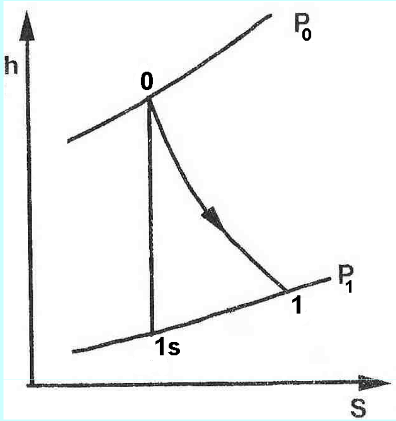
ORC TURBINES

– low power range, large pressure drops, high Mach numbers, short height blades, flow efficiencies relatively low - can be improved

- there is a need for improved loss correlations for design purposes

	ORC 10 kWe	ORC 40 kWe	ORC 300 kWe
HEAT SOURCE	Oil from industrial compressors 80 - 120 °C	IC engine exhaust gases 350 - 550 °C	Industrial waste heat 400 - 500 °C
DESIGN OF ORC SYSTEM	 ✓	 ✓	
PROTOTYPE ASSEMBLY	 ✓	 ✓	
1st STARTUP OF TURBOGENERATOR	 ✓	 ✓	

Flow efficiency and flow losses (definitions)



enthalpy-entropy diagram in a turbine without considering inlet /velocity

$$\eta = \frac{h_0 - h_1}{h_0 - h_{1s}}$$

isentropic efficiency

$$\xi = 1 - \eta = \frac{h_1 - h_{1s}}{h_0 - h_{1s}}$$

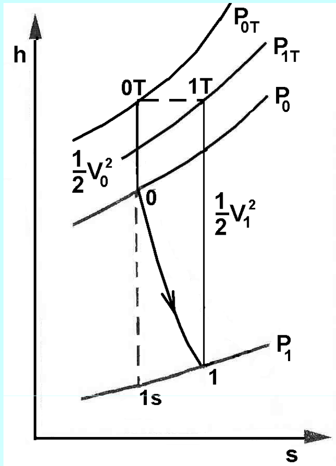
enthalpy loss coefficient

$$\eta \approx \frac{h_0 - h_1}{h_0 - h_1 + T_1(s_1 - s_0)}$$

$$\xi_s = \frac{T_1(s_1 - s_0)}{h_0 - h_1 + T_1(s_1 - s_0)}$$

entropy loss coefficient

$$\xi_s - \xi = 0{,}25(\kappa - 1)Ma^2 \xi \xi_s$$



enthalpy-entropy diagram in an isolated turbine cascade

$$Y = \frac{p_{0T} - p_{1T}}{p_{0T} - p_1}$$

$$Y^* = \frac{p_{0T} - p_{1T}}{p_{1T} - p_1}$$

total pressure loss coefficient

$$\xi_e = 1 - \frac{v_1^2}{v_{1s}^2}$$

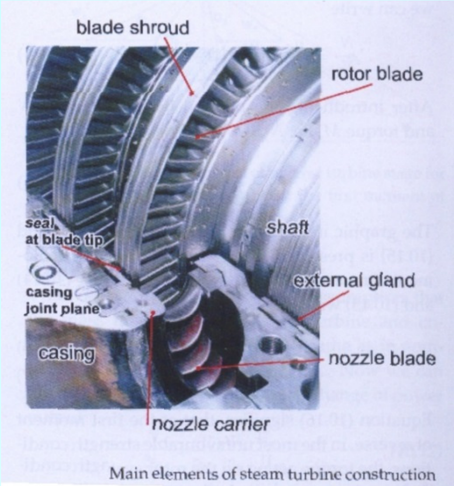
$$v_{1s} = (2(h_{0T} - h_{1s}))^{1/2}$$

Kinetic energy loss coefficient

FLOW LOSS MECHANISMS IN TURBINES

Turbine flow are characterised by:

- **non-uniform fields, large gradients of flow parameters, vortex structures, wakes, unsteadiness,**
- **high Reynolds numbers, turbulence,**
- **high Mach numbers, wet phase content.**



Main elements of steam turbine construction

Sources of entropy production:

⇨ **dissipation of mechanical energy in viscous fluid in non-uniform velocity field and in mixing processes,**

⇨ **dissipation of thermal energy in heat conductive fluid in non-uniform temperature field and in heat transfer processes,**

⇨ **shock waves and phase change.**

Main loss components considering their location in a turbine flow:

⇨ **profile losses,**

⇨ **endwall losses,**

⇨ **leakage losses,**

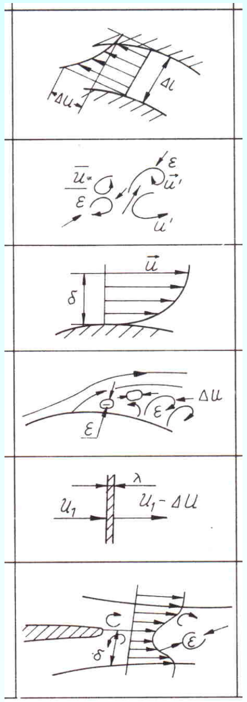
⇨ **leaving energy losses,**

⇨ **disk friction losses,**

⇨ **partial admission losses,**

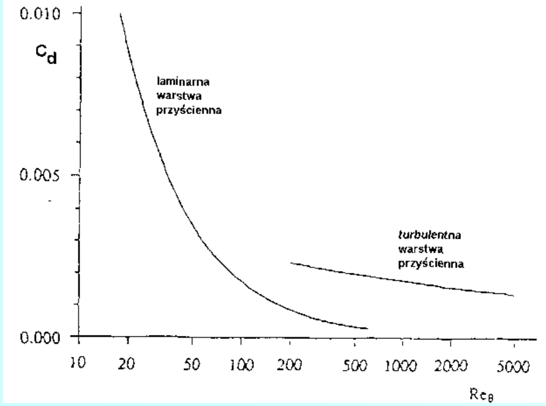
⇨ **wet steam losses…**

$$\xi = \xi_{pr} + \xi_{end} + \xi_{leak} + \xi_{leav} + \xi_{dfr} + \xi_{wet} + \xi_{part} + \ldots$$



Boundary layer loss diagram

$$\xi = \frac{T\Delta s}{0{,}5 v_{\delta,te}^{2}} = \sum \frac{C}{p} \frac{2}{\cos\alpha_1} \int_0^1 C_D \left(\frac{v_\delta}{v_{\delta,te}}\right)^3 d(x/C)$$ **(Denton)**



Dissipation coefficient in laminar and turbulent boundary layer

ASSUMPTIONS:

- model of profile evenly loaded along its chord

$$V_s - V_p = 2\Delta V = const \qquad \overline{V} = \left(V_s + V_p\right)/2 \qquad \overline{V}\cos\alpha = V_x$$

- - tgα varies linearly with chord between tgα$_0$ and tgα$_1$

⇨ **loss coefficient**

$$\xi = 4\sqrt{3c_1c_2}\, C_D \cos^2\alpha_1$$

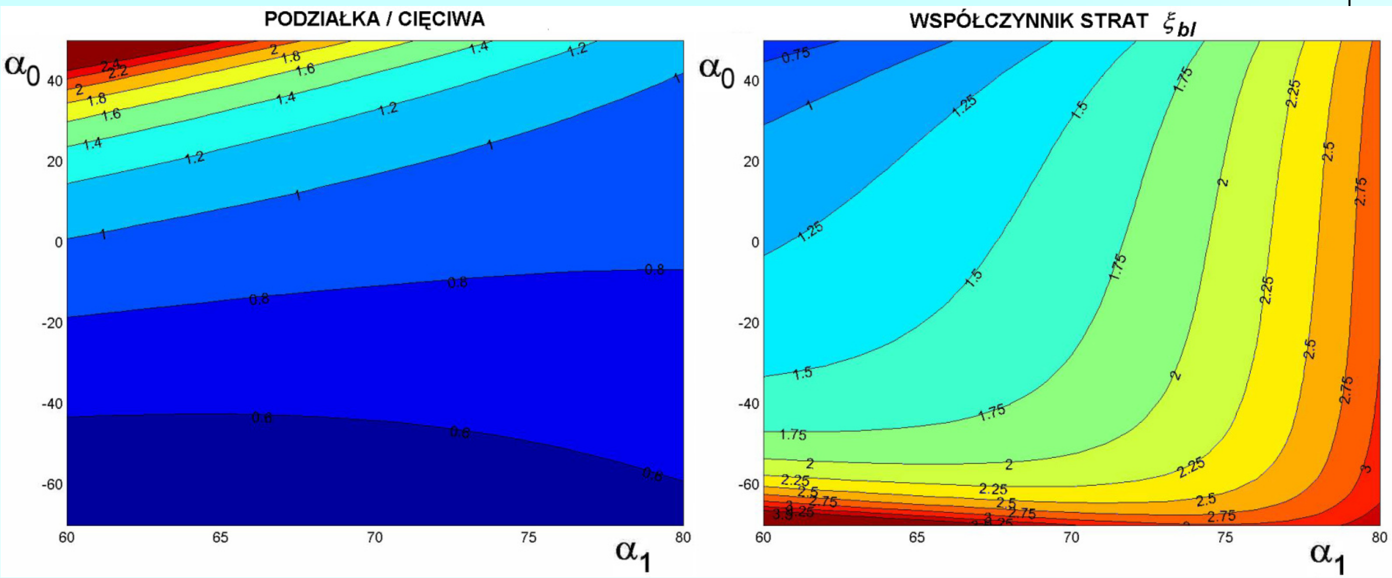
⇨ **optimum p/C**

$$p/C = 2\sqrt{\frac{c_1}{3c_2}} \frac{1}{(\mathrm{tg}\,\alpha_1 - \mathrm{tg}\,\alpha_0)}$$

⇨

$$c_1 = \frac{1}{4}\left(\frac{\mathrm{tg}\,\alpha_1}{\cos^3\alpha_1} - \frac{\mathrm{tg}\,\alpha_0}{\cos^3\alpha_0} + 3c_2\right)$$

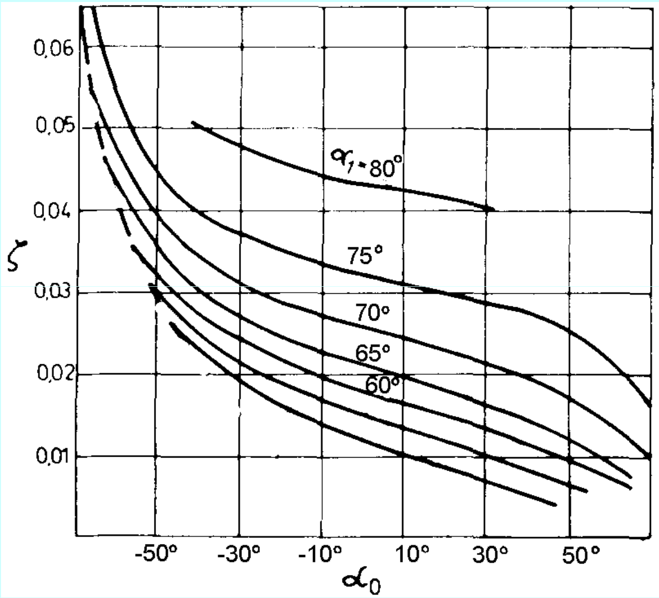
$$c_2 = \frac{1}{2}\left(\frac{\mathrm{tg}\,\alpha_1}{\cos\alpha_1} - \frac{\mathrm{tg}\,\alpha_0}{\cos\alpha_0} + \ln\frac{\mathrm{tg}\,\alpha_1 + \frac{1}{\cos\alpha_1}}{\mathrm{tg}\,\alpha_0 + \frac{1}{\cos\alpha_0}}\right)$$

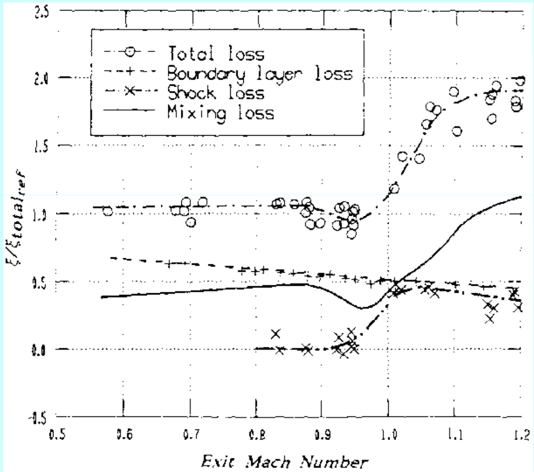


Optimum p/C and boundary layer loss coefficient in a turbine cascade for given inlet and exit angles

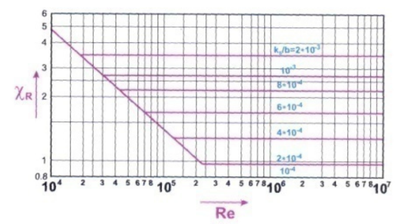
Profile loss (correlation for cascade design)

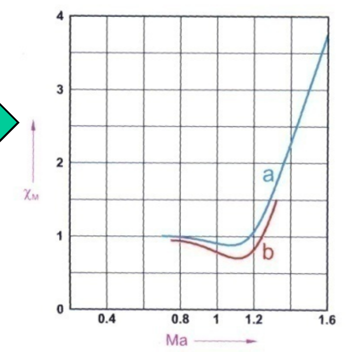
$$\xi_{pr} = \chi_{Re,k}\,\chi_{Ma}\,\xi_{bas} + \xi_{te}$$



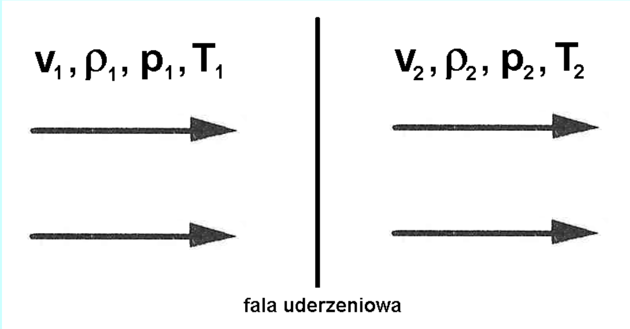


Profile loss and its components
as a function exit Mach number (Mee et al.)





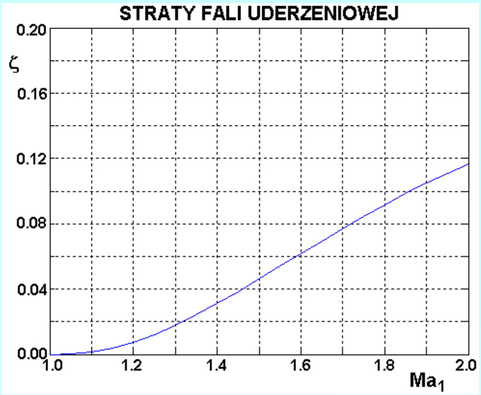
Shock wave losses



Rankine Hugoniot conditions

$$\xi = \frac{h_{2a} - h_1}{h_{1T} - h_1} \approx \frac{T_1(s_2 - s_1)}{h_{1T} - h_1} = \frac{T_1 \Delta s}{0{,}5 v_1^2}$$

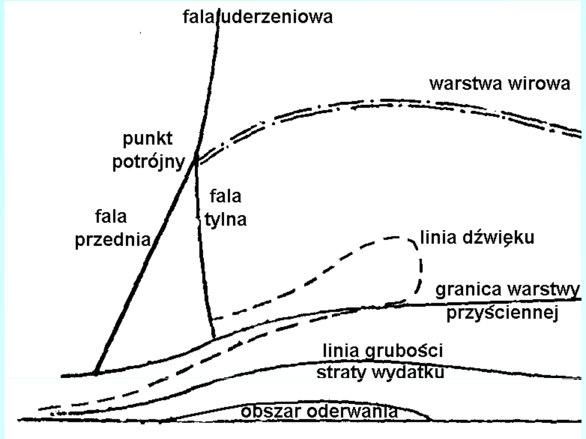
$$\xi = \frac{2}{\kappa R}\frac{\Delta s}{Ma_1^2} = \frac{2}{\kappa(\kappa-1)Ma_1^2}\ln\left(\frac{2\kappa Ma_1^2 - \kappa + 1}{(\kappa+1)}\left(\frac{2+(\kappa-1)Ma_1^2}{(\kappa+1)Ma_1^2}\right)^{\kappa}\right)$$



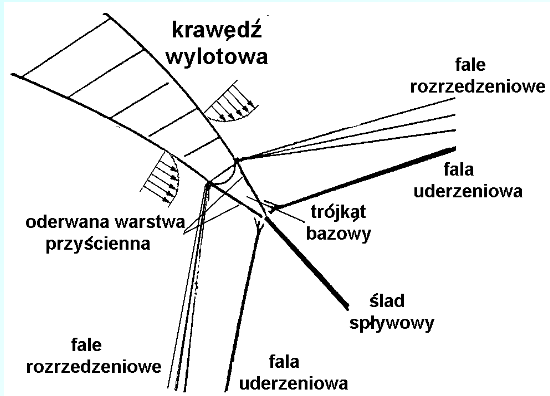
Shock wave losses as a function of upstream Mach number (κ=1.4)

$$\Delta s = \sum_{n=0}^{\infty} \frac{\Delta s^{(n)}(1)}{n!}(Ma_1^2 - 1)^n$$

$$\Delta s \approx c_v \frac{2\kappa(\kappa-1)}{3(\kappa+1)^2}(Ma_1^2 - 1)^3$$

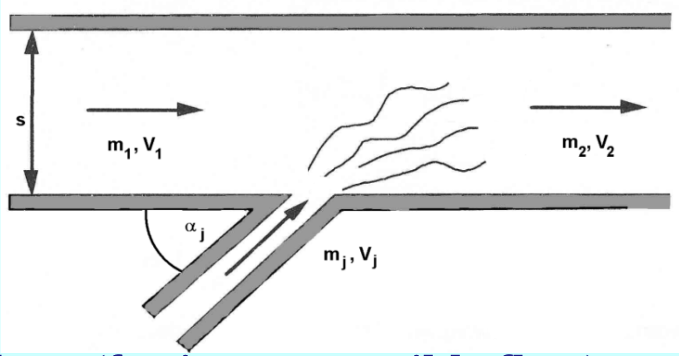


Shock wave boundary layer interaction



Supersonic flow over the trailing edge (Ma_{ex}>1)

Mixing losses



$$m_1 + m_j = m_2$$

$$p_1 s + m_1 v_1 + m_j v_j \cos\alpha_j = p_2 s + m_2 v_2$$

$$m_j \ll m_2$$

- total pressure loss (for incompressible flow)

$$p_{01} - p_{02} = p_1 - p_2 + \frac{1}{2}(\rho v_1^2 m_1 + \rho v_j^2 m_j)/(m_1 + m_j) - \frac{1}{2}\rho v_2^2$$

$$Y = \frac{p_{o1} - p_{o2}}{0{,}5\rho v_2^2} = 1 - 2\left(\frac{m_1}{m_2}\right)^2 - 2\frac{m_1 m_j}{m_2^2}\frac{v_j \cos\alpha_j}{v_1} + \left(\frac{m_1}{m_2}\right)^3 + \frac{m_1^2 m_j}{m_2^3}\left(\frac{v_j}{v_1}\right)^2$$

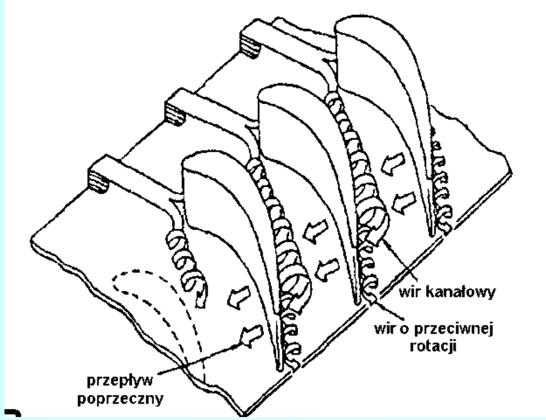
$$Y = \frac{m_j}{m_2}\left(1 - 2\frac{v_j}{v_1}\cos\alpha_j + \left(\frac{v_j}{v_1}\right)^2\right)$$

- kinetic energy loss (assuming that the kinetic energy of relative motion is dissipated)

$$\xi = \frac{m_j}{m_2}\frac{v_{rel}^2}{v_2^2} = \frac{m_j}{m_2}\frac{m_1^2}{m_2^2}\frac{(v_j \cos\alpha_j - v_1)^2 + (v_j \sin\alpha_j)^2}{v_1^2} = \frac{m_j}{m_2}\left(1 - 2\frac{v_j}{v_1}\cos\alpha_j + \left(\frac{v_j}{v_1}\right)^2\right) = Y \qquad m_j \ll m_2$$

Endwall / secondary flows

⇨ The source of endwall losses are specifically evolving boundary layers at the endwalls.



Model of secondary flows
In turbine cascade (Langston)

Endwall loss diagram

ASSUMPTIONS:

-model of profile evenly loaded along its chord

- optimum p/C

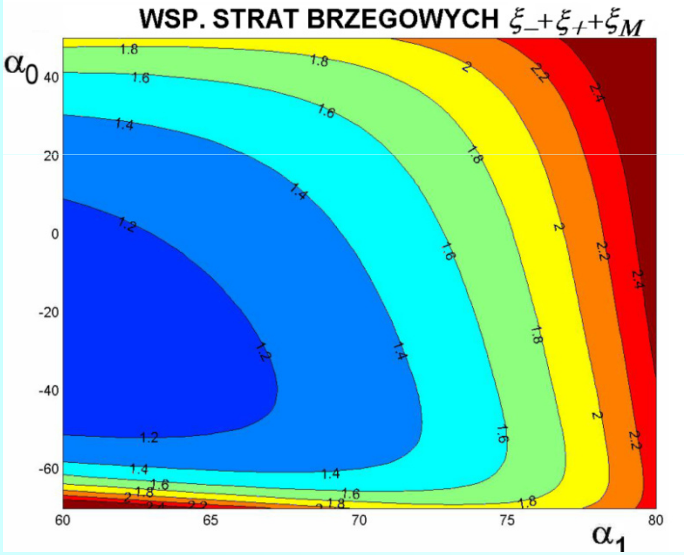
- tgα varies linearly with chord between $tg\alpha_0$ and $tg\alpha_1$

⇨ Loss coefficient

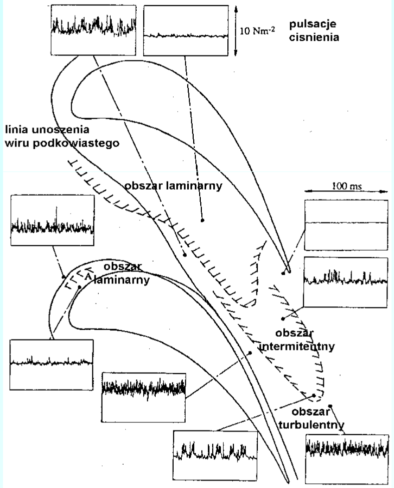
$$\xi_- = 4C_D \frac{\Delta x_-}{h} \frac{\cos^2\alpha_1}{\cos^3\alpha_0}$$

$$\xi_M = \frac{8}{3} C_D \cos^2\alpha_1 \cos\varphi \frac{p}{C}\frac{C}{h}\sqrt{3c_1c_2}$$

$$\xi_+ = 4C_D \frac{\Delta x_+}{h} \frac{1}{\cos\alpha_1}$$



Endwall boundary layer coefficient $\xi_-+\xi_++\xi_M$ for given inlet and exit angle



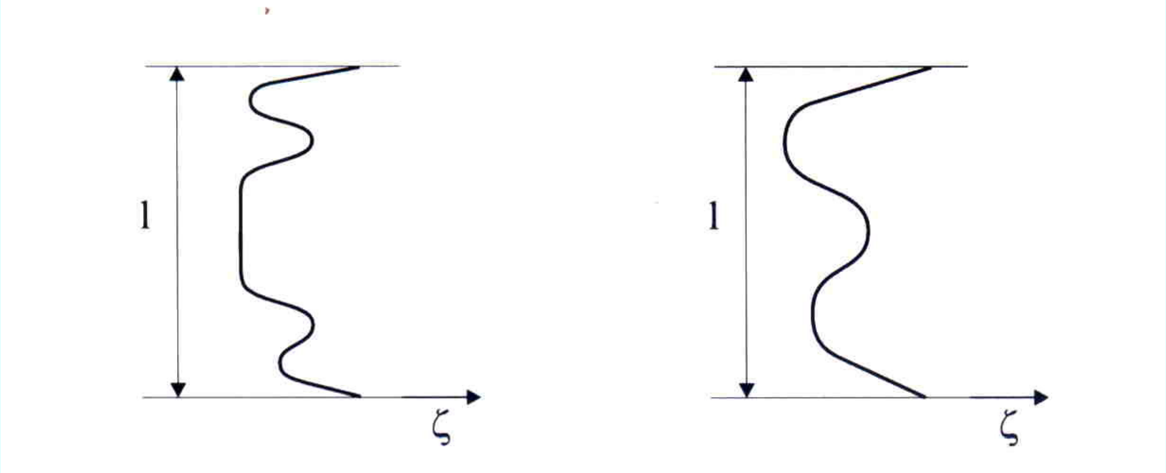
Secondary flows modify boundary layers at the endwalls, Harrison

- Sample formula for secondary flow losses, Puzyrewski

$$\xi_{sec} = \frac{c_2}{(2\cos\alpha_1 + (h/C)(C/p))^2} \frac{\sin^2(\alpha_1 - \alpha_0)}{(\cos\alpha_1 + \cos\alpha_0)^2} \frac{\cos^4\alpha_1}{\cos^4\alpha_0}$$

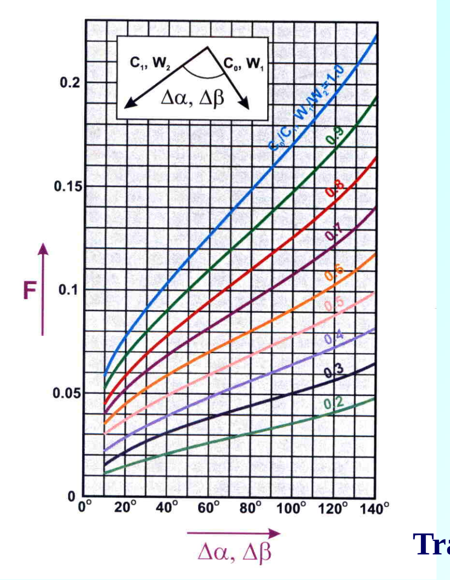
Assuming that the secondary kinetic energy of passage vortex is lost during mixing

Endwall loss correlations



Long blades

$$\zeta_{\sec} = \chi_R F \frac{p}{C}\frac{C}{h}$$

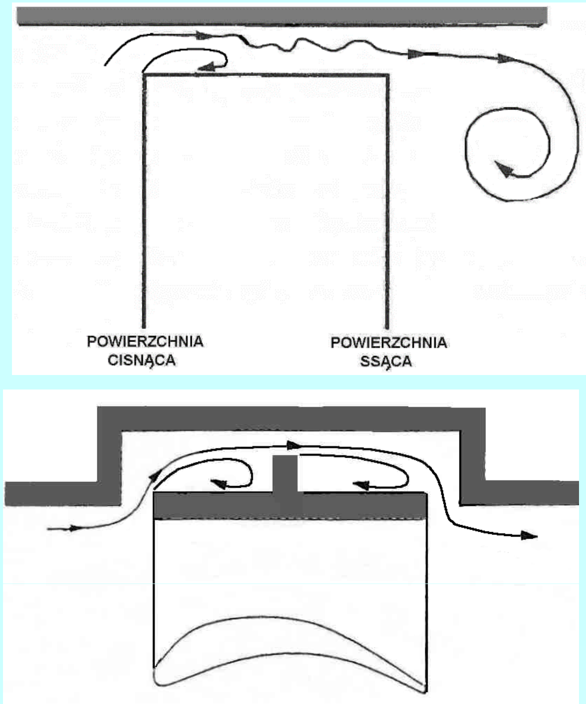


Traupel

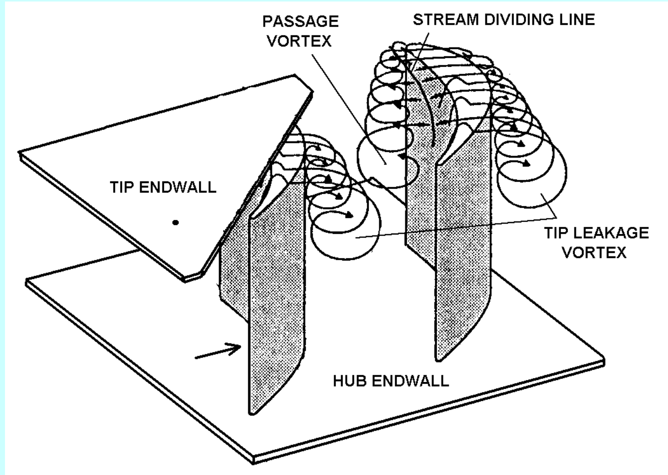
short blades

$$\zeta_{\sec} = \chi_R F \frac{p}{C}\frac{1}{(h/C)_{gr}} + A\left[\frac{C}{h} - \frac{1}{(h/C)_{gr}}\right]$$

TIP / SHROUD LEAKAGE



Scheme of the tip leakage over unshrouded or shrouded rotor blades (Denton).



Tip leakage vortex and passage vortex at the tip endwall (Sjolander).

➲ **Tip / shroud leakage - loss of work in a turbine stage rotor. Its energy is still available for work in the subsequent stage.**

➲ **Typically, tip / shroud leakage at re-entry to the blade-to-blade passage has different parameters as compared to the main stream. It gives rise to mixing losses in the blade-to-blade passage.**

➲ **The mechanisms of formation of leakage loss over unshrouded blades is different than that over shrouded blades.**

➲ **Tip leakage rolls up into tip leakage vortex and interacts with the main flow and endwall flows.**

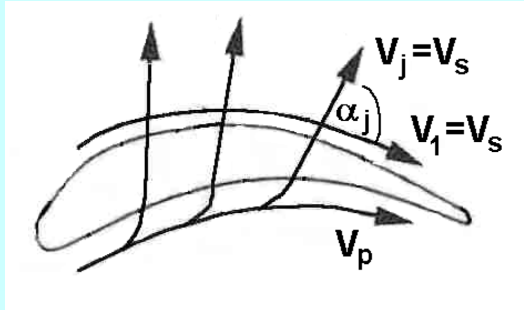
➲ **Tip / shroud leakage means an off-design inflow onto the downstream stator blade.**

Tip leakage loss diagram and correlations

$$m_1 = \rho h p V_x$$

$$dm_j = \rho V_{jn} C_\delta \delta dC = \rho \sqrt{V_s^2 - V_p^2}\, C_\delta \delta dC$$

$$\xi = \int_C \frac{dm_j}{m_2}\frac{e_{rel}}{e_2} = \int_C \frac{dm_j}{m_1} 2\left(1 - \frac{V_p}{V_s}\right)$$



Model of mixing in the region of tip leakage over an unshrouded rotor blade (Denton)

ASSUMPTIONS:

-model of profile evenly loaded along its chord

- optimum p/C

- tgα varies linearly with chord between tgα_0 and tgα_1

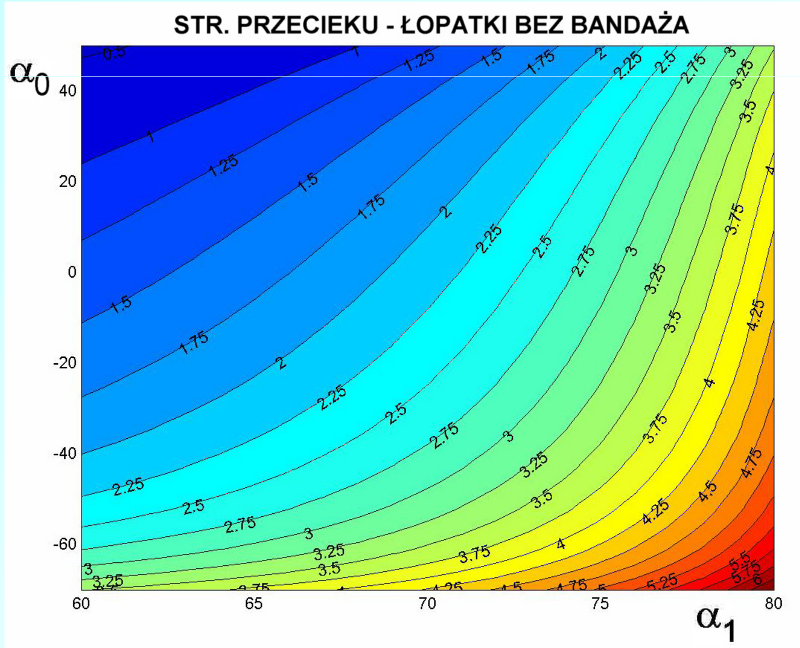
$$\xi = \frac{2C_\delta \delta}{h} \int_{\mathrm{tg}\alpha_0}^{\mathrm{tg}\alpha_1} \sqrt{1 - \frac{\left(-\sqrt{c_1/3c_2} + \sqrt{1+x^2}\right)^2}{\left(\sqrt{c_1/3c_2} + \sqrt{1+x^2}\right)^2}}\, dx$$

Tip leakage correlations

$$\zeta_{tip} = \frac{\cos^2\alpha_2}{\cos^3\alpha_m}\frac{1}{p/C}\,0{,}5\frac{\delta}{p}\frac{c_L^2}{h/C}$$ - Ainley i Mathiesn

$$\zeta_{tip} = \frac{\cos^2\alpha_2}{\cos^3\alpha_m}\frac{1}{(p/C)^2}\,0{,}47\left(\frac{\delta}{C}\right)^{0{,}78}\frac{c_L^2}{h/C}$$ Dunham i Came

$$\zeta_{tip} = 2K_E \frac{1}{p/C}\frac{\delta}{h} C_D \frac{\cos^2\alpha_2}{\cos^3\alpha_m} c_L^{1{,}5}$$ - Yaras i Sjolander



Tip leakage loss coefficient for unshrouded blades as a function of cascade inlet and exit angles α_1, α_2; δ=0.01h, C_δ=0.4.

Leakage loss diagram for shrouded blades

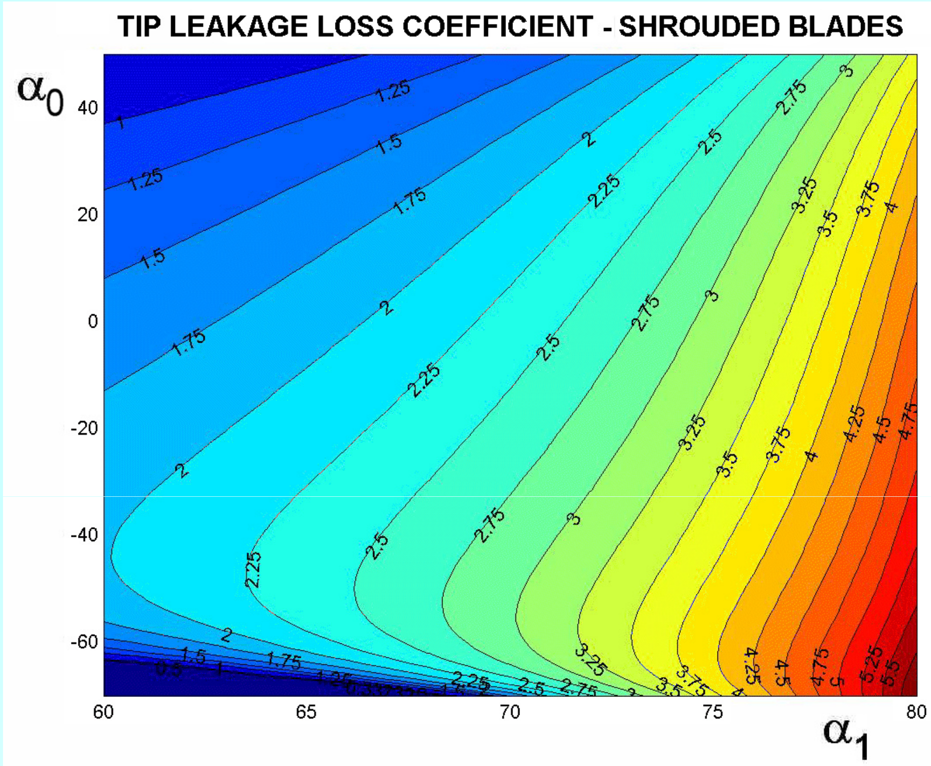
$$m_j = \rho C_\delta \delta p V_x \sqrt{1 + \mathrm{tg}^2\alpha_1 - \mathrm{tg}^2\alpha_0}$$

$$\xi = \frac{m_j}{m_2}\frac{e_{rel}}{e_2} = \frac{m_j}{m_2}\frac{v_{rel}^2}{v_2^2} \approx \frac{m_j}{m_1}\frac{v_{rel}^2}{v_1^2} =$$

$$= \frac{m_j}{m_1}\frac{v_x^2 + v_x^2(\mathrm{tg}\alpha_1 - \mathrm{tg}\alpha_0)^2 + v_{jx}^2}{v_x^2 + v_x^2\mathrm{tg}^2\alpha_1} =$$

$$= 2\frac{m_j}{m_1}\left(1 - \frac{\mathrm{tg}\alpha_0}{\mathrm{tg}\alpha_1}\sin^2\alpha_1\right)$$

Denton



Leakage loss coefficient for shrouded blades as a function of cascade inlet and exit angles α_0, α_1; δ=0.01h, C_δ=0.4.

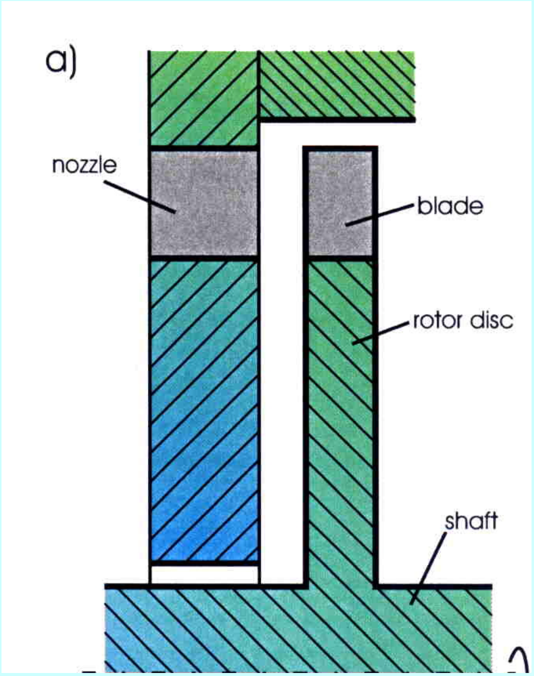
Leakage loss correlations for shrouded blades

$$\xi_{leak} = \left[(1+\mu)\frac{m'_{leak}}{m_0} + \frac{m''_{leak}}{m_0}\right] \qquad m_{leak} = \alpha_c \pi D \delta \rho c_s \frac{1}{\sqrt{z}}$$

$$\xi_{leak} = \left[(2+\mu)\frac{\alpha}{\sqrt{z}}\frac{\delta}{h\cos\alpha_1}\right]\eta_u$$

For drum-type turbine

Disc friction losses



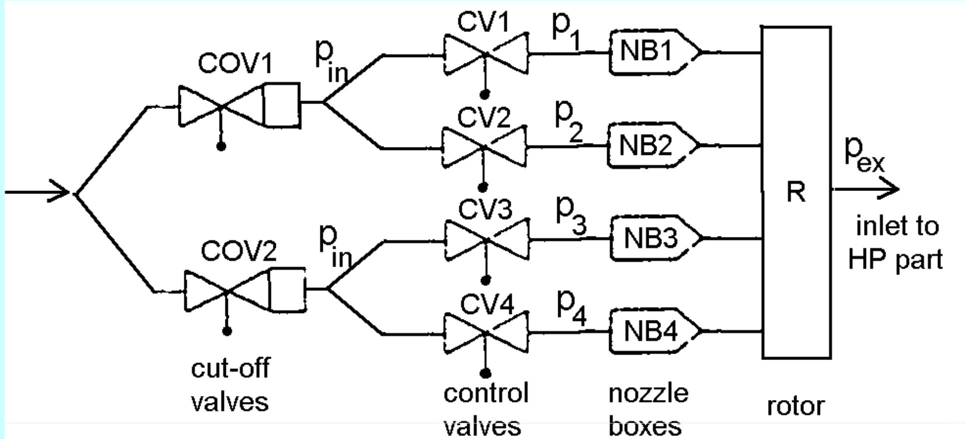
● **Friction of the leakage stream against the disc walls (disc windage);**

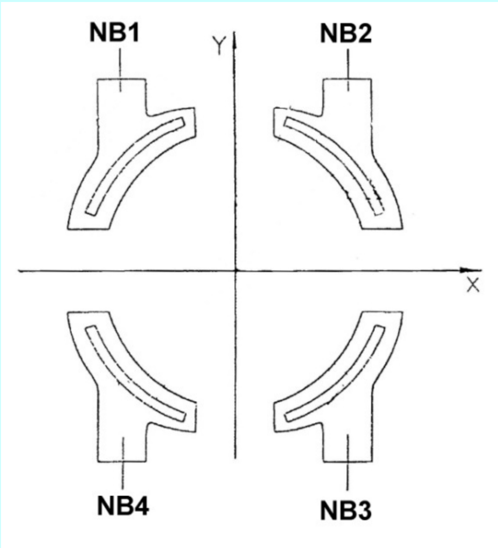
$$\zeta_{fr} = \frac{N_{fr}}{N_{th}} = \frac{K_{fr}\rho D^2 u^3}{\dot{m}\Delta H_s}$$

$$\zeta'_{fr} = \frac{N'_{fr}}{N_{th}} = \frac{K'_{fr}\rho D B u^3}{\dot{m}\Delta H_s}$$

For drum-type turbine

Partial admission losses

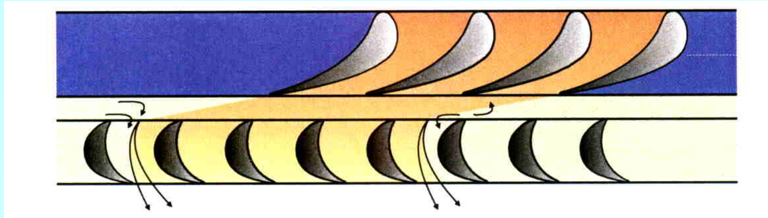




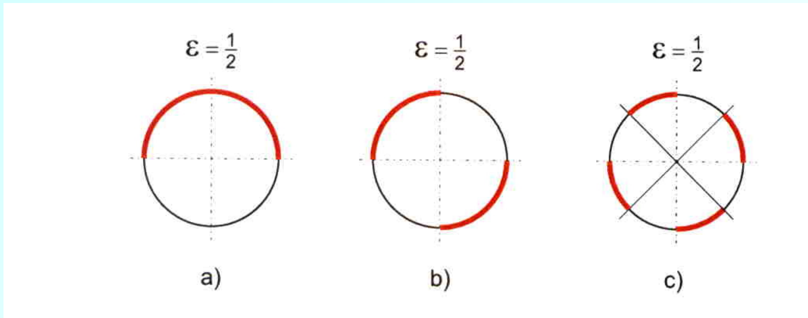
Four-nozzle supply

- **Windage loss, energy needed to conquer circulation induced in non-aqdmitted channels,**
- **End-arc effect – shear between admitted and non-admitted channels, recirculating flows and stream mixing**
- **filing previously non-admitted channels, removing stagnant fluid,**

$$\xi_{partadm} = \xi_{wind,endarc} + \xi_k^{'}$$



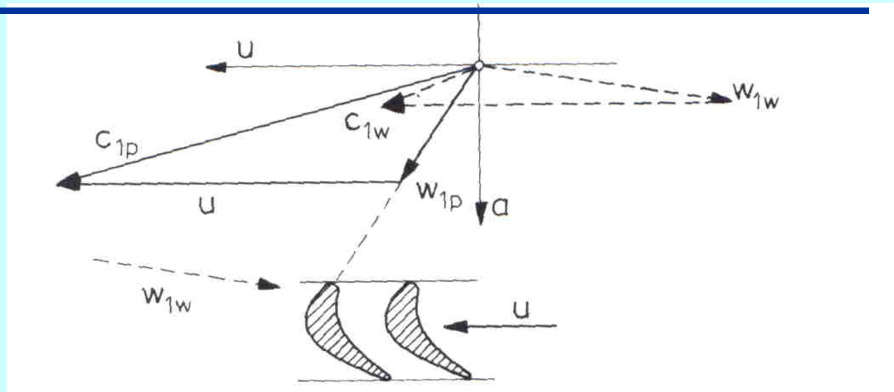
$$\xi_{wind,endarc} = \frac{N_{wind,endarc}}{N_{th}} = \frac{K_v\left(1-\varepsilon\right)\rho D h u^3}{\dot{m}\Delta H_s}$$



$$\xi_k^{'} == \frac{K_k B_2 h_2 v \eta_c \left(k-1\right)}{\varepsilon \pi D h_1 \sin\alpha_1}$$

Wet steam loss mechanisms

- lost work of water drops,
- lost work due to vapour subcooling,
- condensation shock,
- thermal energy dissipation
  in heat transfer during condensation,
- droplet wall collisions

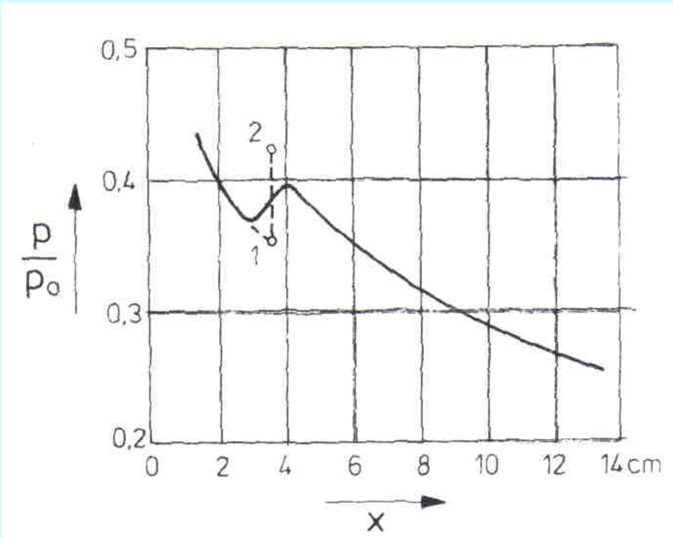


Velocity traingle in wet steam region

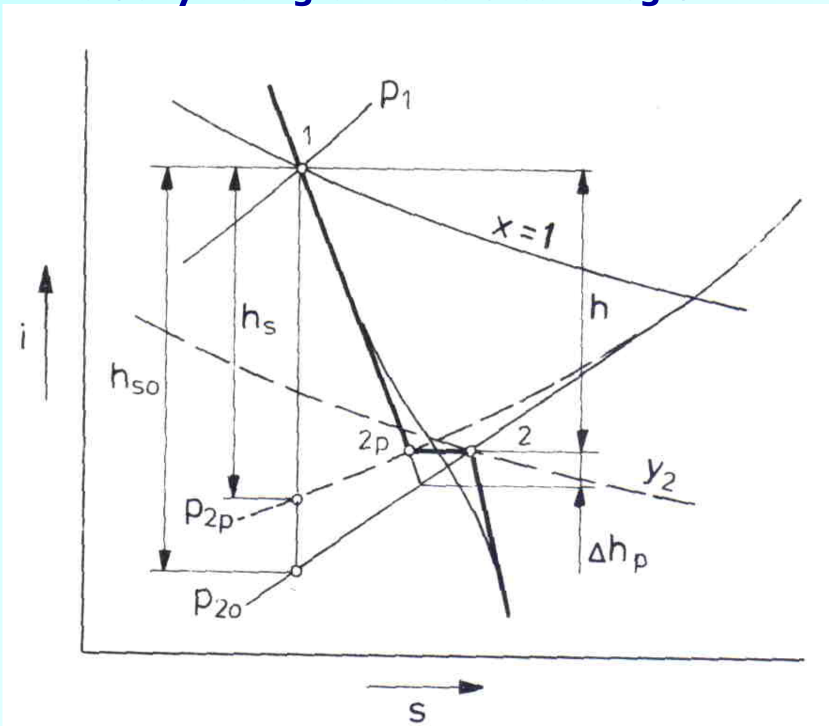
Baumann formula

$$\eta_x = (1 - \alpha y)\eta_c;$$

$$y = 1 - x$$



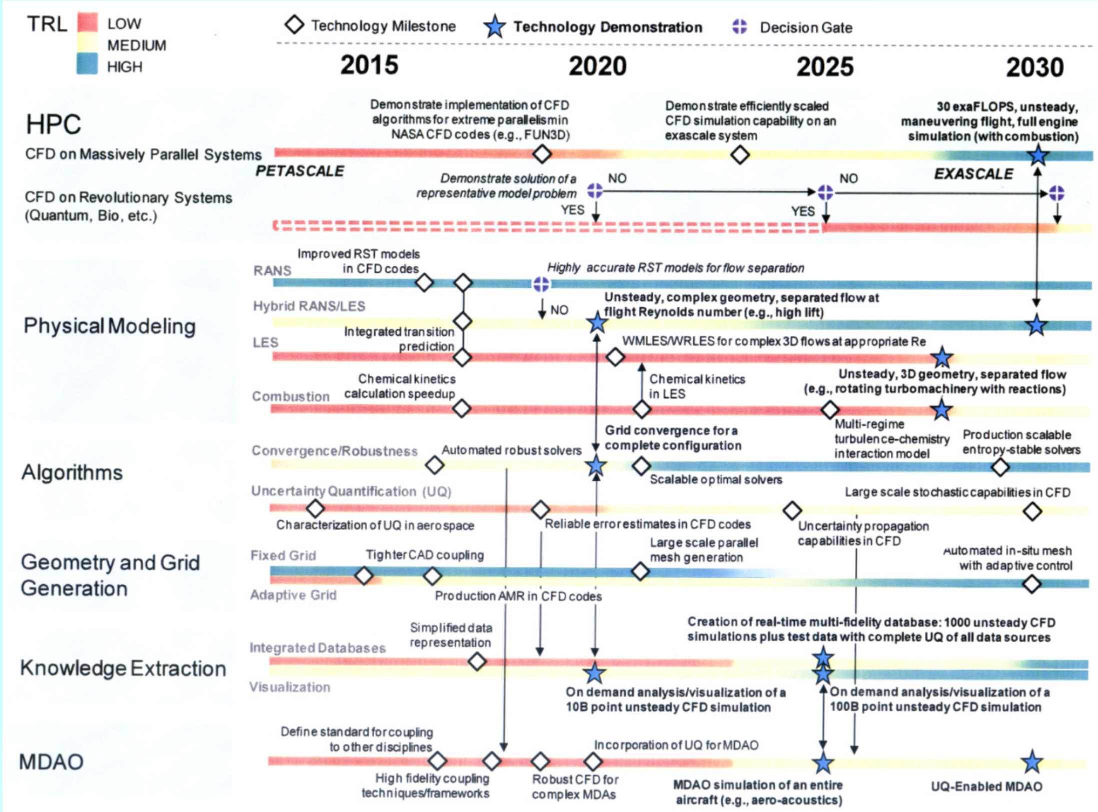
expansion in wet steam region



expansion in wet steam region

Prospests of development of CFD up to 2030

Technical road map of NASA, 2014

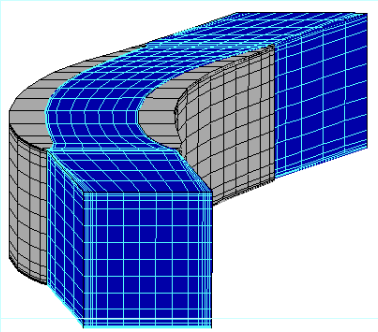


- **Recommended CFD method – RANS with REYNOLDS STRESS MODELS (RSM) - available LRR, SSG**

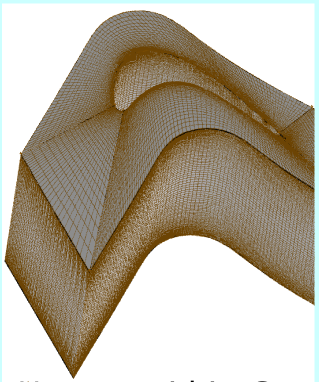
- **Giving good results – RANS with TURBULENT VISCOSITY MODELS**
  - **TWO-EQUATION MODEL k-ω SST,**
    Additional features:
  - **compressibilty, intermittence, SAS**

ERCOFTAC TEST CASE –
DURHAM LOW SPEED TURBINE CASCADE

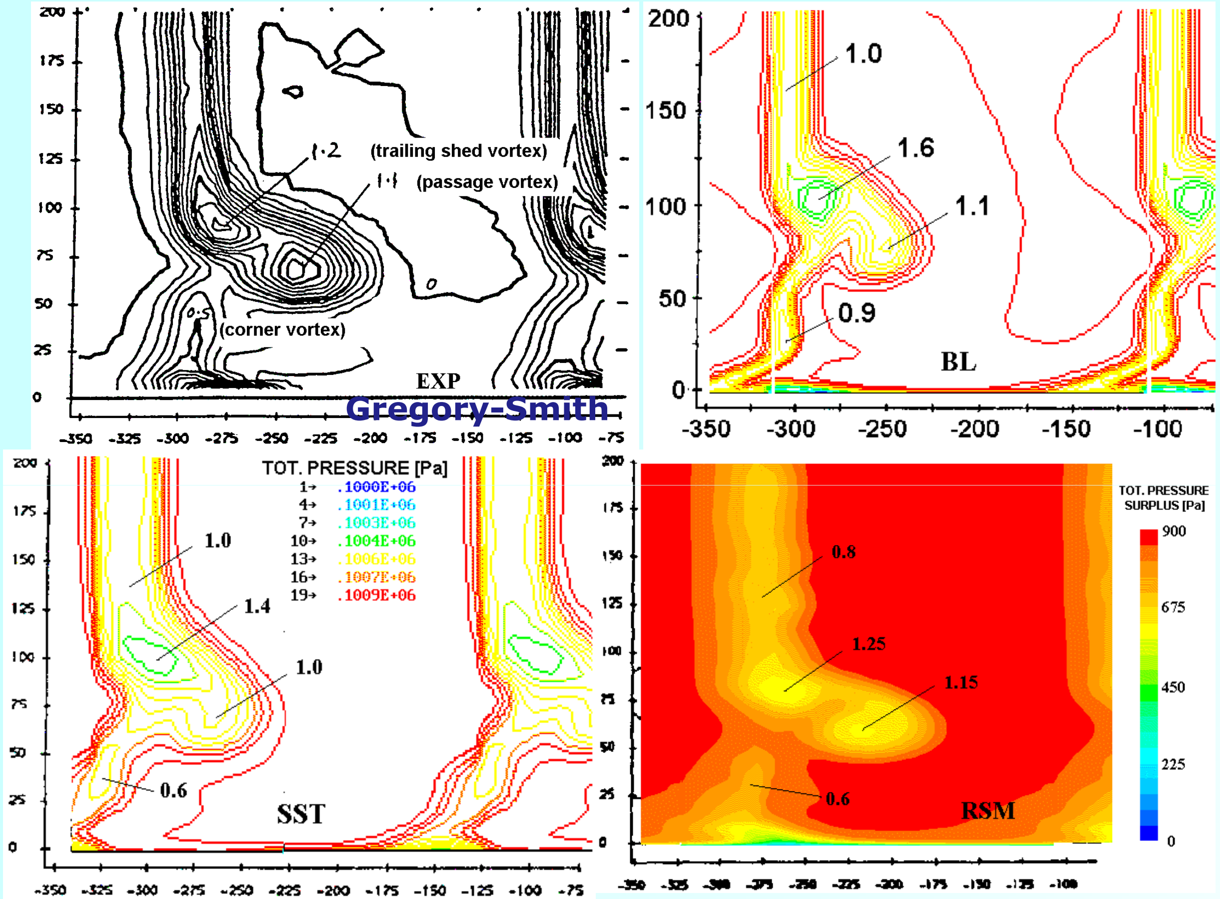
CFD codes
⇨ FLOWER
⇨ ANSYS FLUENT



H type grid in FlowER



O–H type grid in Gambit

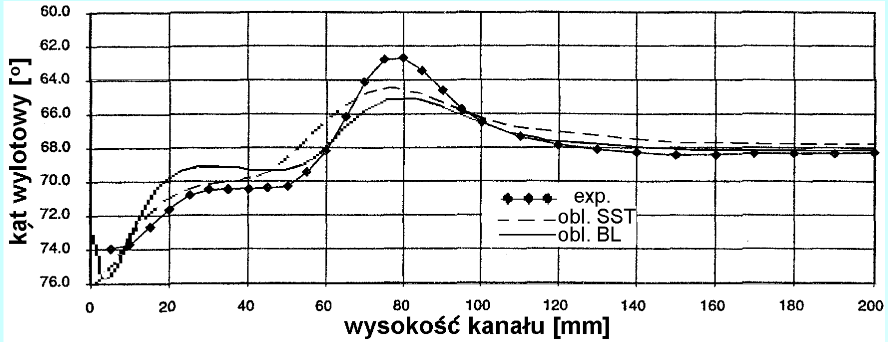


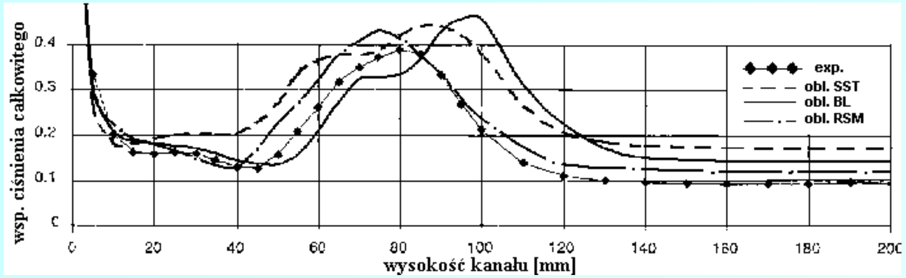
Experimental and numerical total pressure contours (turbulence models of Baldwin-Lomax, *k–ω* SST Menter, Reynolds stress model LLR)

⇨Turbulent viscosity models are capable of predicting basic features of 3D flow. However, they overpredict losses in wake and secondary flow.

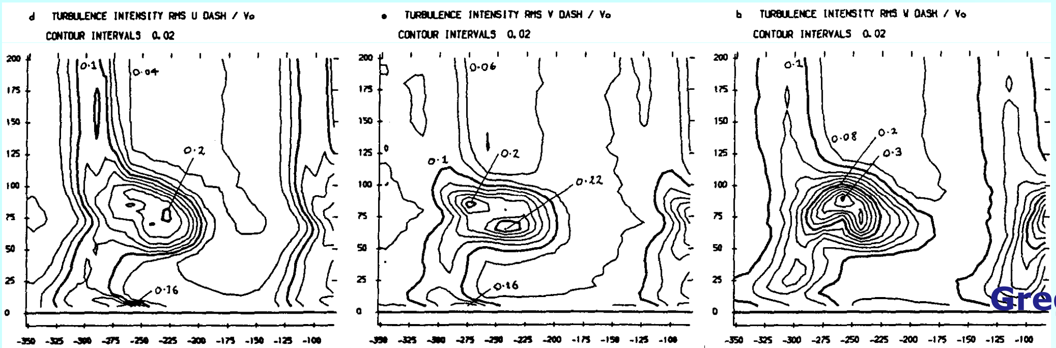
⇨ Reynolds stress model improves the solution, however it takes place at increased computational costs

DURHAM LOW SPEED TURBINE CASCADE

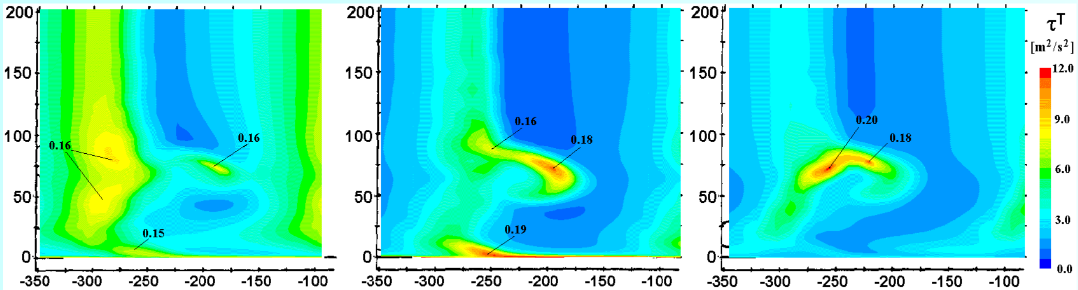




Experimental and numerical total pressure loss and exit flow angle



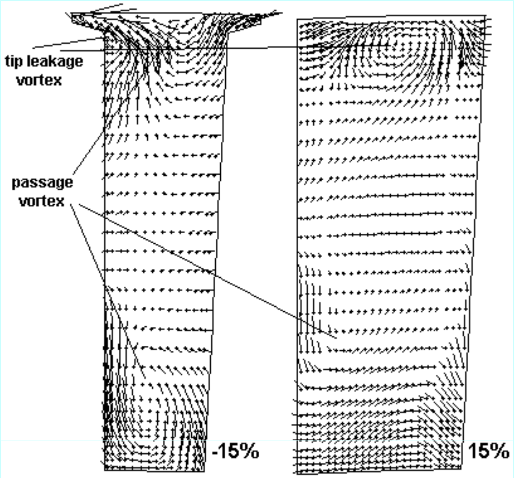
Gregory-Smith

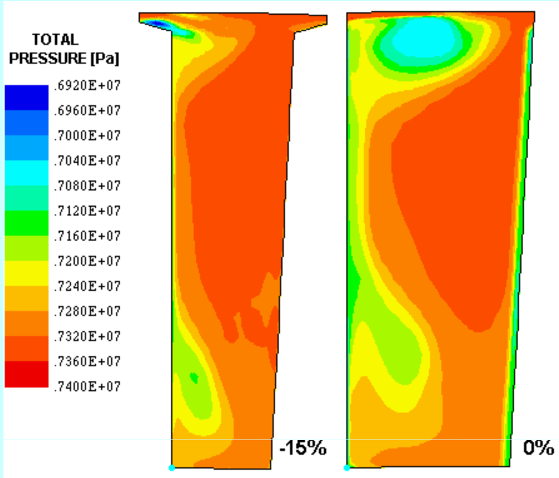


Measured and computed main components of Reynolds stress tensor

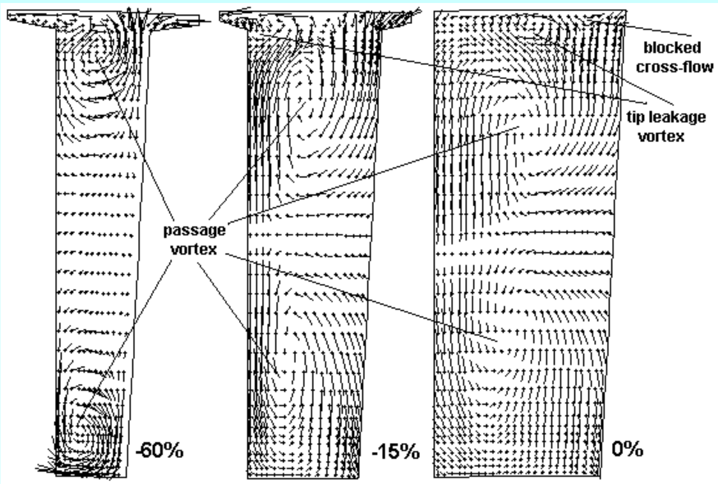
SECODARY FLOW / TIP LEAKAGE INTERACTIONS - USEFUL CFD RESULTS

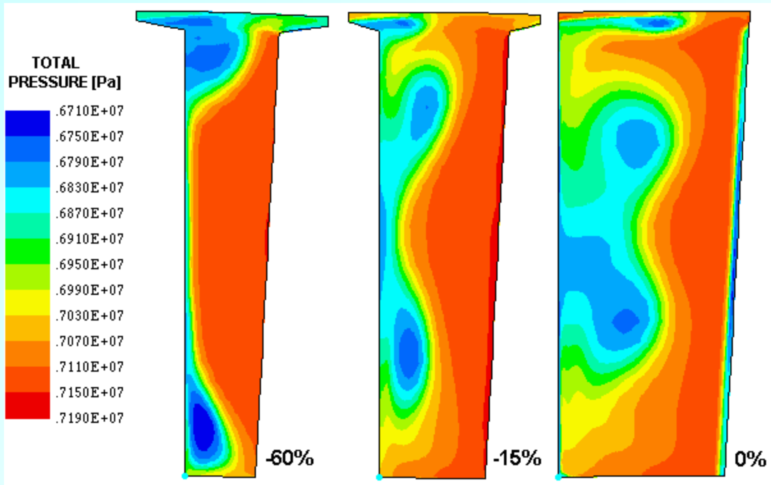
Flow turning in the cascade with tip clearance





Secondary flow vectors and total pressure contours in the HP rotor cascade in selected sections located 15% axial chord upstream of the trailing edge, at the trailing edge and 15% axial chord downstream of it; tip gap size – 2%, *Ma*=0.2, α_0 = 63°, α_1 = -63°.

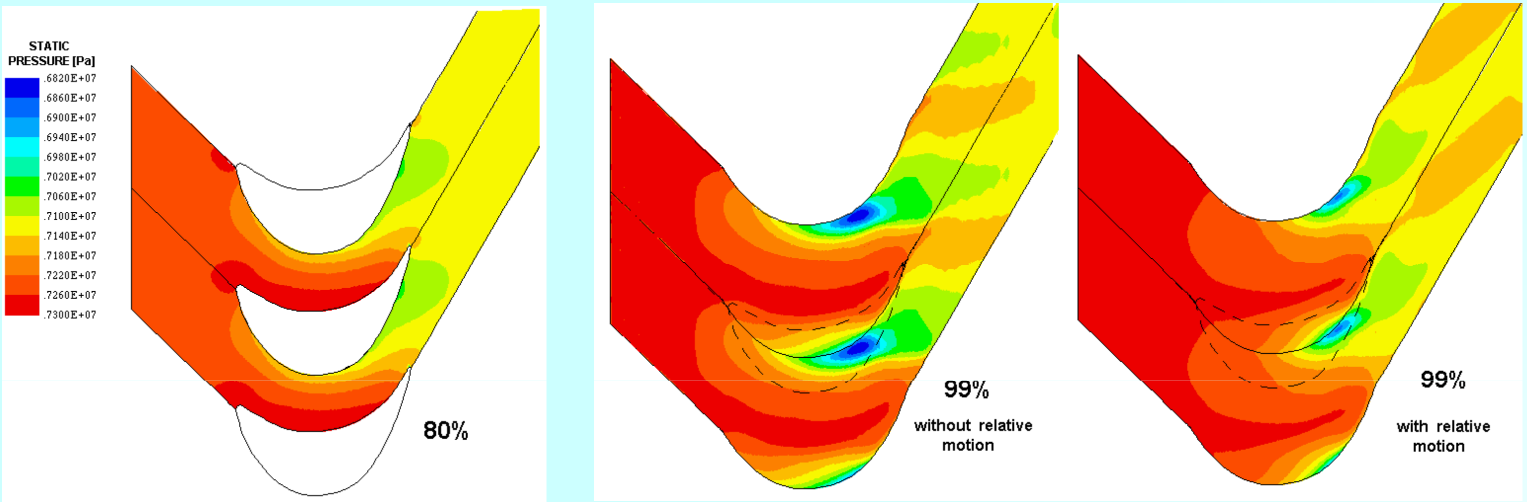




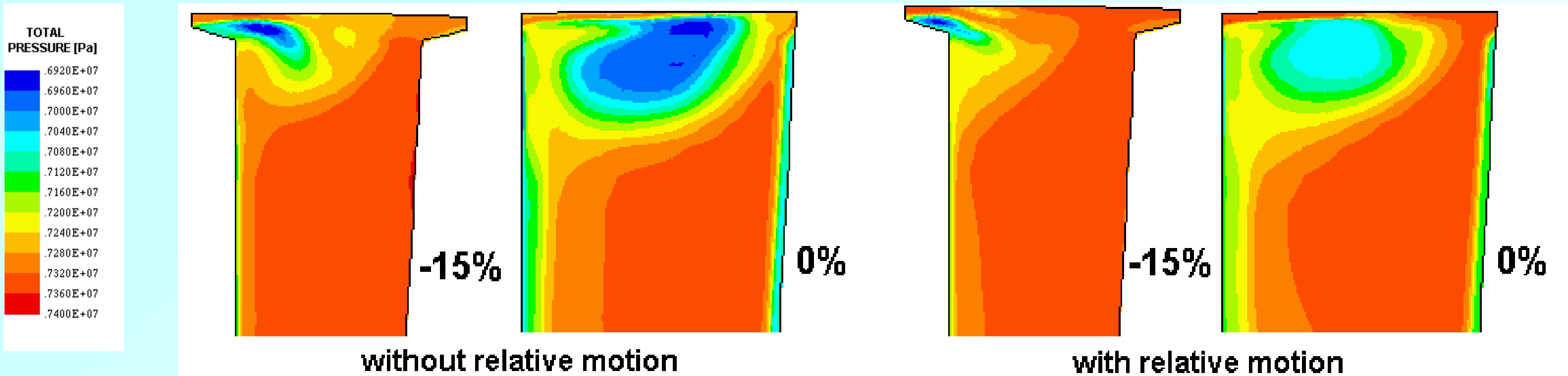
Secondary flow vectors and total pressure contours in the HP rotor cascade in selected sections located 60% and 15% axial chord upstream of the trailing edge and at the trailing edge; tip gap size – 2%, *Ma*=0.4, α_0 = 75°, α_1 = -72°.

SECODARY FLOW / TIP LEAKAGE INTERACTIONS - USEFUL CFD RESULTS

Relative motion of the blade tips and endwall

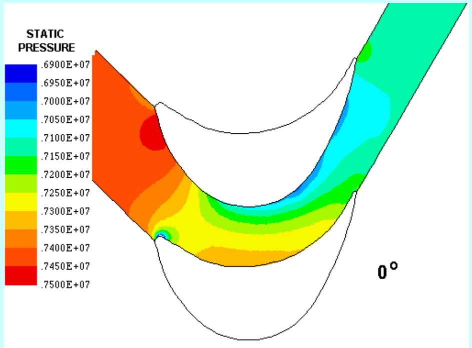


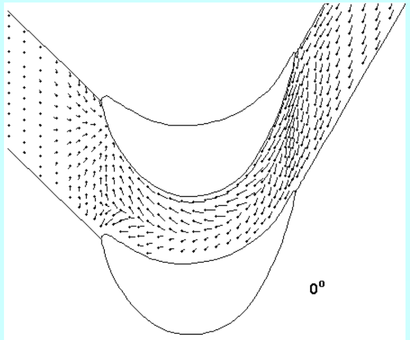
Static pressure field in the blade-to-blade passage located 80% channel height from the hub (left) and in the mid-gap section of the HP rotor cascade calculated without relative motion (centre), and with relative motion (right); tip gap size – 2%.



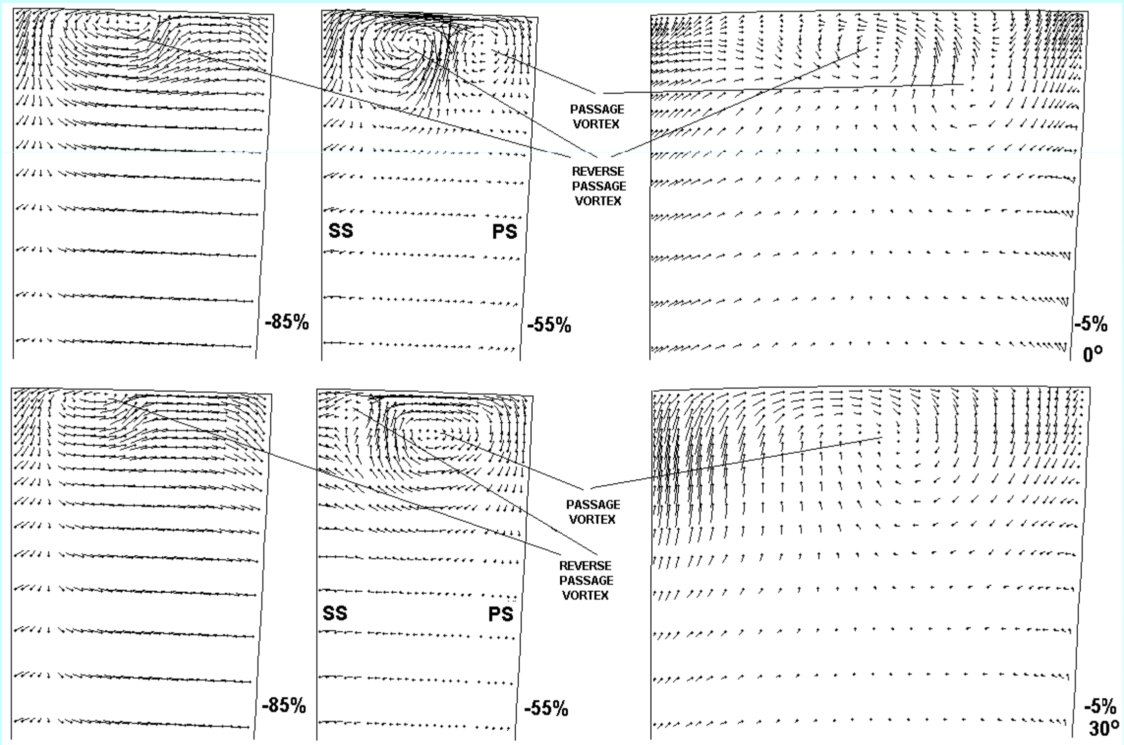
Total pressure contours 15% axial chord upstream of the trailing edge and at trailing edge of the HP rotor cascade calculated without relative motion (left) and with relative motion (right); tip gap – 2%.

The case of non-nominal inflow onto the suction side of the blade

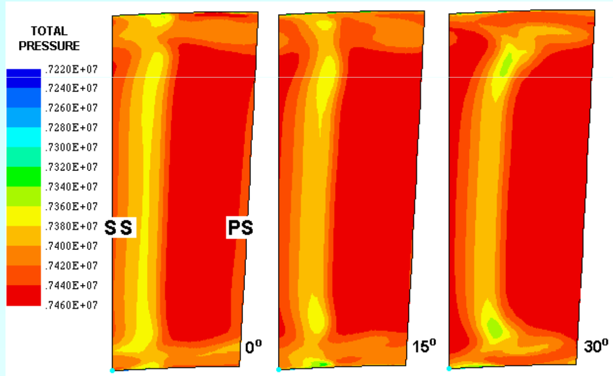




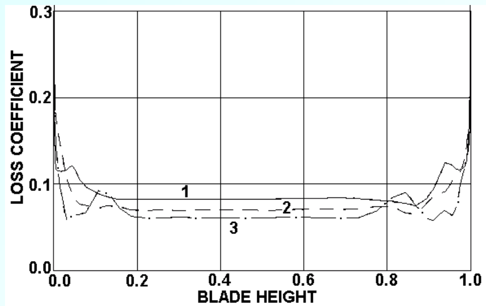
Static pressure contours and velocity vectors at the endwall of the rotor cascade for the case of non-nominal inflow onto the suction side of the blade, α_0 = 0°.



Secondary flow vectors 85%, 55% and 5% axial chord upstream of the trailing edge of the rotor cascade for the case of non-nominal inflow onto the suction side of the blade for α_0 = 0° and 30°;

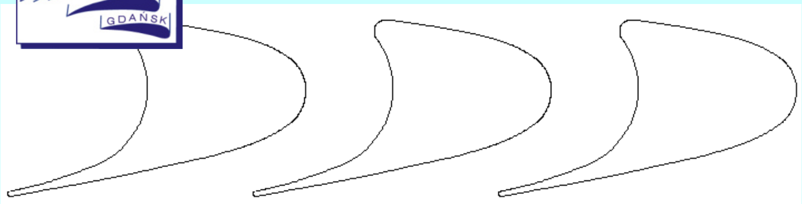


Loss contours and distribution



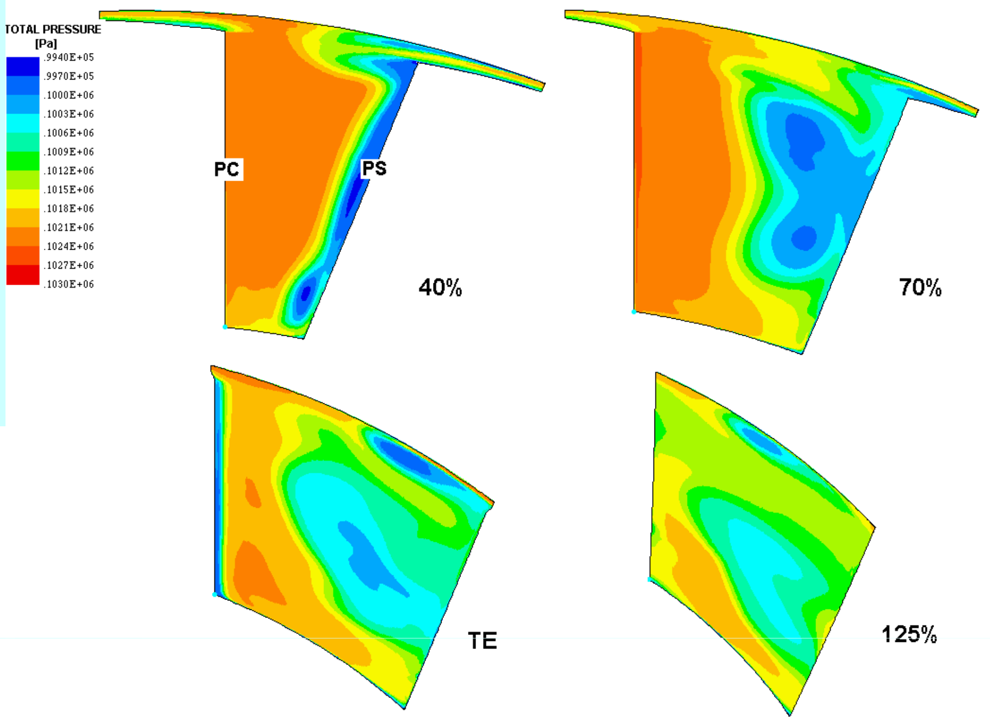
ULTRA HIGH LOAD CASCADES

IMP PAN GDANSK

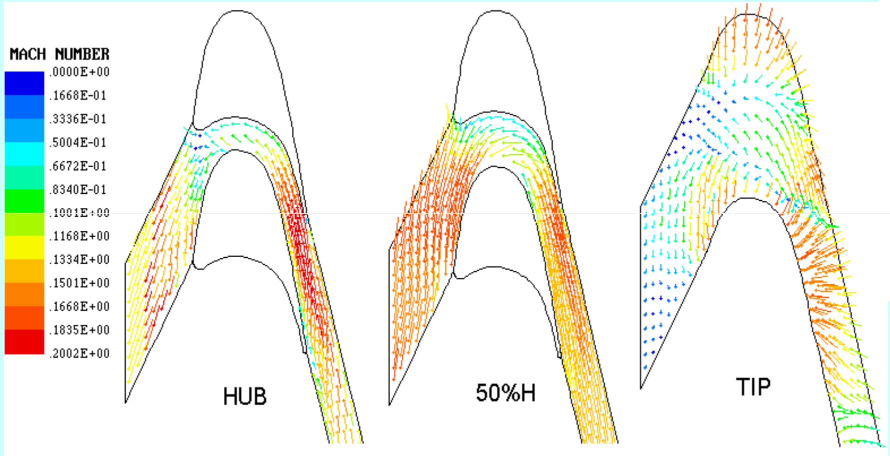


UHL cascade of Yamamoto

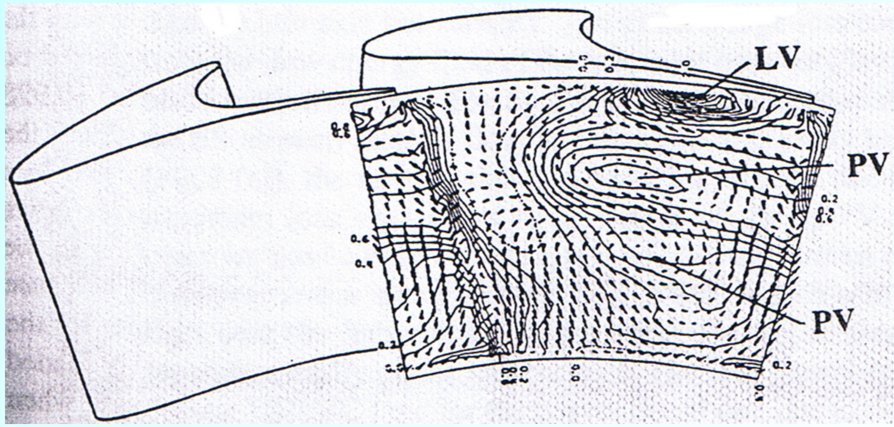
⇨ Profiles used in gas turbines
for a low weight-to-power ratio



Total pressure contours in normal sections



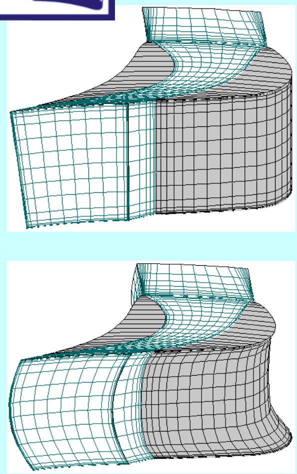
Velocity vectors in sections from hub to tip



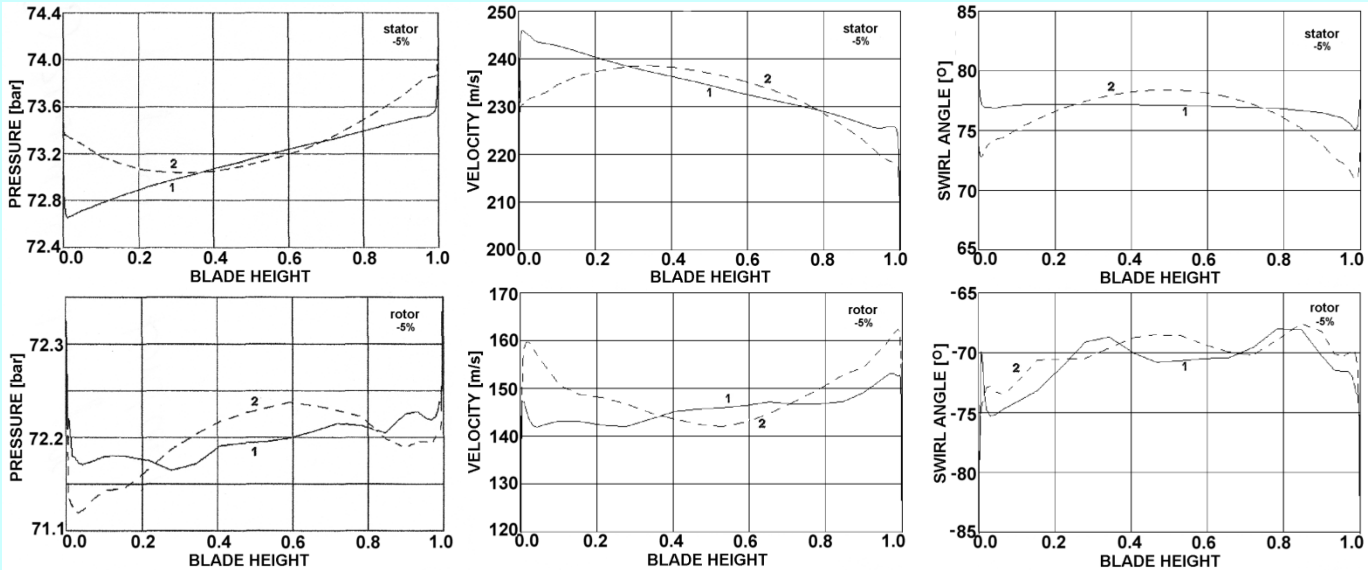
Total pressure contours and secondary flow vectors
in exit section – experiment, Yamamoto

Enthalpy losses

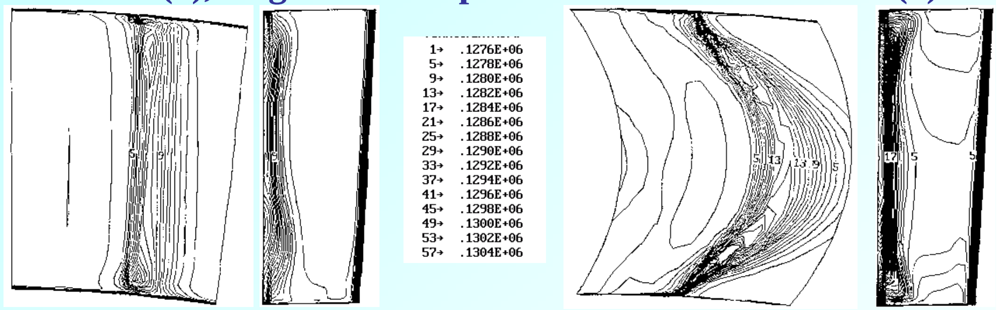
The effect of span-wise distribution of static pressure and cascade load (3D blading)



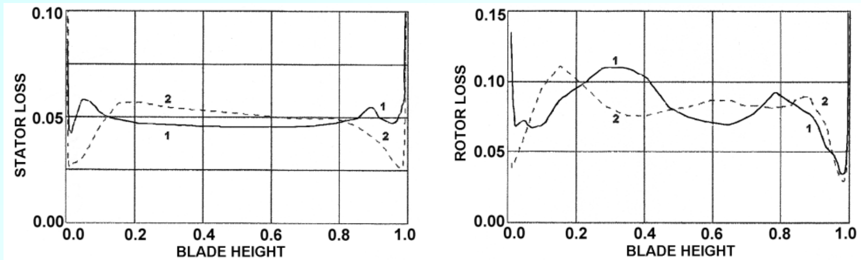
Straight and compound leaned stator blade (HP turbine stage)

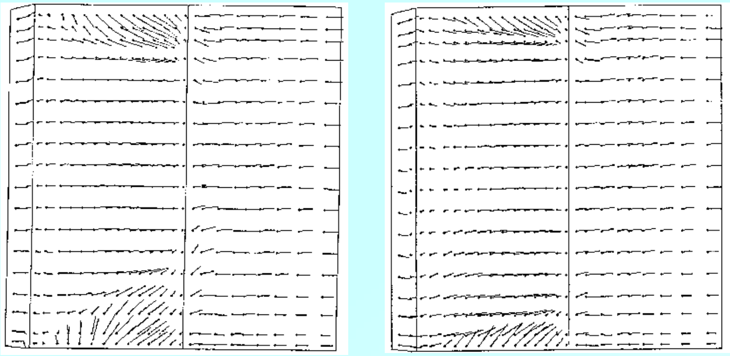


Spanwise distribution of static pressure, relative velocity and swirl angle in the stator and rotor 5% axial chord upstream of the trailing edge; stage with straight stator blades (1), stage with compound leaned stator blades (2)



Redistribution of loss in the stator and rotor; straight blades (left, 1), compound leaned blades (right, 2)



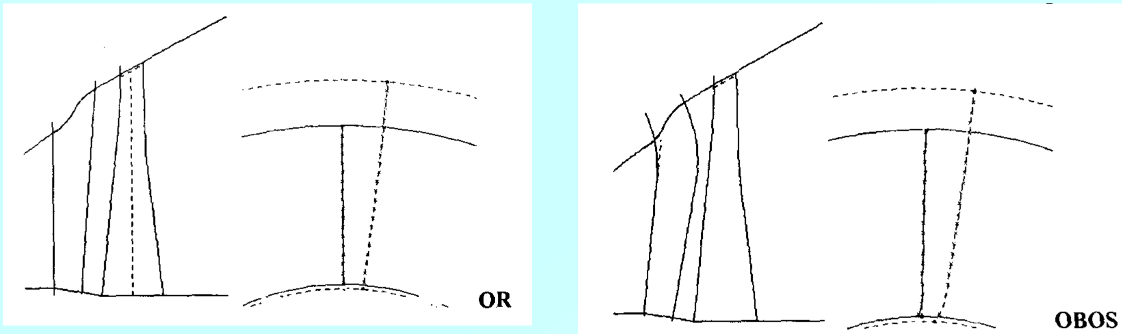


Velocity vectors at the rotor suction surface; stage with straight stator blades (left), stage with compound leaned stator blades (right)

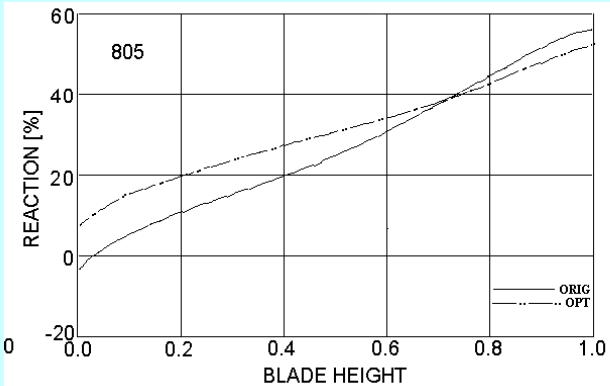
The effect of span-wise distribution of static pressure and cascade load (3D blading)

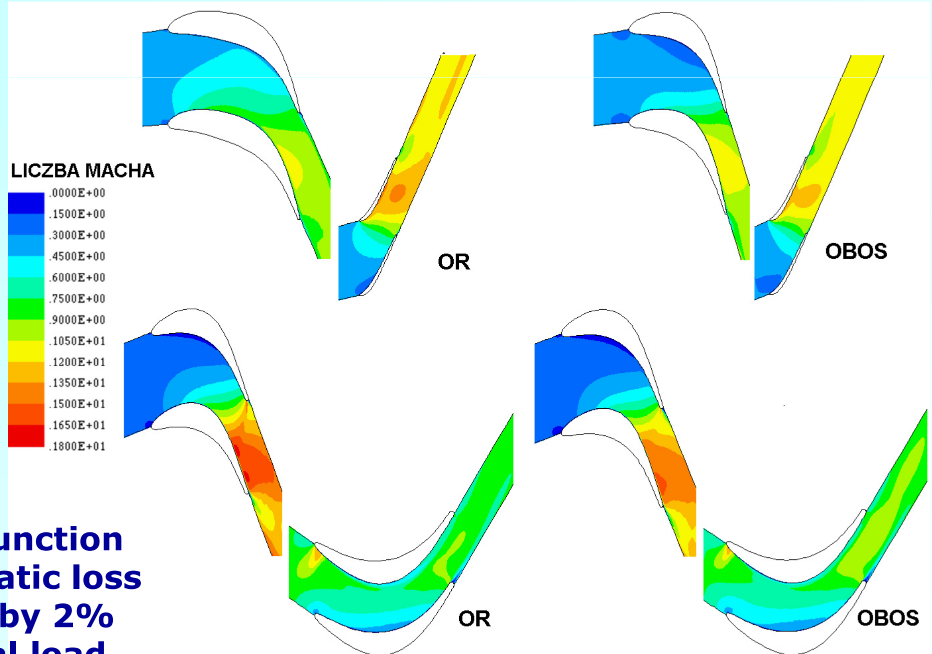
Stator and rotor blade
for LP turbine exit stage (Alstom)

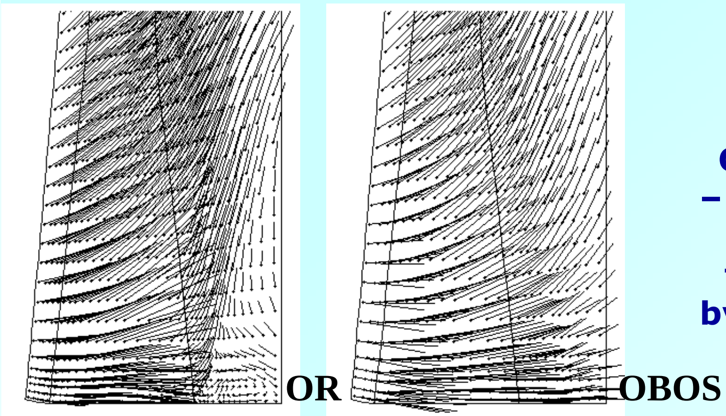
- **LP exit stage - nominal operating conditions:**
  p_{in}/p_{ex}=0.34, G=56.1 kg/s,



Initial and 3D geometry





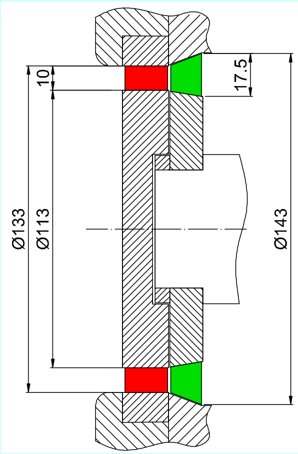


Objective function
– total-to-static loss
decreased by 2%
for niominal load,
by 5.5% for low load

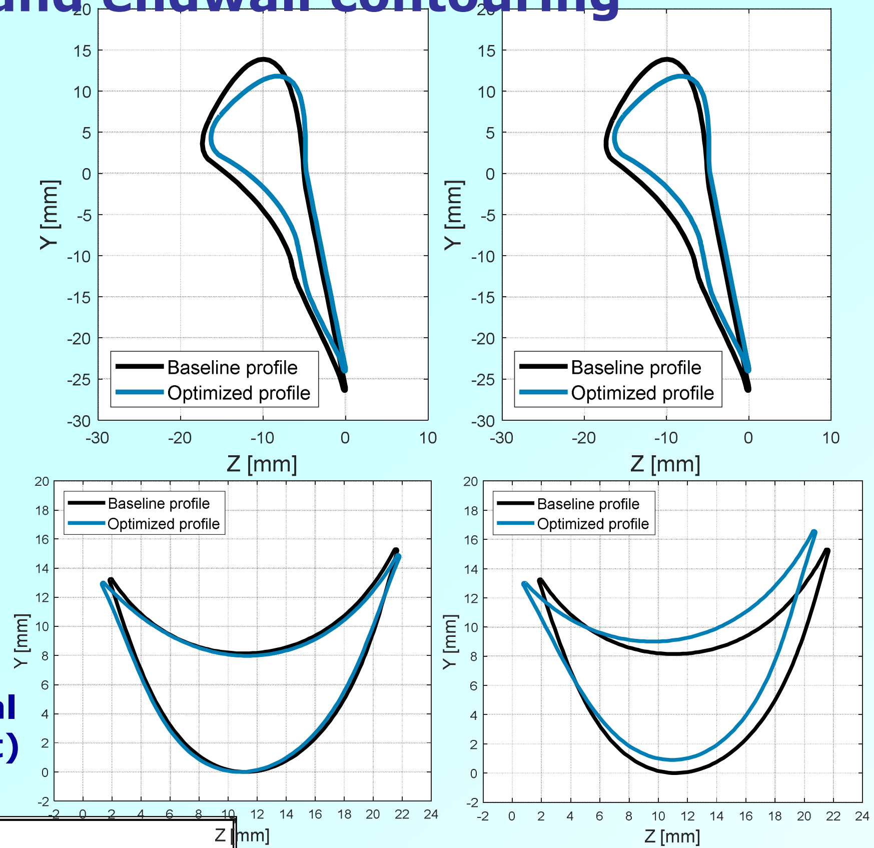
Mach number contours in stator and rotor
at tip and root

ORC turbine optimisation: hub-to-tip profiling, 3D blade stacking and endwall contouring

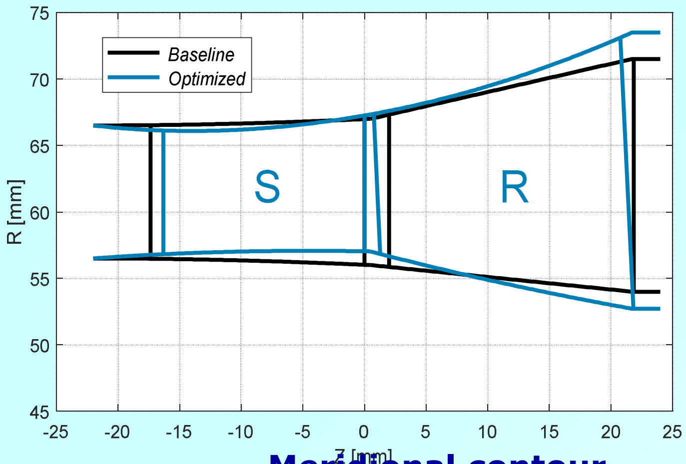
Power - 45 kW ;
Pressure - from 8.45 to 2 bar (MM)
Mach number - 2.3 (stator exit)



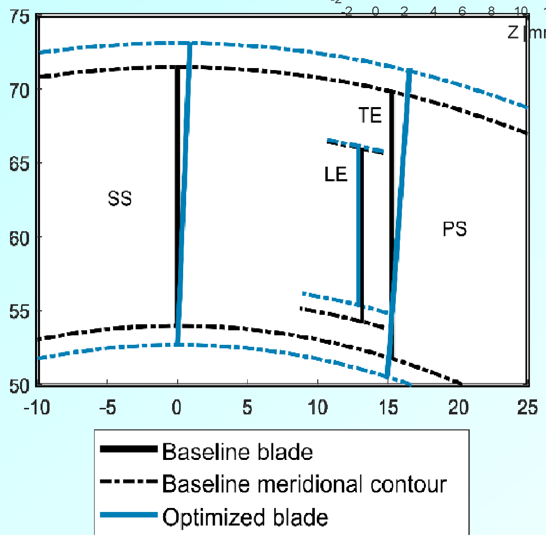
Meridional section of the baseline single-stage axial ORC turbine (left) and 3D model of the rotor (right)



Hub and tip profiles optimisation

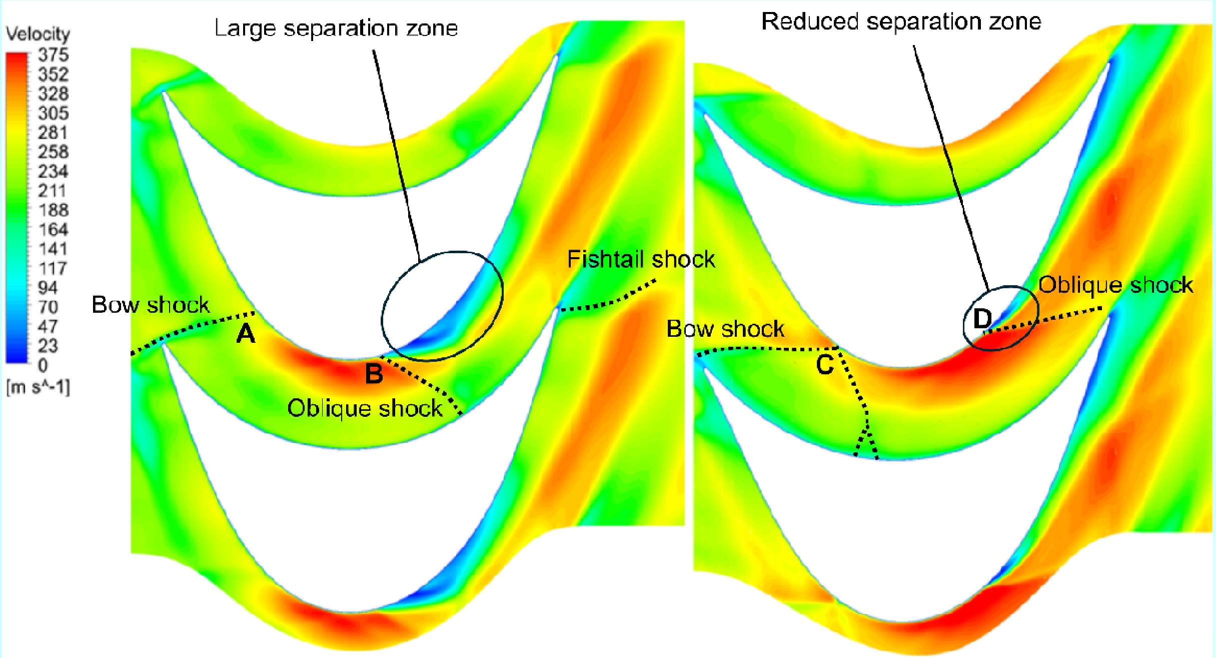


Meridional contour and blade lean optimisation

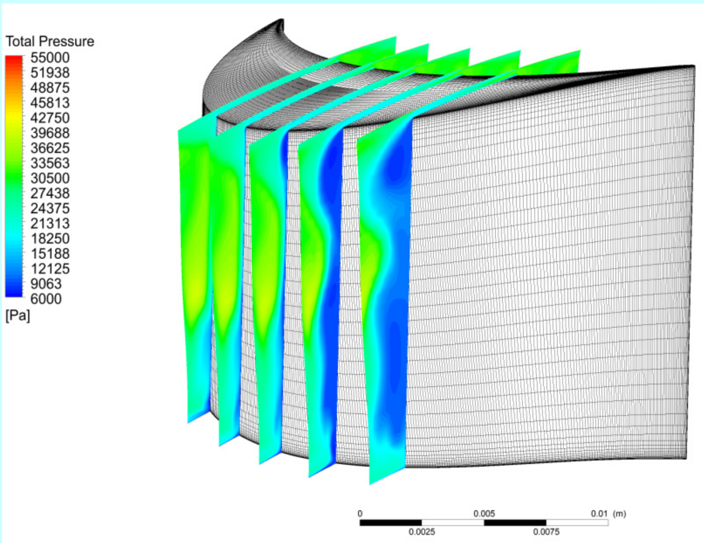


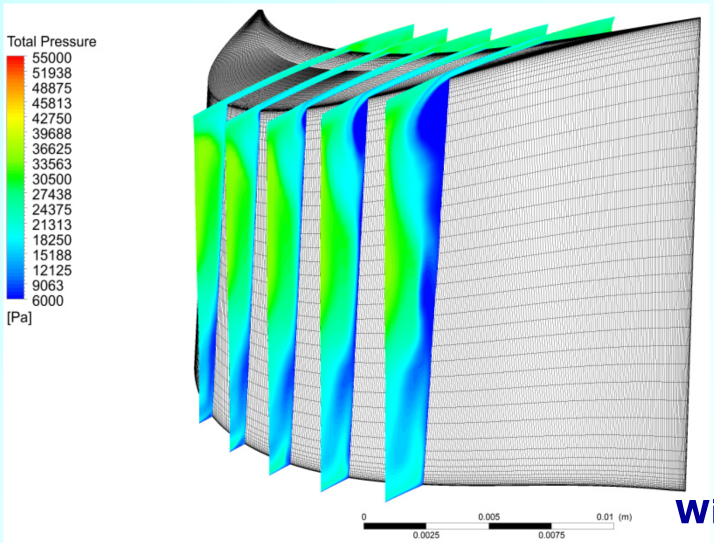
Objective function – total-to-static loss decreased by almost 3%

ORC turbine optimisation: hub-to-tip profiling, 3D blade stacking and endwall contouring



Velocity contours in the rotor at the mid span: baseline design (left), optimized design (right).

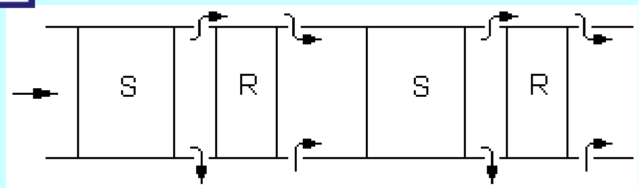




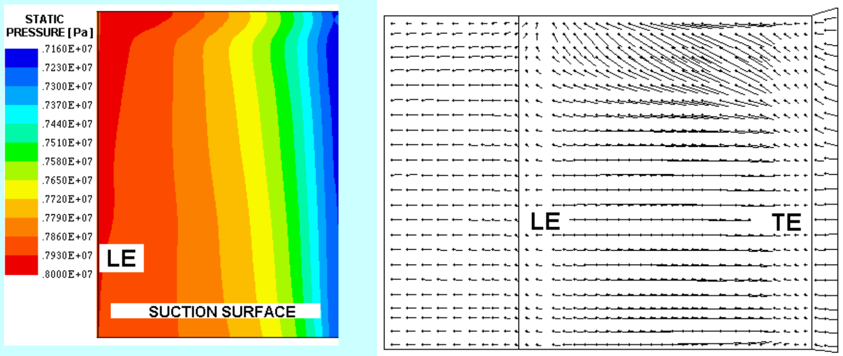
Witanowski et al.

Total pressure contours in the rotor blade passage: before (top) and after (bottom) optimization

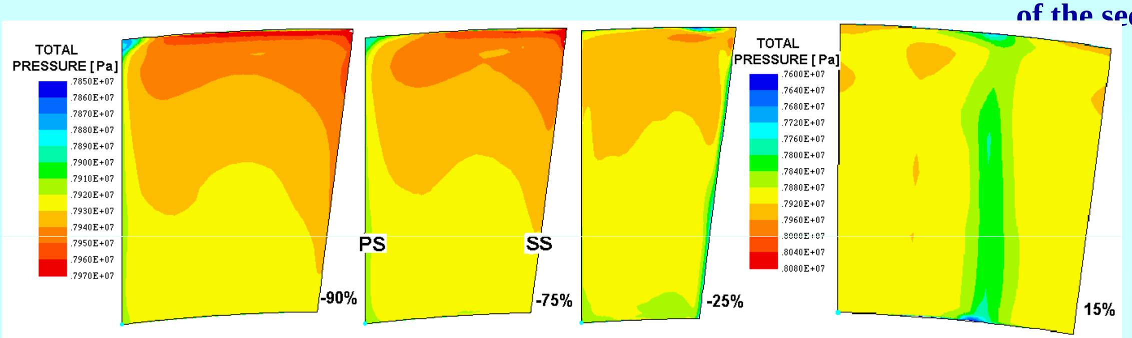
MULTI STAGE EFFECTS OF SHROUD LEAKAGE



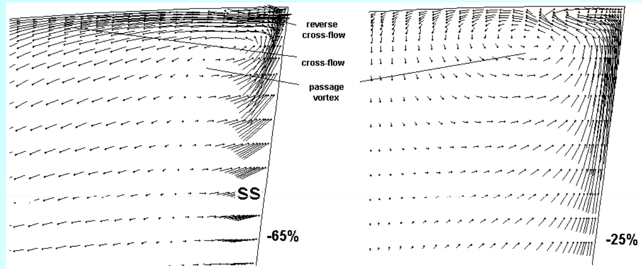
second stator flow (HPT)



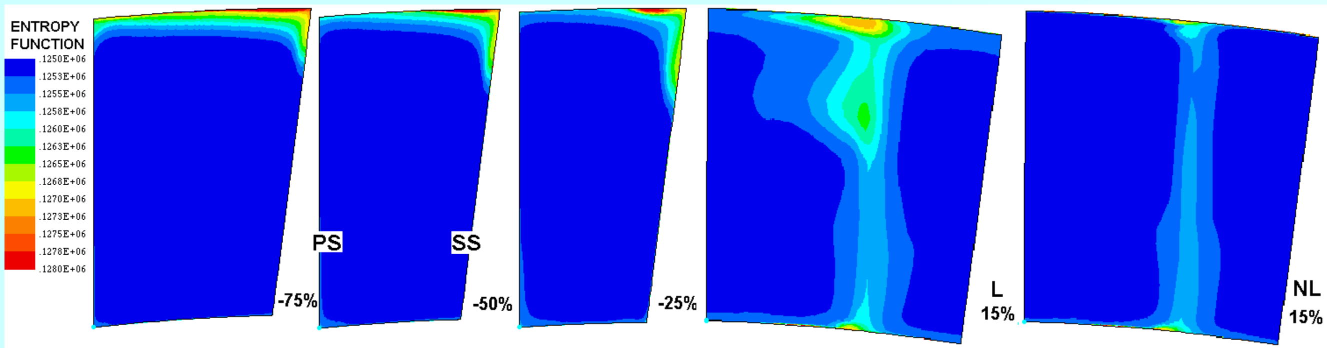
Static pressure contours and velocity vectors at the suction surface of the second stator; LE – leading edge, TE – trailing edge



Total pressure contours in the second stator in subsequent sections located 90%, 75% and 25% axial chord upstream of the trailing edge and 15% axial chord downstream of the trailing edge



Secondary flow vectors in the second stator 35% and 75% axial chord downstream of the leading ed



Entropy function contours in the second stator in subsequent sections located 75%, 50% and 25% axial chord upstream of the trailing edge and 15% axial chord downstream of the trailing edge (L). Also entropy function contours behind the second stator computed without leakage (NL)

HOW TO DECREASE LEAKAGE LOSSES ?

Brush seals – abradable seals

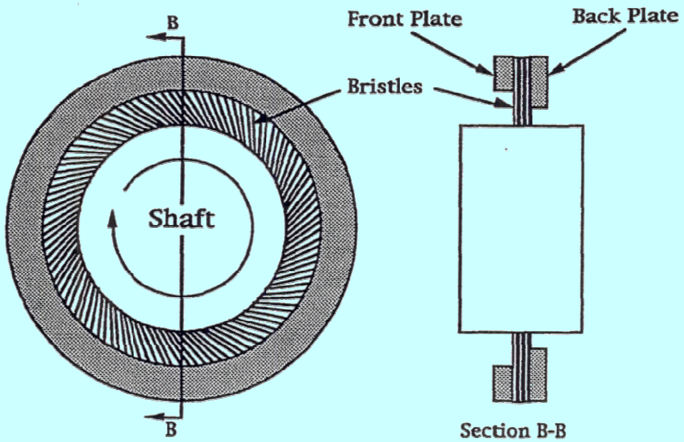
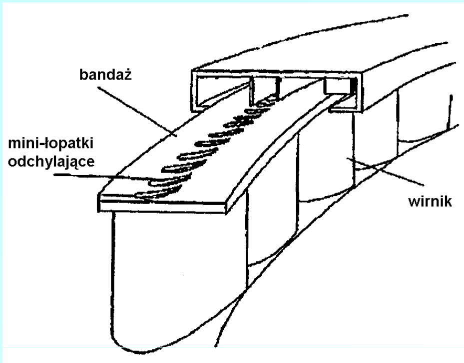


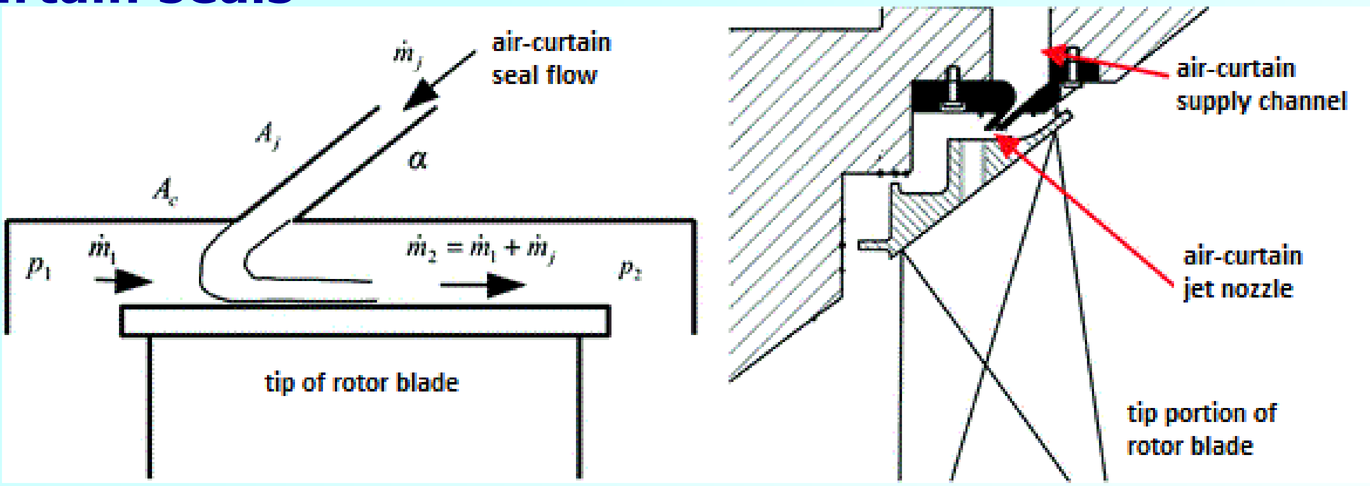
Diagram of a brush seal (Fellenstein, Dellacorte)

Bladelets in shroud / casing



(Wallis, Denton)

Air curtain seals



Schematic diagram of a seal that uses an air curtain (Curtis, Denton, Longley, Rosic)

HOW TO DECREASE LEAKAGE LOSSES ?

Honeycomb seals – reduce flow rate and circumferential velocity

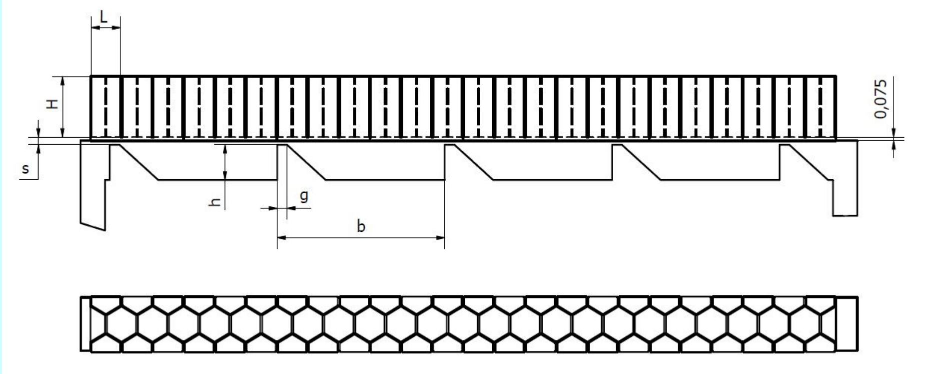
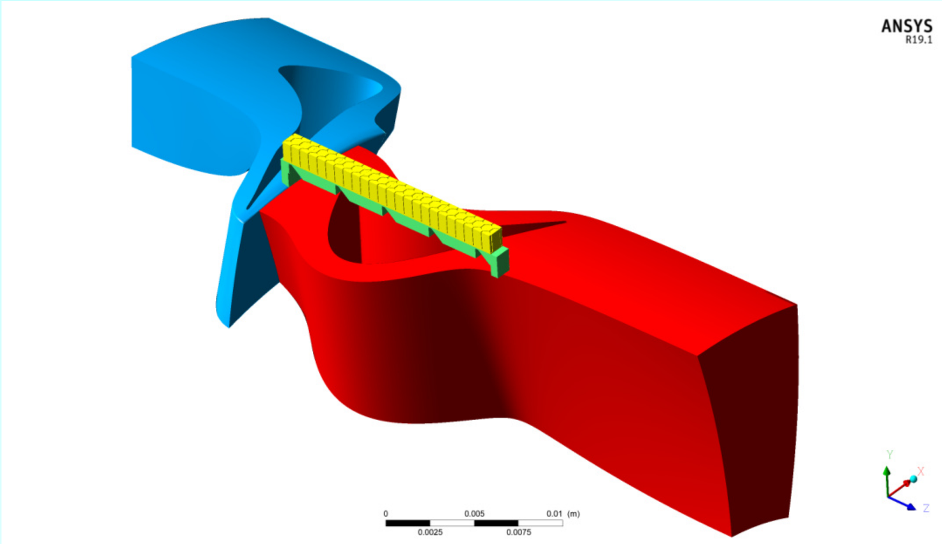
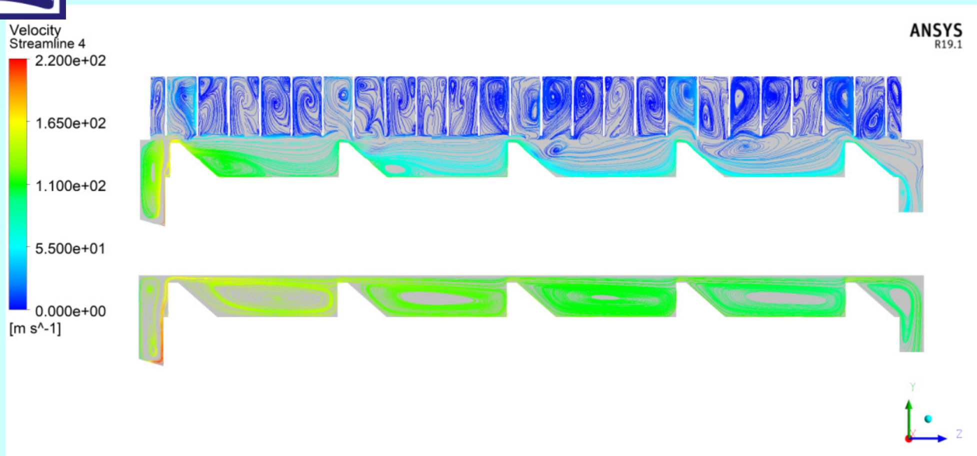


Diagram of labyrinth seal with honeycomb-shaped filling.

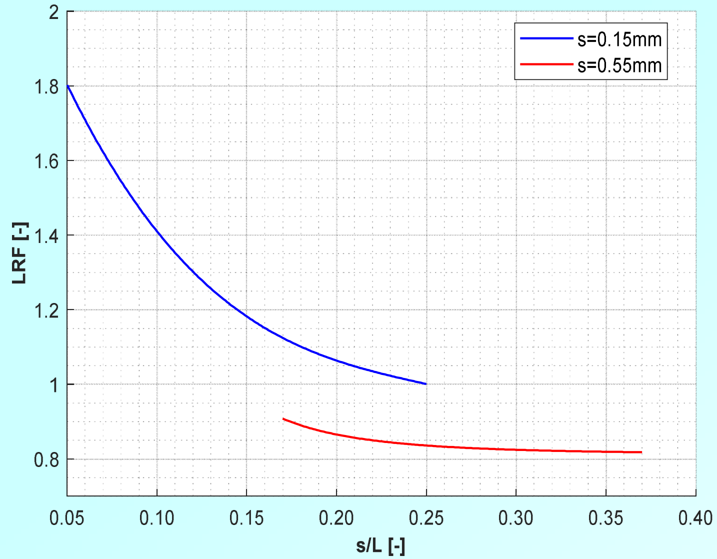


Numerical model of the flow domain in Ansys CFX (10 kW ORC turbine working on HFE7100)

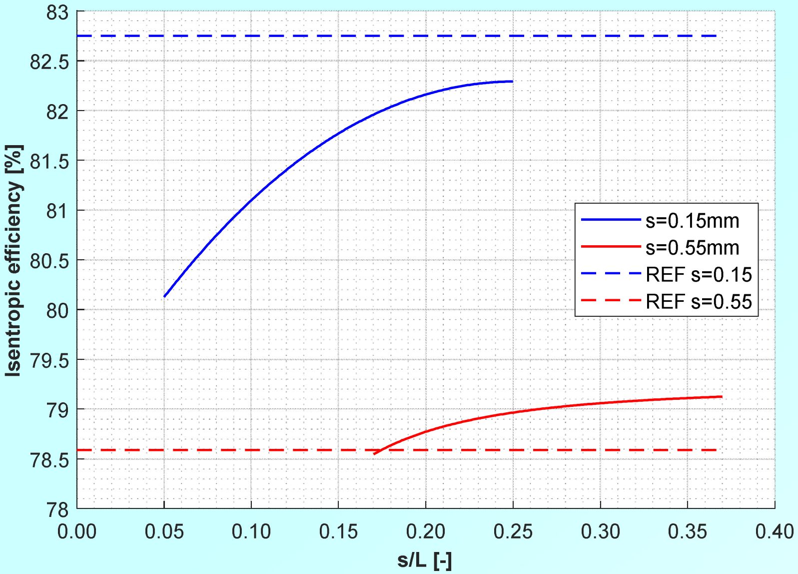
Effect of honeycomb seal



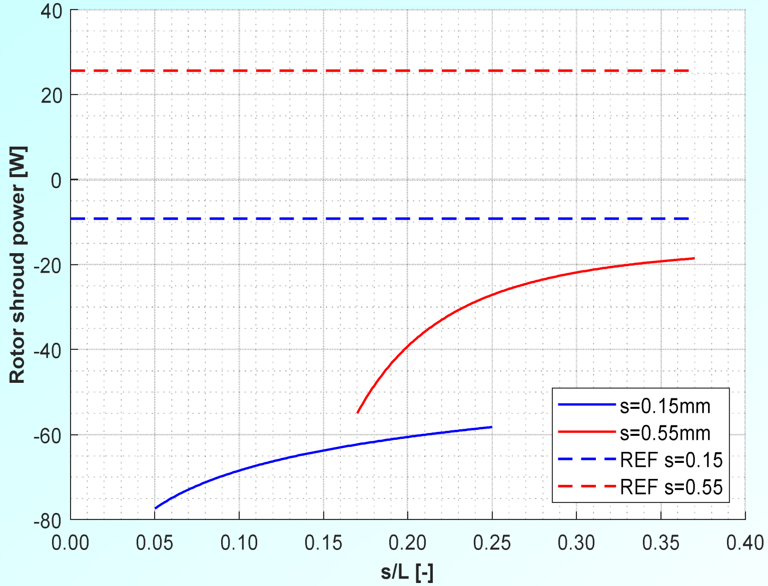
Surface streamlines (coloured by velocity magnitude) in the labyrinth seal domain with honeycomb (top) and without honeycomb (bottom): s=0.15 mm and s/L=0.25.



Leakage reduction factor vs. relative tip clearance



Isentropic efficiency vs. relative tip clearance

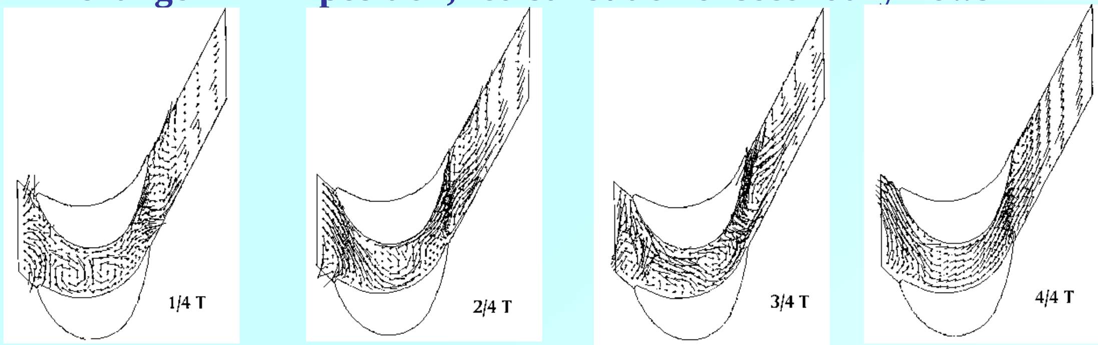


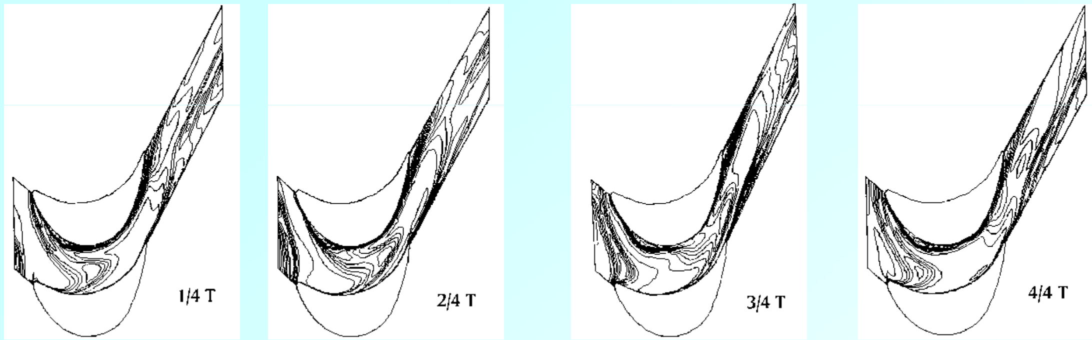
Rotor shroud power vs. relative tip clearance

Zaniewski et al.

Unsteady effects of stator/rotor interaction

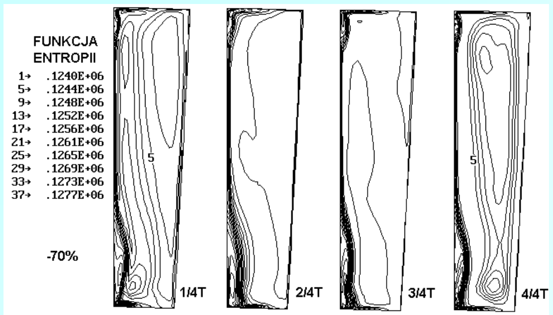
- upstream interaction of the moving blade row,
- downstream transport of 2D and 3D wakes,
- local changes of inlet velocity and angle,
- change in LTT position, redistribution of secondary flows

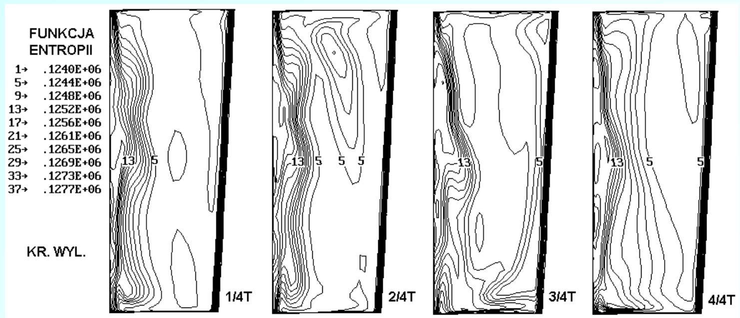




Velocity vectors and entropy function contours at midspan of the rotor

Entropy function contours upstream and downstream of the rotor trailing edge

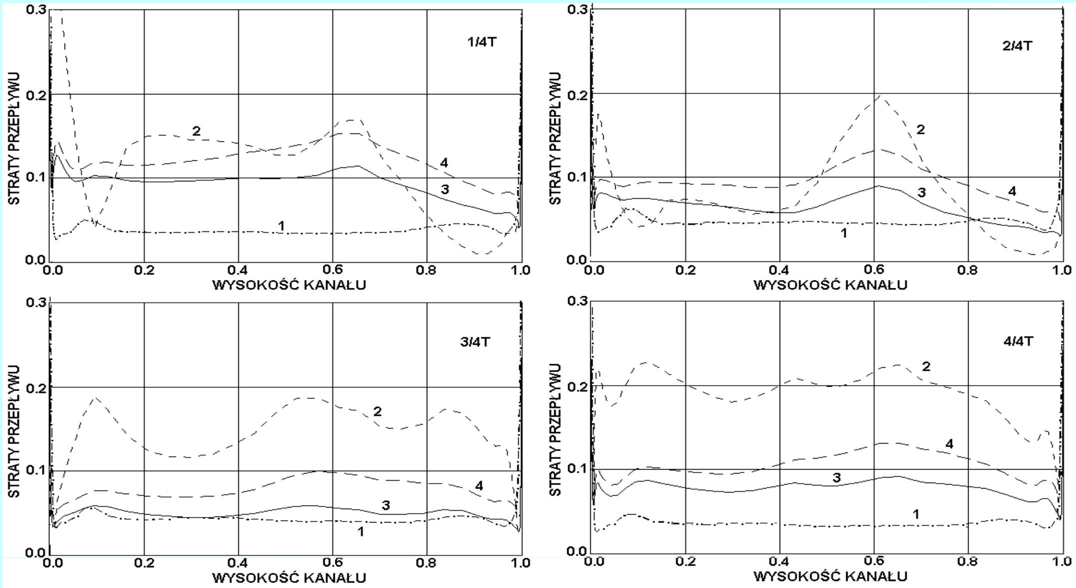


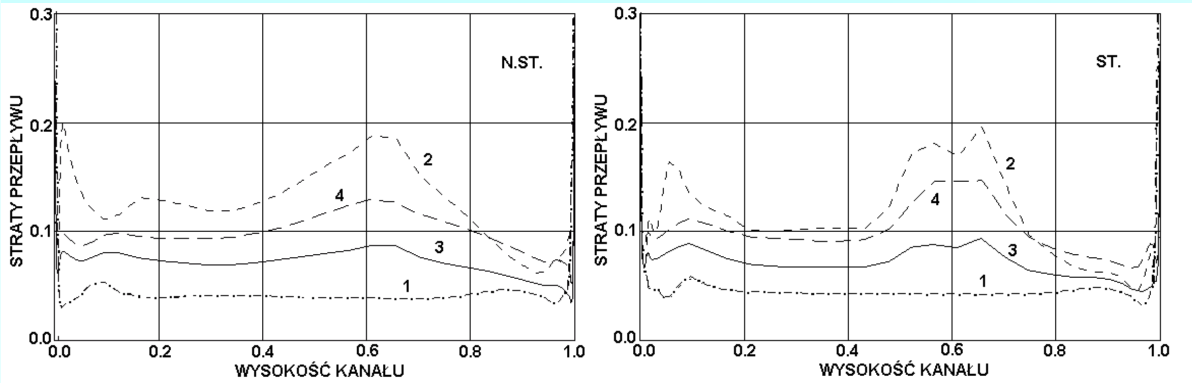


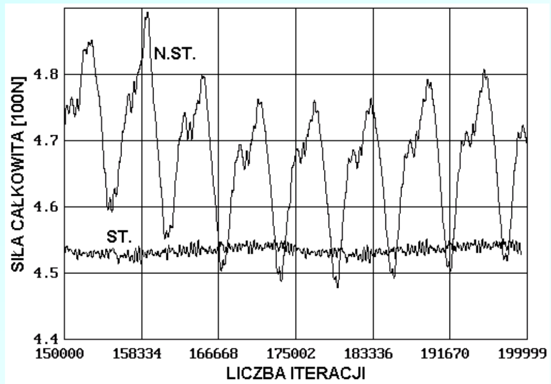
HP turbine stage

Unsteady effects of stator/rotor interaction

Instantaneous enthalpy losses in stator, rotor and stage







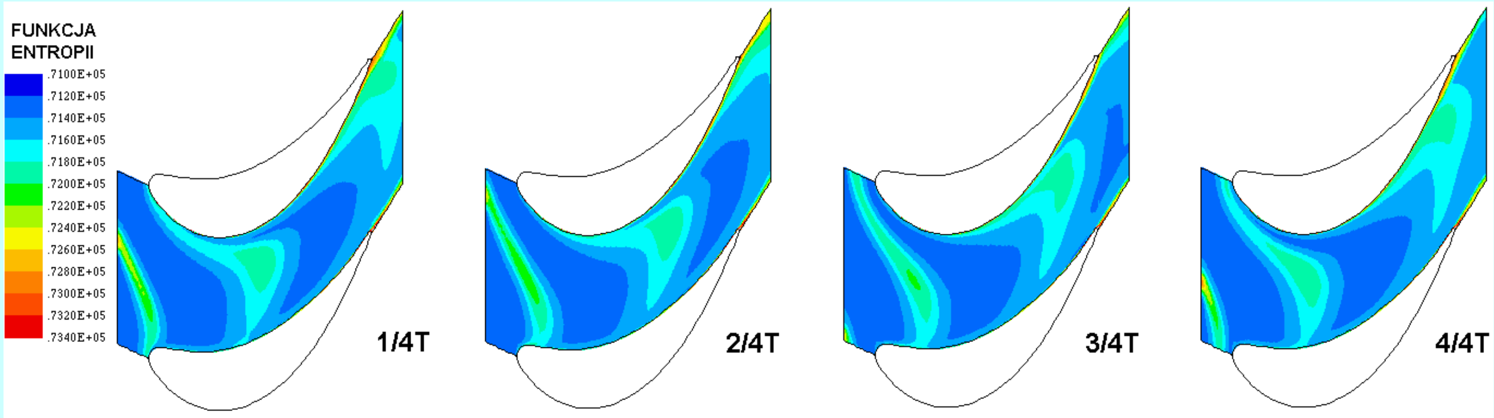
Unsteady averaged and steady-state calculated enthalpy losses in stator, rotor and stage

Unsteady and steady-state calculated force at the rotor blade

HP turbine stage

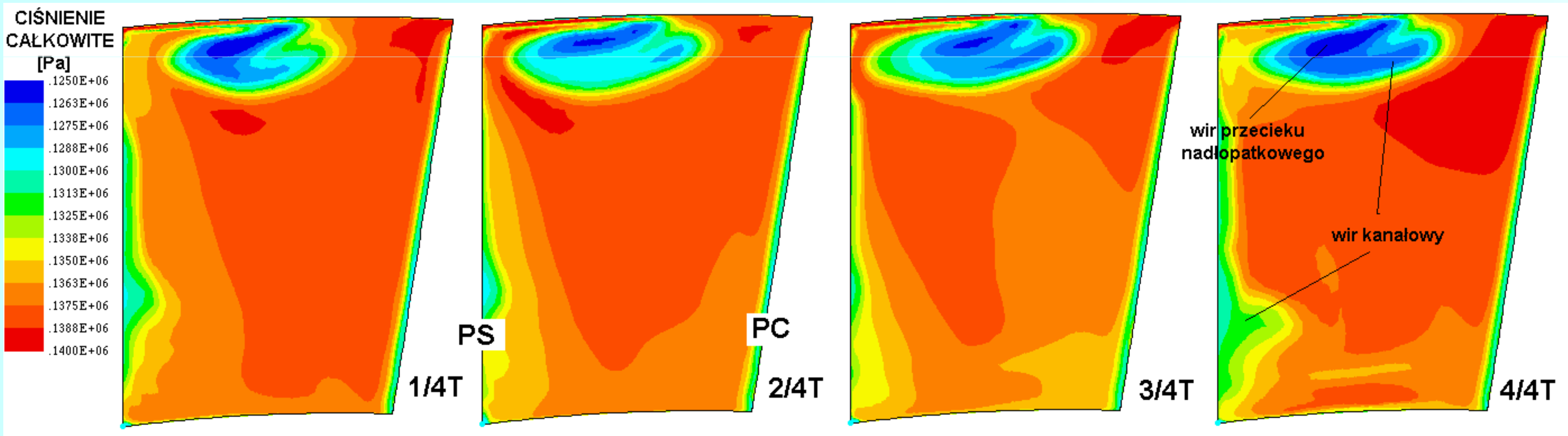
Redistribution of secondary / tip leakage flows due to unsteady effects

R1



Instantaneous entropy function contours in the rotor at the mid-span in unsteady flow

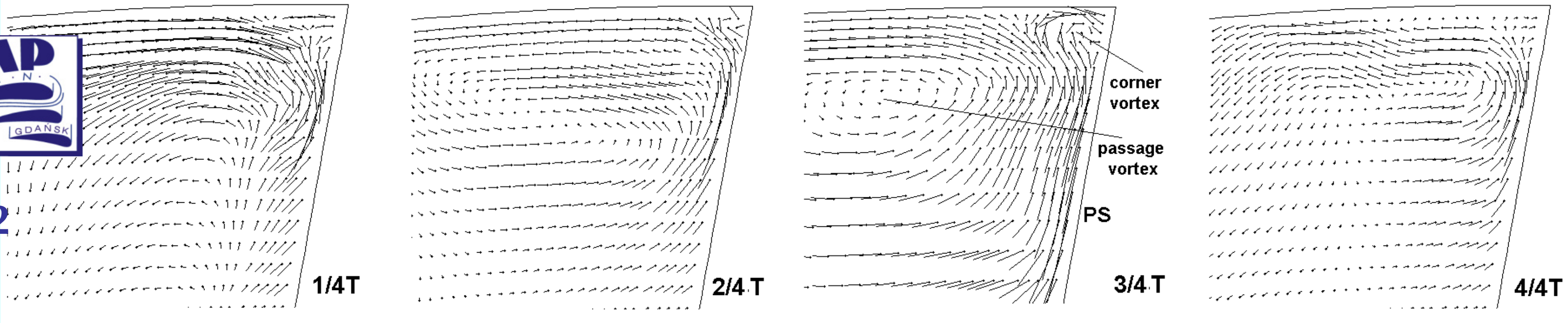
R1



Instantaneous total pressure contours at the rotor trailing edge in unsteady flow

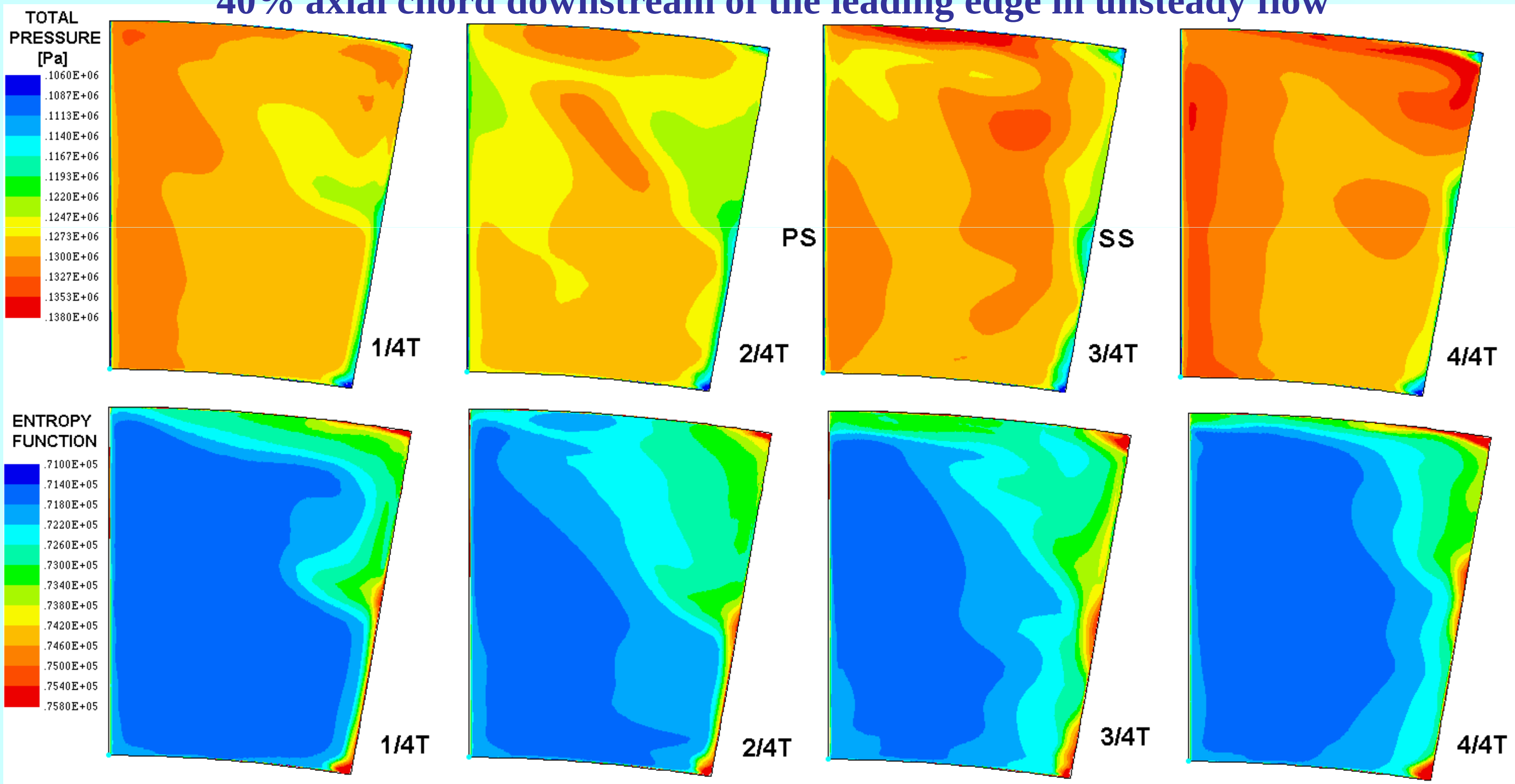
Aachen turbine S1/R1/S2

S2



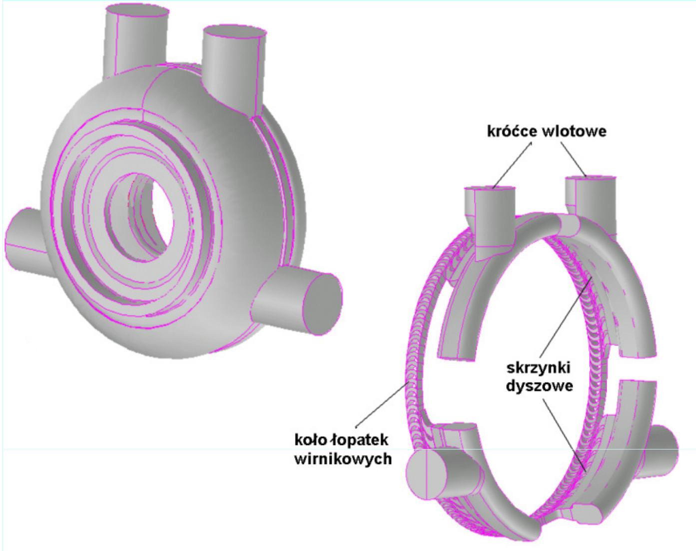
Instantaneous secondary flow vectors in the second stator
40% axial chord downstream of the leading edge in unsteady flow

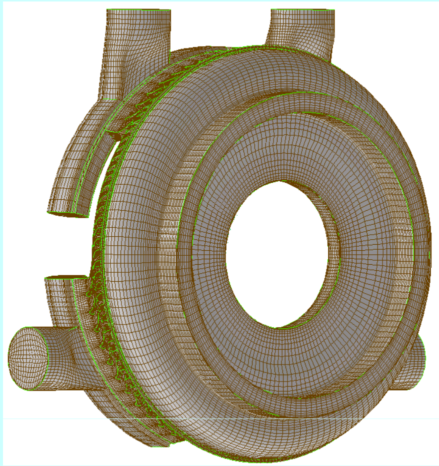
S2

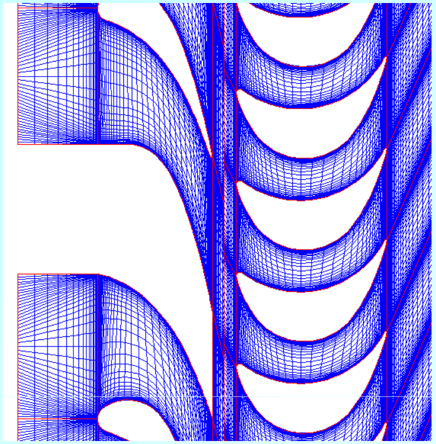


Instantaneous total pressure and entropy function contours
at the second stator trailing edge in unsteady flow

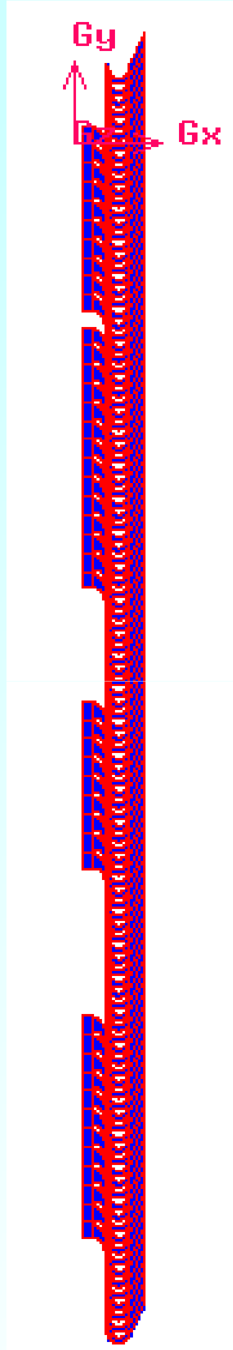
USEFUL CFD RESULTS
PARTIAL ADMISSION TURBINES







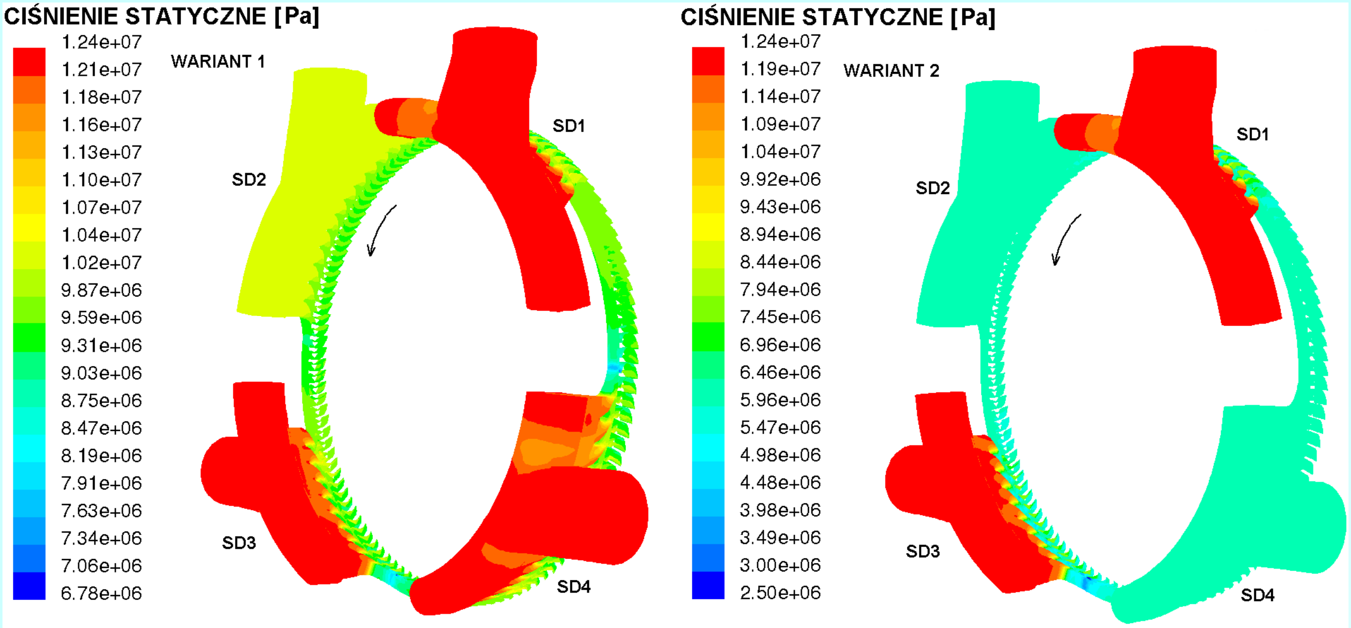
Computational grids



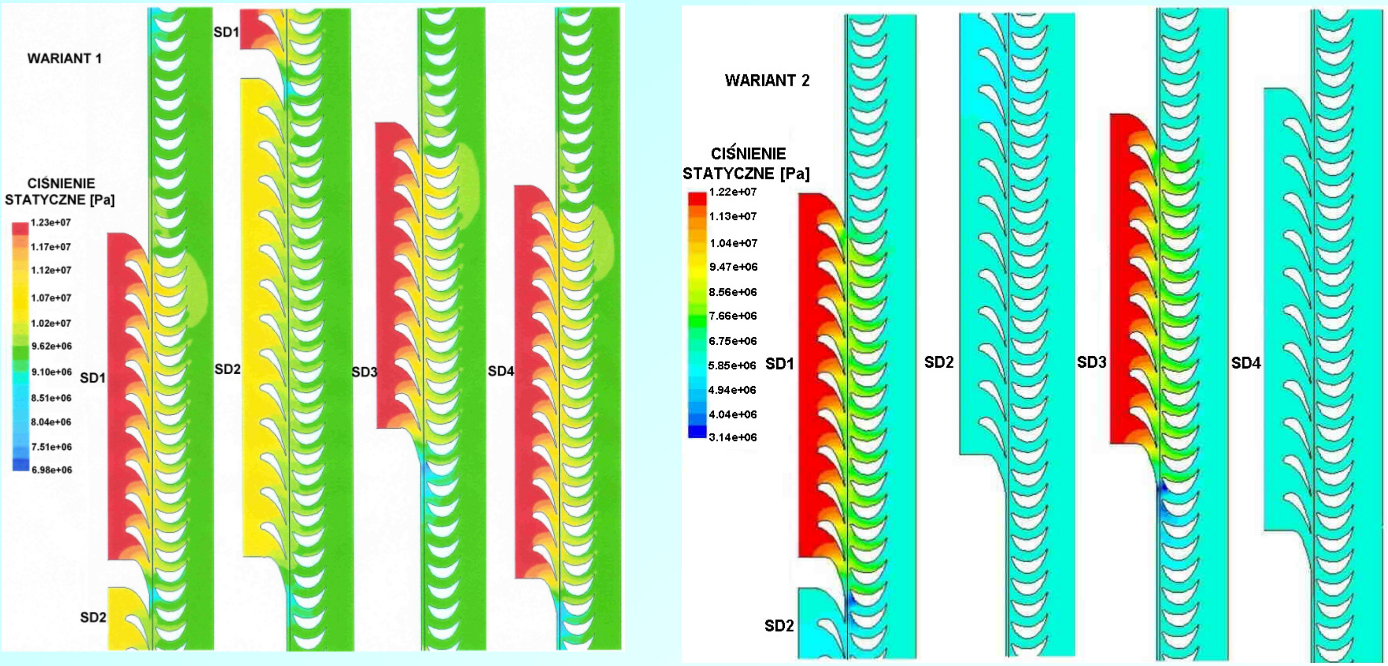
CONTROL STAGE OF A 200MW TURBINE

Variant	Turbine power [MW]	Flow rate [kg/s]	Nozzle box inlet pressure [bar]		Inlet temperature [^oC]	Exit pressure [bar]
1	215	182.0	1	122.0	532.0	95.7
			2	103.1		
			3	122.3		
			4	122.1		
2	140	115.4	1	120.9	532.0	59.8
			2	Closed		
			3	121.5		
			4	60.1		

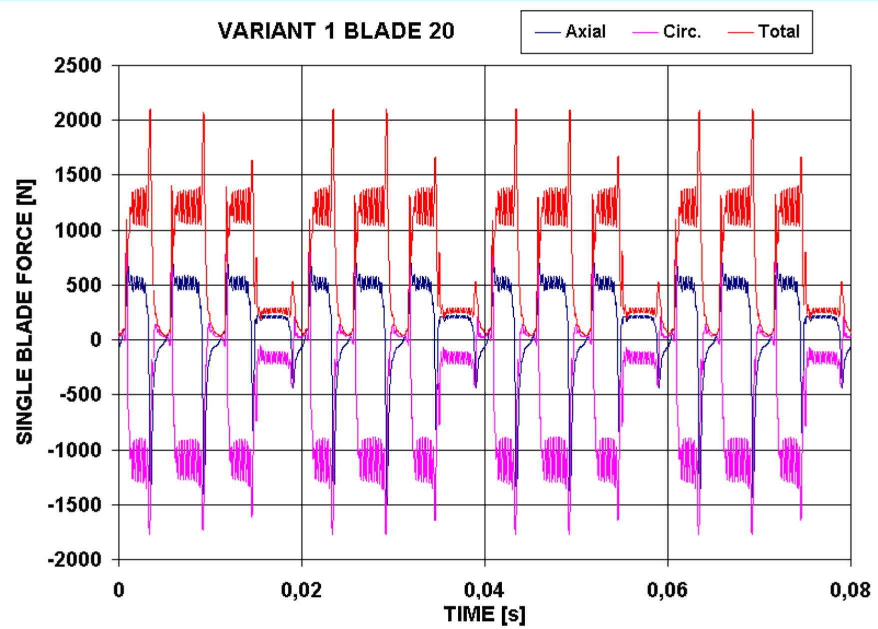
Flowfield

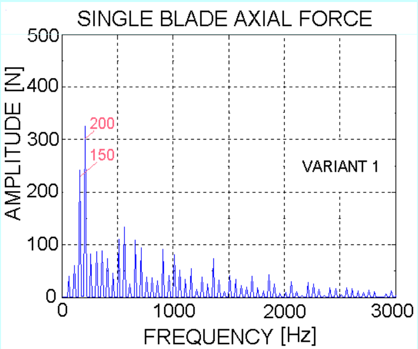


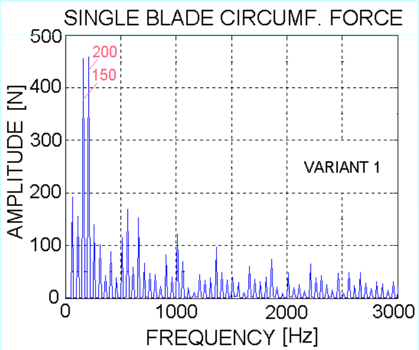
Instantaneous isolines of static pressure in the control stage cascades

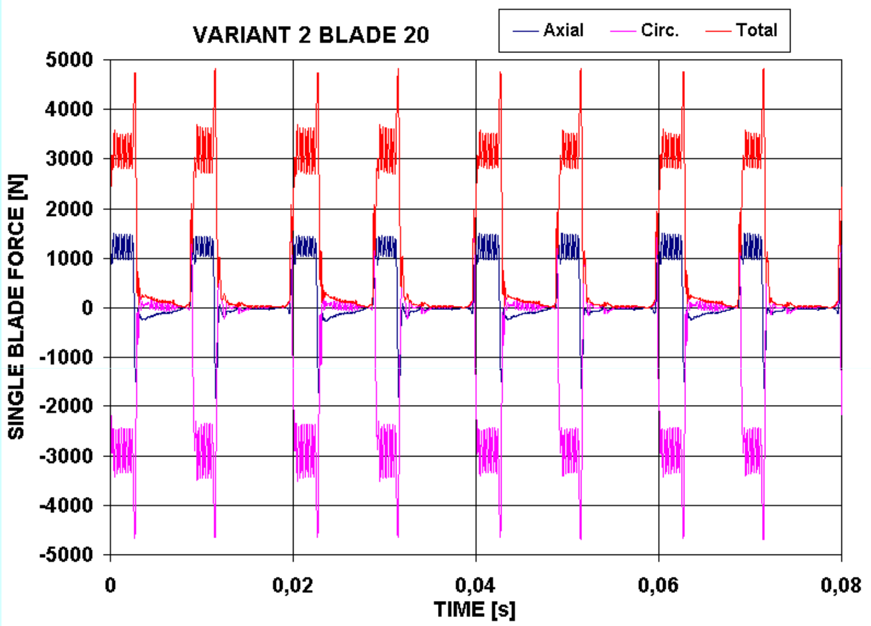


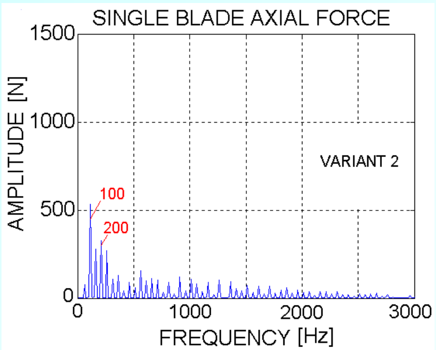
ROTOR BLADE LOAD
(2D mid-span)

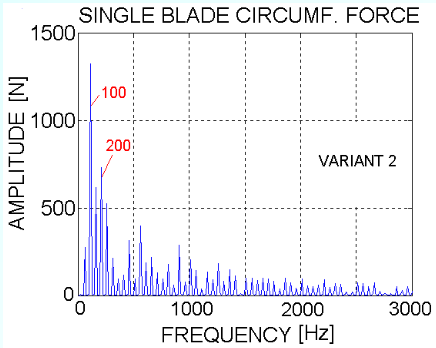








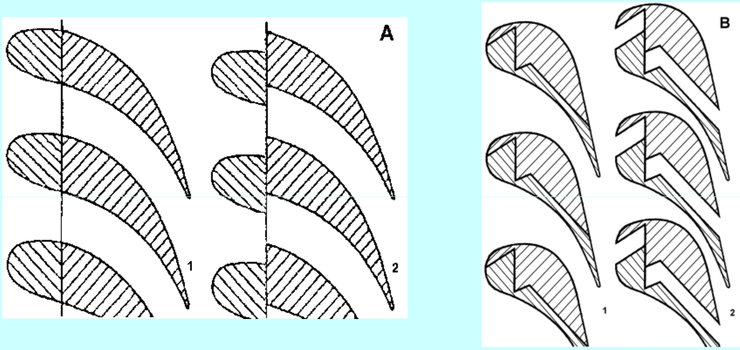




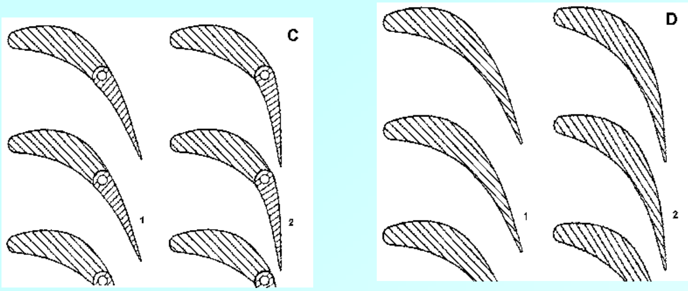
The forces at the rotor blades of the partial admission control stage exhibit an unsteady character. The largest changes in forces are when the rotor blade enters or leaves the arc of admission. Inside the admission region, oscillations of forces are due to the transport of stator wakes through the rotor.

ADAPTIVE STAGE AERODYNAMICS

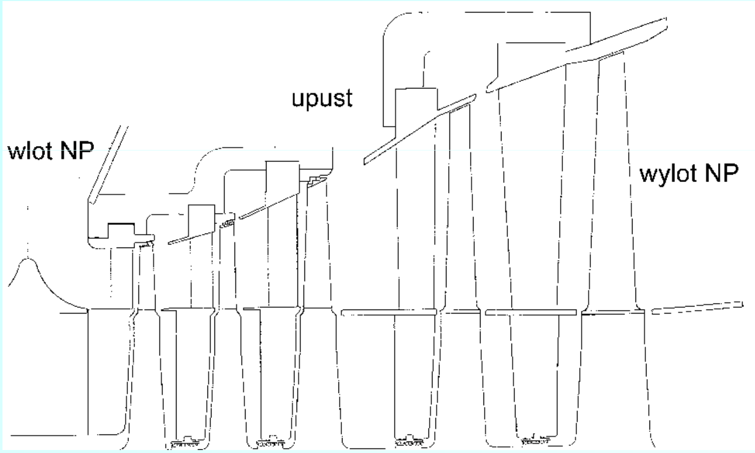
➲ **Cogeneration of electric energy and heat in heat and power turbines requires application of adaptive control to adapt them to variable operating conditions. The main element of adaptive control is the so-called adaptive stage of flexible geometry located directly downstream of the extraction point.**



Throttling nozzles (LMZ, ABB-Zamech, Alstom)

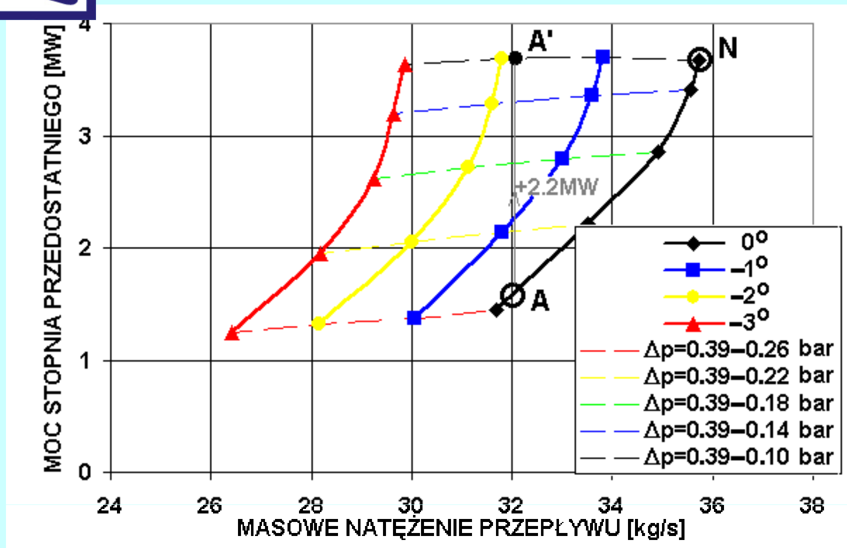


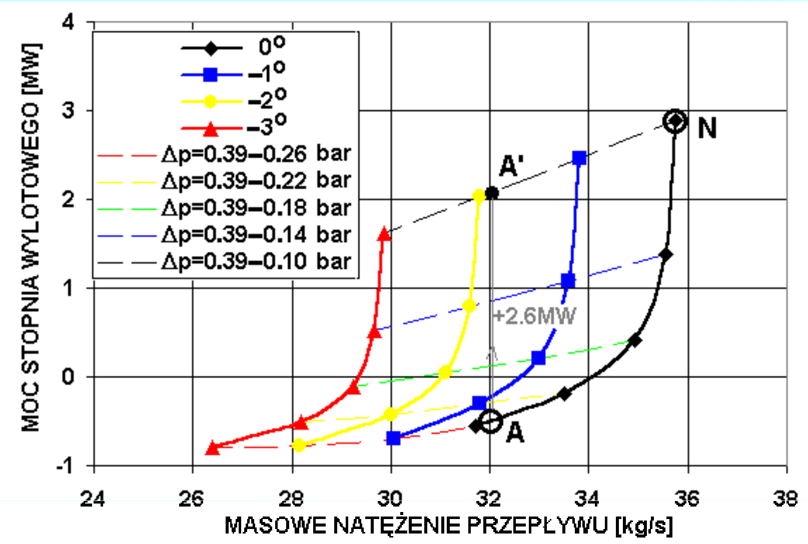
Flap nozzles (Puzyrewski)

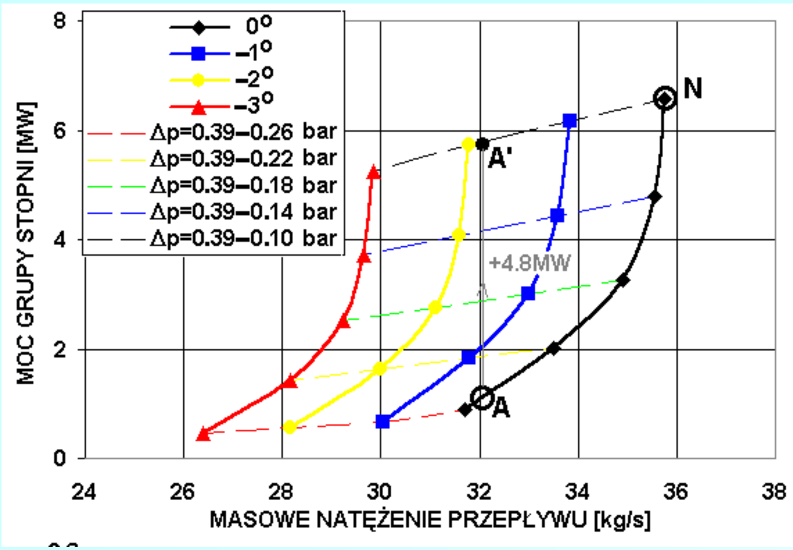


Extraction condensing turbine of power 50MW

ADAPTIVE STAGE AERODYNAMICS







N – nominal operating point
A – steam extraction
A' – steam extraction with adaptivwe control

Change of power of stage L and L-1 for given setting of adaptive nozzles as a function of massflow rate

Summary – ways to reduce turbine flow losses and raise turbine efficiency

1. **Hub-to-tip profiling and 3D blade stacking to reduce span-wise gradient of reaction (especially in LP turbines). These should reduce profile losses, including boundary layer losses, separation losses, supersonic flow losses;**

2. **Improved wet steam designs for LP turbines;**

3. **3d blade stacking, endwall contouring, non-symmetric endwall contours. These should reduce endwall / secondary flow losses in LP/IP turbines;**

4. **Labyrinths with honeycomb seals (possibly abradable) and air curtains. These should reduce leakage and mixing losses;**

5. **Improved control stage and adaptive stage solutions for cogeneration turbines.**

6. **Numerical optimisation of increased number of geometric parameters with improved optimisation methods and improved CFD models.**