Aerothermal Engineering

C204 Turbomachinery

Budimir Rosic

budimir.rosic@eng.ox.ac.uk

Lecture 4

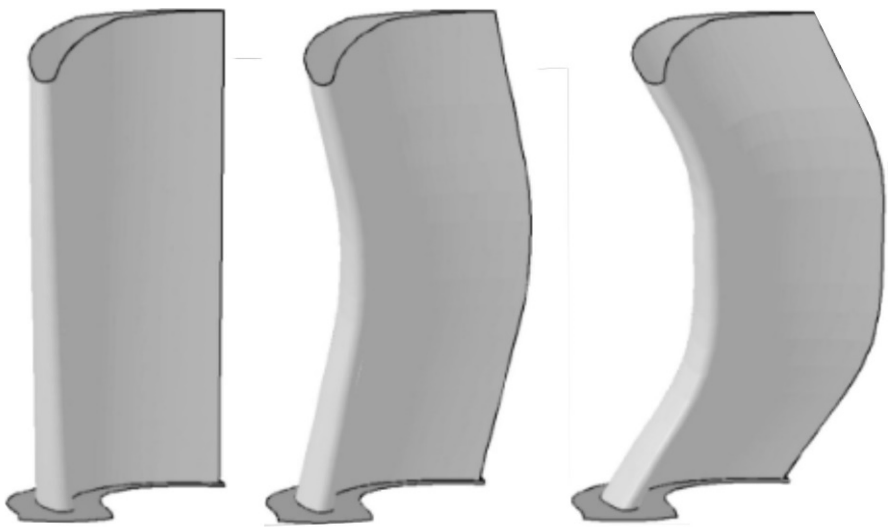
1) Three-dimensional flow structures:

- Secondary flows
- Leakage flows for unshrouded and shrouded blading

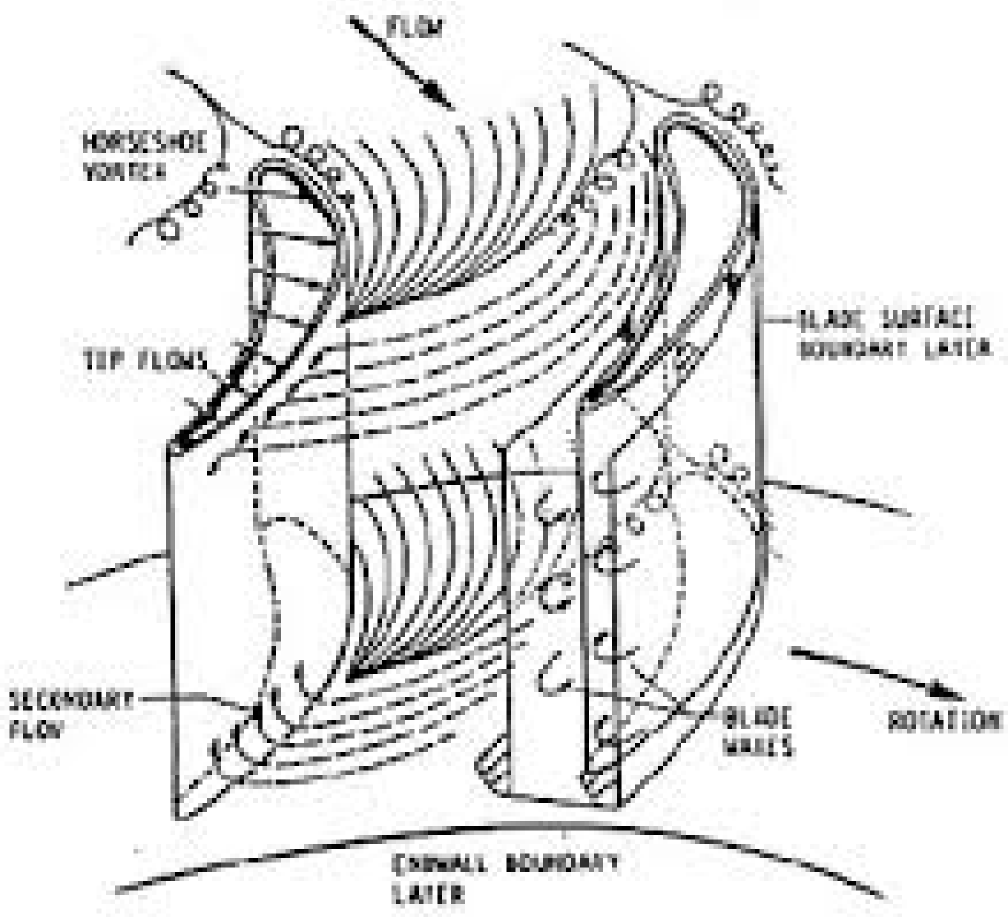
2) Three-dimensional blade design:

- Blade lean
- Blade sweep

3) Secondary air system and cooling flows.



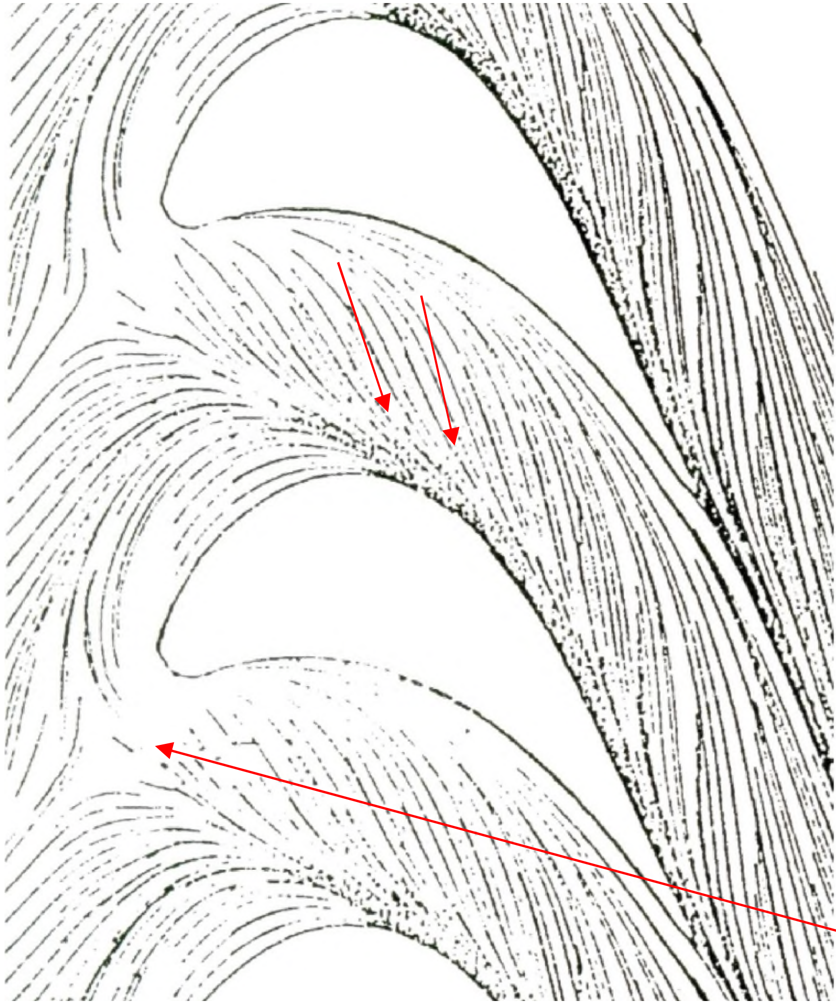
Example of compound lean applied on a turbine blade



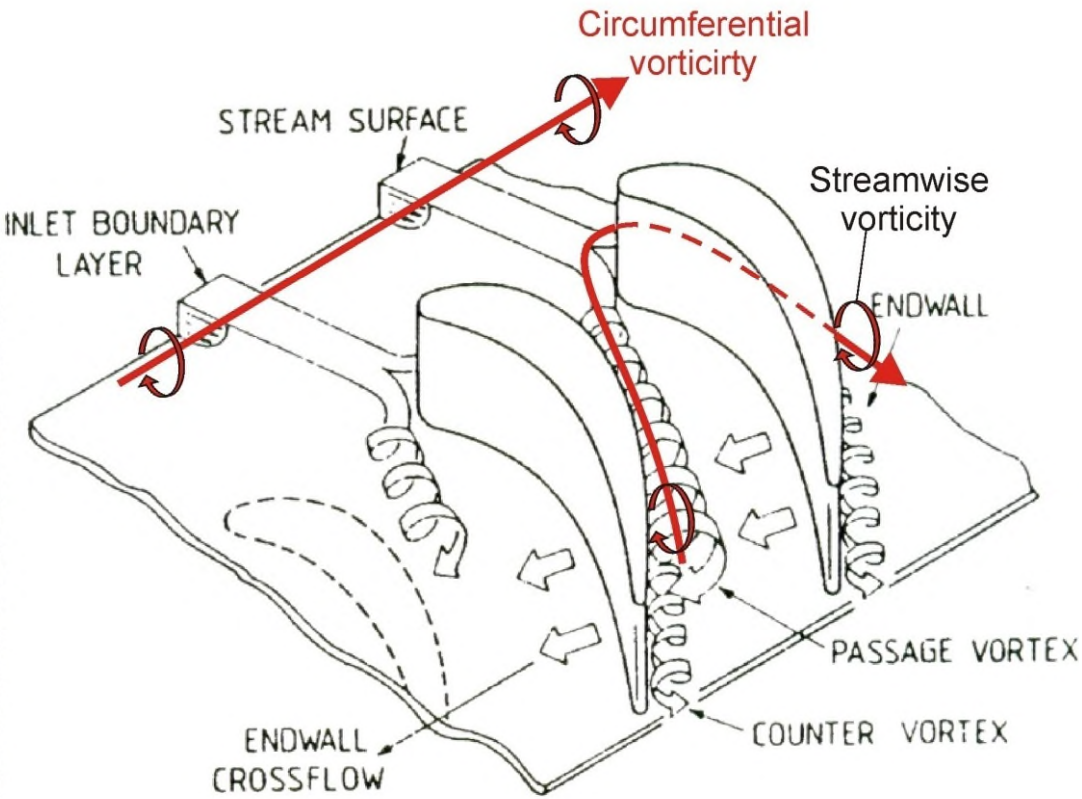
Secondary flows

Secondary flows arise when a fluid flow has a vorticity component in the direction of the streamlines (streamwise vorticity). This happens when the streamlines in a boundary layer are forced to curve (usually under the action of imposed pressure field) so that the boundary layer vorticity vector is rotated to have a component in the flow direction. It both turbines and compressors this occurs when the inlet boundary layer on both endwalls (hub and casing) is turned by the blades.

The inlet boundary layer is forced by the leading edge pressure field to roll up into a 'horseshoe vortex'. The vortex forms two legs and wrap around the leading edge and enters the blade passage.

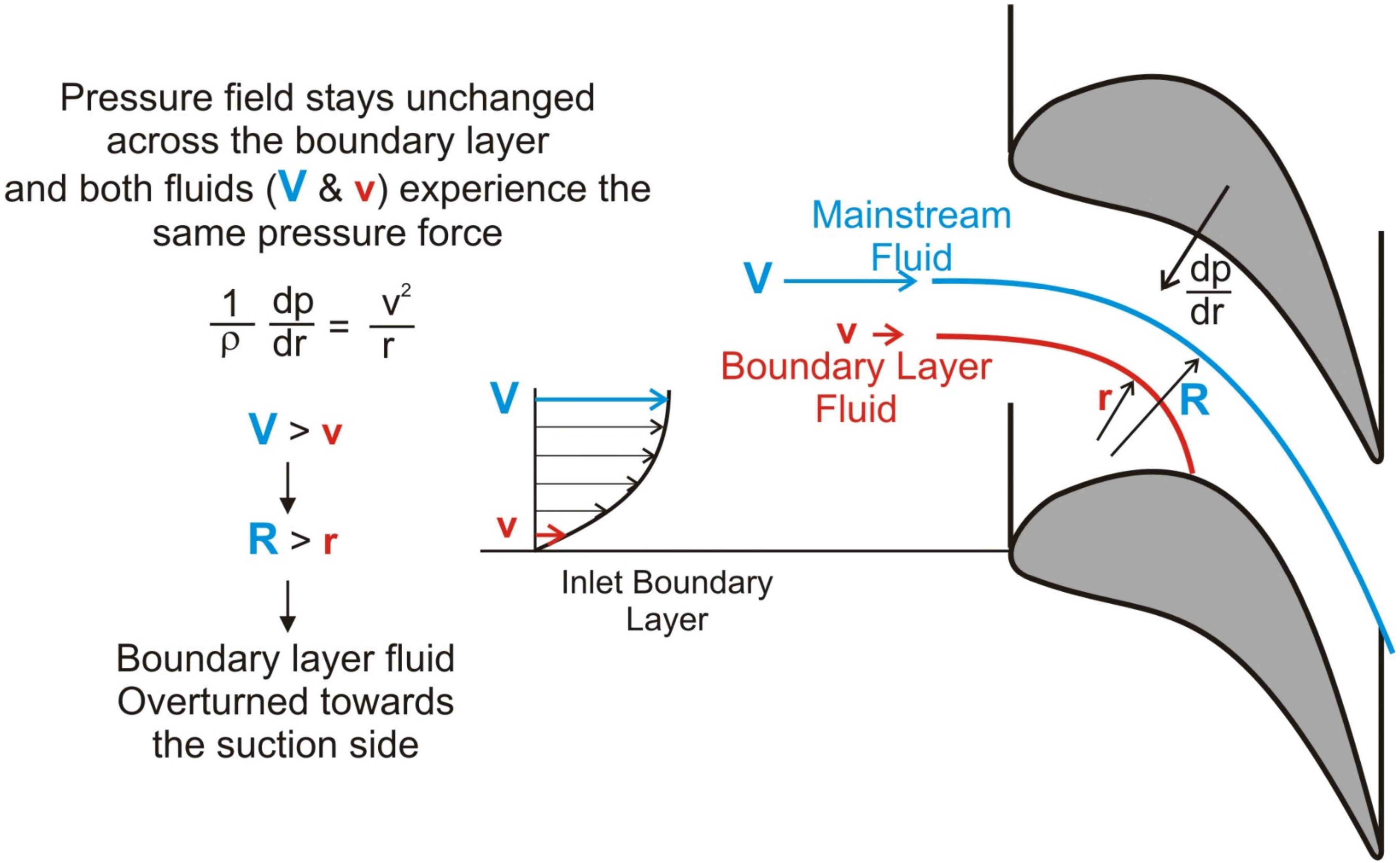


Endwall streamlines in a turbine blade passage

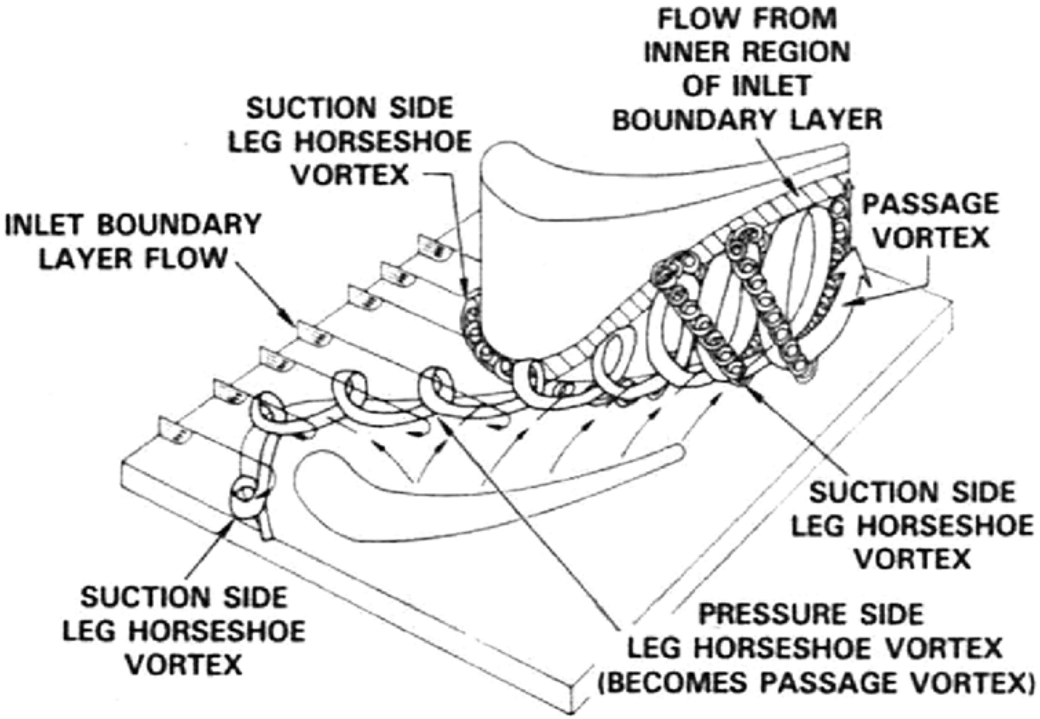


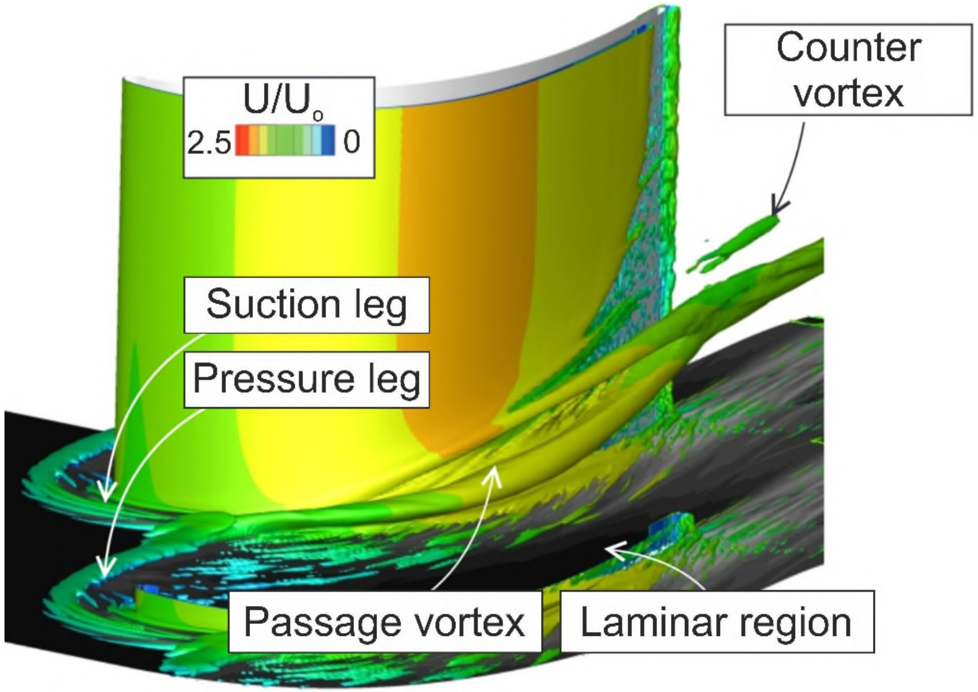
'Saddle point' where the inlet endwall boundary layer rolls up into the horseshoe vortex

The mainstream flow establishes a pressure field as a combination of blade loading and any swirling flow. The pressure does not change through a boundary layer. Therefore, the pressure gradient acting on the boundary layer is almost the same as that acting on the primary (mainstream) flow. The boundary layer fluid is unable to support the imposed pressure field and turns more rapidly with a smaller radius of curvature than that in the mainstream.



The suction leg of the horseshoe vortex soon moves onto the suction surface (forming a weak counter rotating vortex). The pressure leg of the horseshoe vortex is driven by the cross-passage pressure field towards the suction side of the adjacent blade. As it moves across the passage it grows by sweeping up the inlet boundary layer fluid on the endwall forming the passage vortex. On arrival at the blade suction surface the low momentum fluid migrates up the blade span.





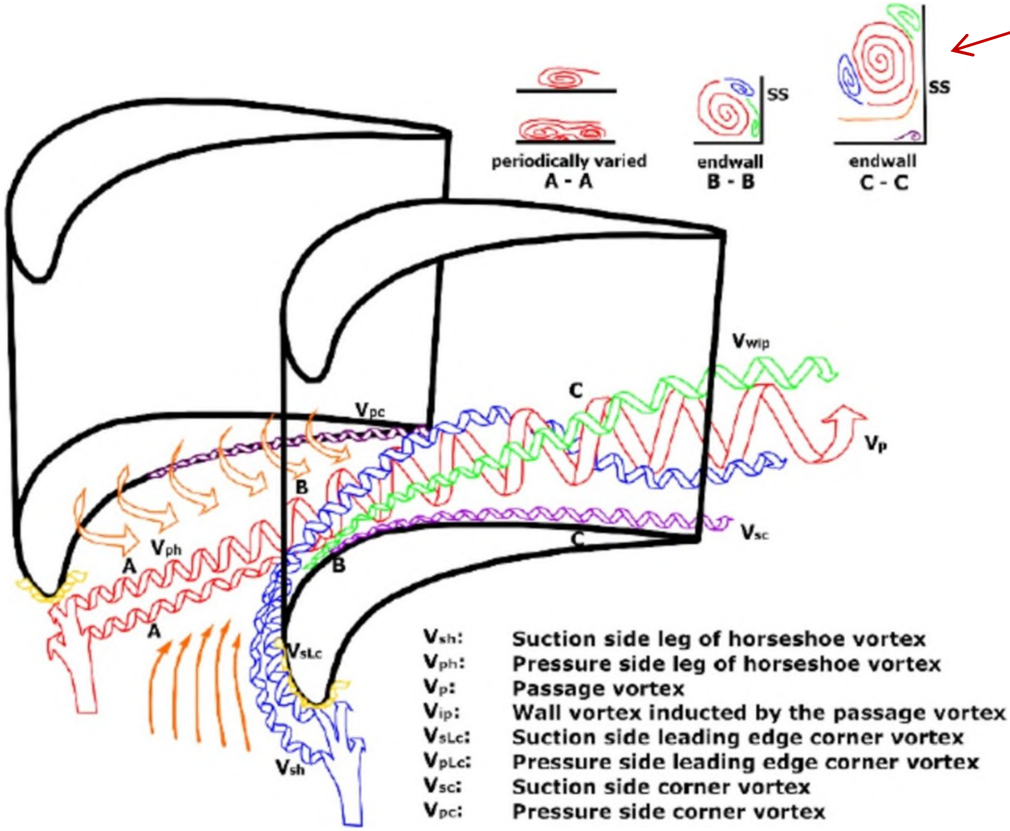
Cui, GT2013-94416

Secondary flows are present in both turbines and compressors, but is stronger in turbines because of the larger turning of the blades (higher pressure gradient). The whole process of secondary flow formation causes a considerable increase in loss (called secondary loss). This is usually about 1/3 of the total loss in a turbine.

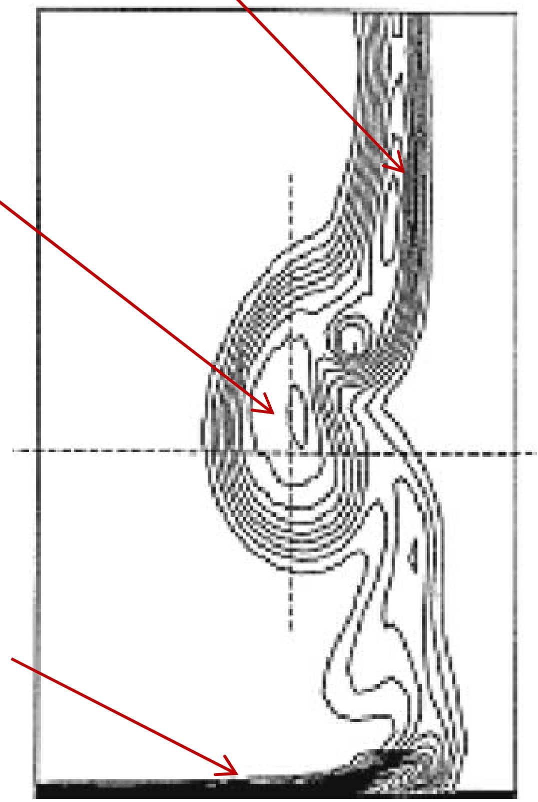
In turbines the cross passage flow is so strong that the centre of the passage vortex (loss core) ends up on the suction side away from the endwall. This has and effect on the spanwise loss distribution, and flow deviation.

It is believed that the strength of secondary flows could be reduced by delaying turning inside the passage as much as possible (aft-loaded profile).

Total pressure loss core downstream of TE

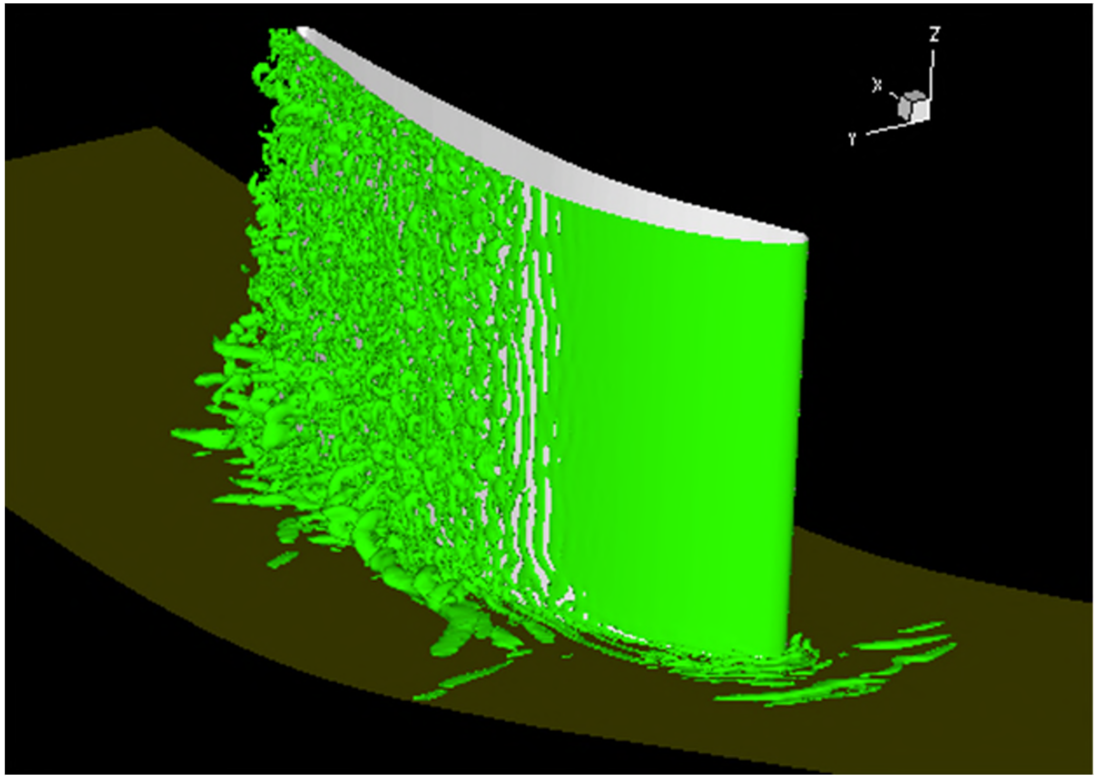


Blade wake

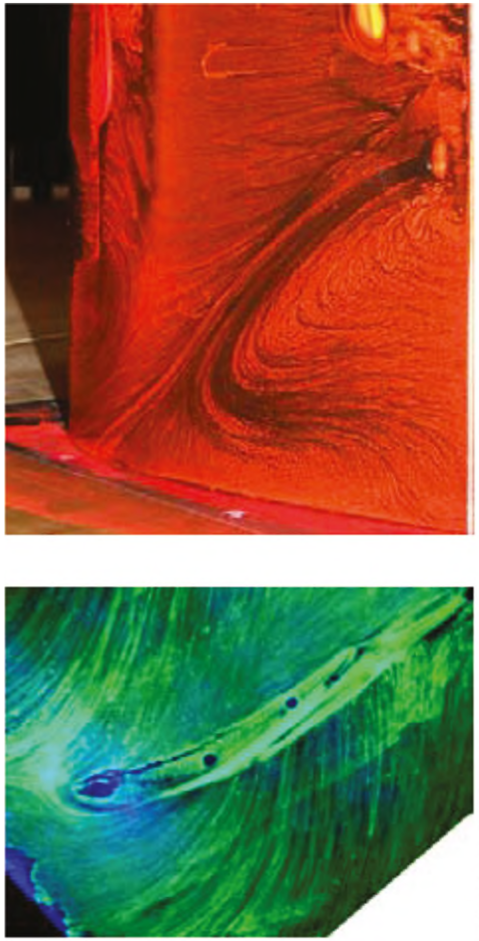


Newly developed endwall boundary layer

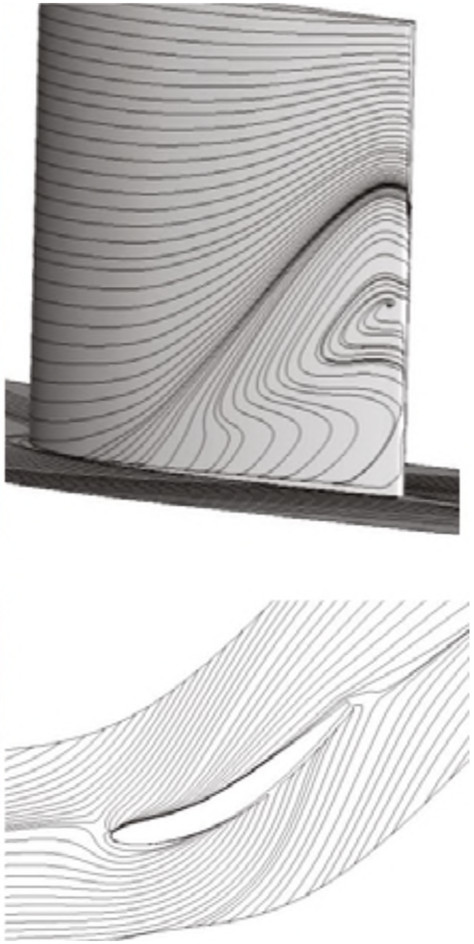
In compressors blade turning is less so secondary flows are not so strong, but the endwall boundary layers are thicker and more fluid is involved in the secondary flows.
Due to adverse pressure gradient on the suction side the low momentum fluid often separates. This ‘corner separation’ grows rapidly causing a significant blockage and loss at the exit of the blade.



Numerical simulation of the flow in a compressor linear cascade
(Visualisation of turbulent structures in the blade passage)



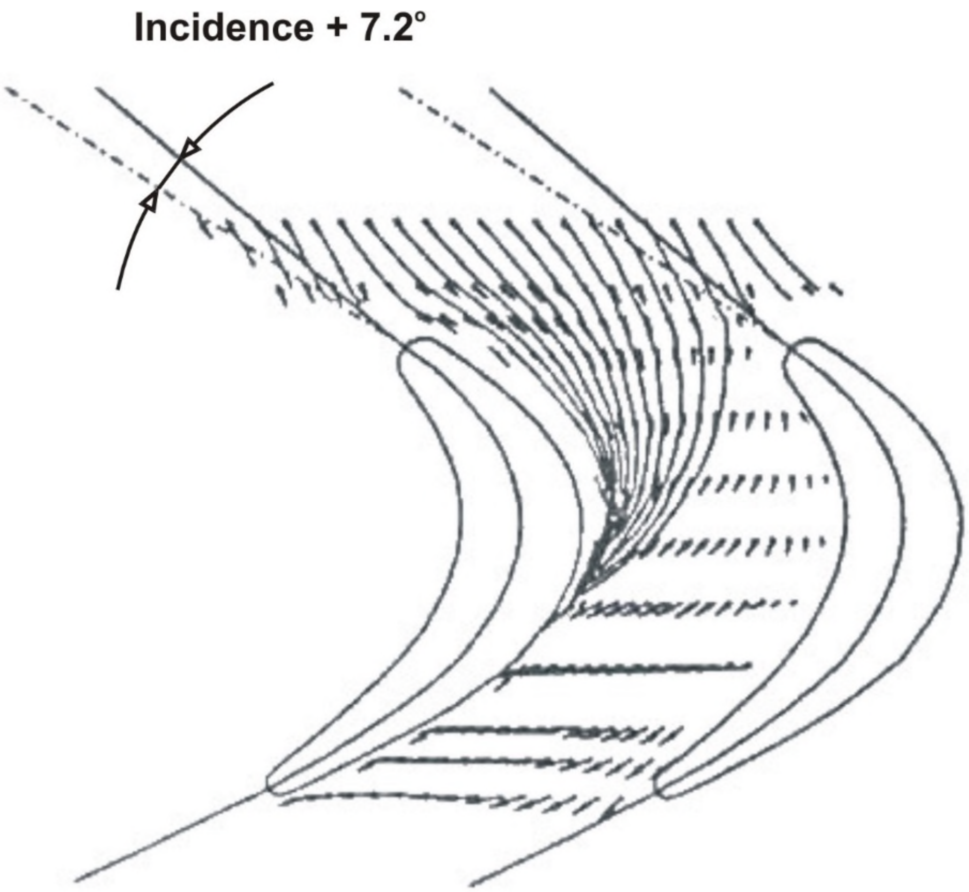
Flow visualisation



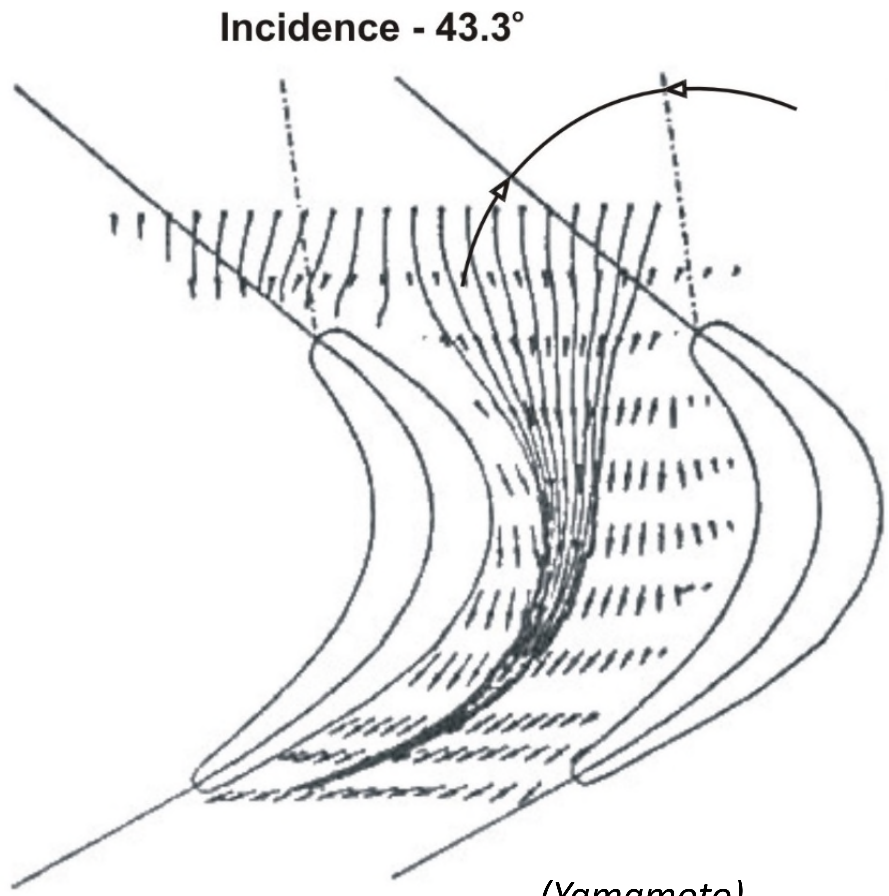
CFD

Effect of Incidence angle on Secondary Flows in a Turbine Passage

Change of the flow incidence angle, due to change in engine operating condition, has a significant effect on development of secondary flows in a blade passage. This has direct consequences on the losses generated in the passage and the downstream flow angle.



a) Positive incidence

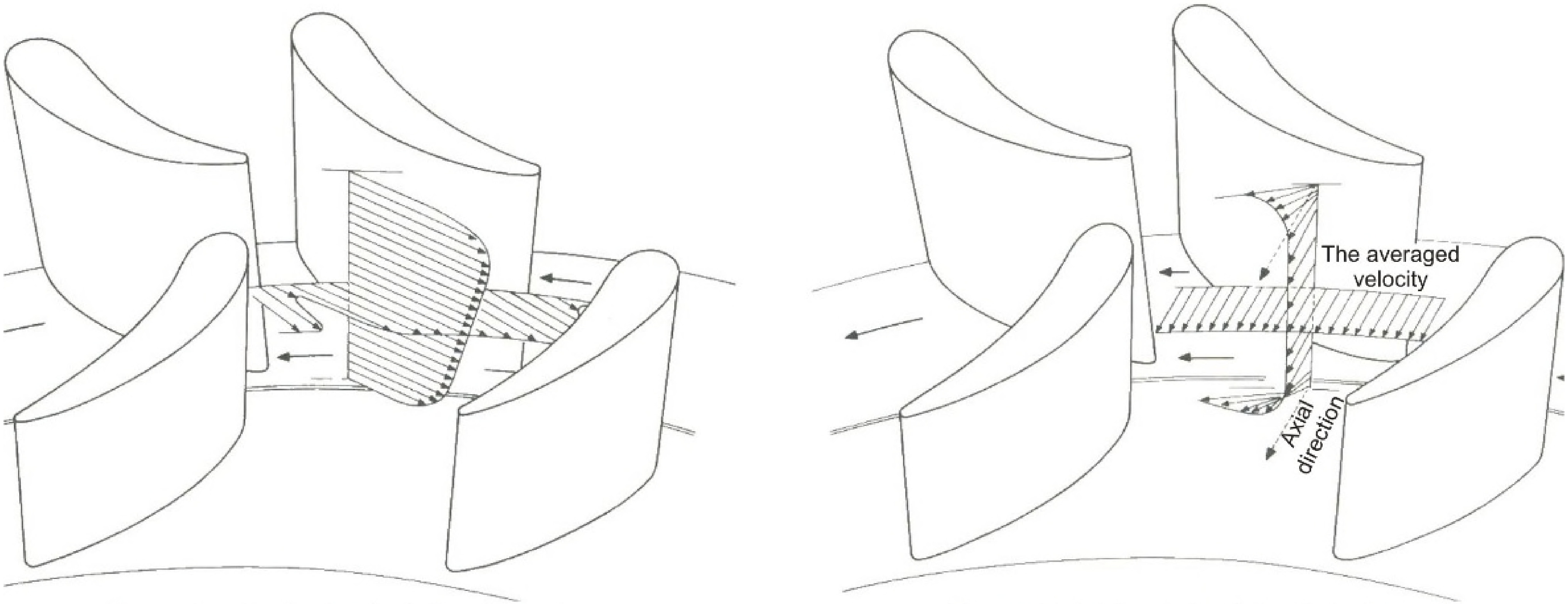


(Yamamoto)

a) Negative incidence

Effect of Inlet Boundary Layer Skew

The secondary flows also influence flow when it moves from a rotating row to a stationary or vice-versa. The reduced velocity in the endwall boundary layer region alters the flow direction (velocity triangles are different) relative to the mainstream (primary flow).



Flow at exit of rotor (relative frame)

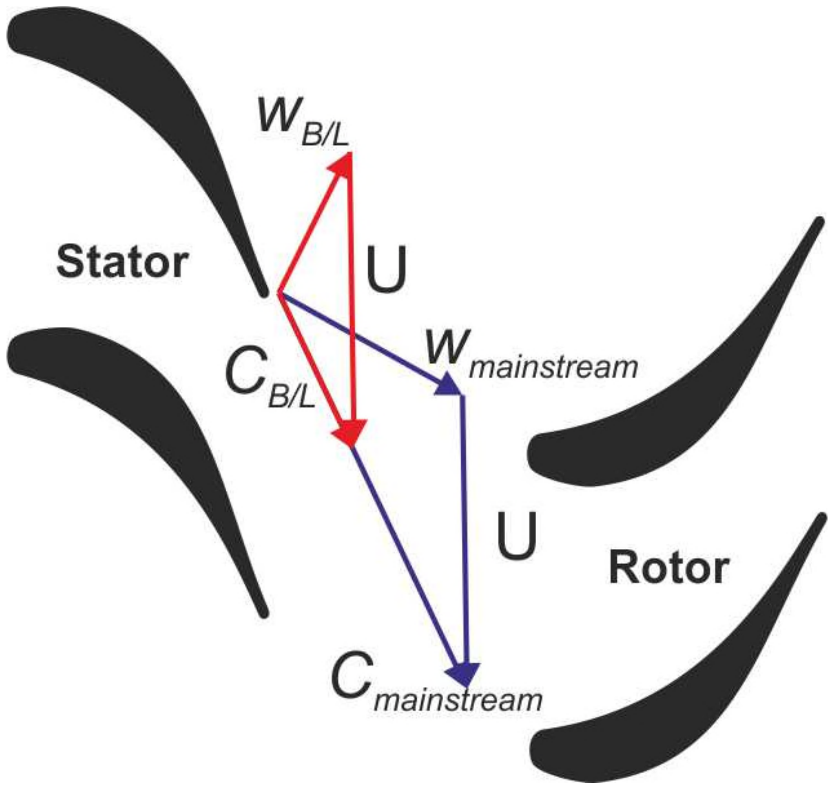
Flow at inlet to stator (absolute frame)

a) The occurrence of inlet boundary layer skew (Boletis et al. 1983)

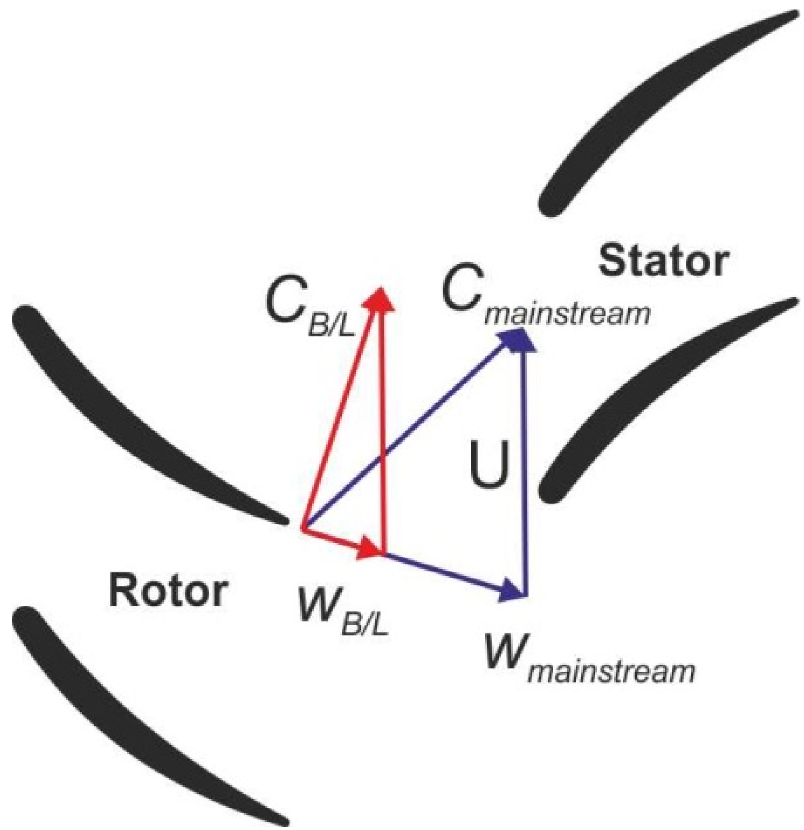
Effect of Inlet Boundary Layer Skew

In compressors the endwall boundary layer fluid is skewed toward the pressure side in the downstream blade row (against the direction of secondary flows formation). It turbines the opposite is observed - the boundary layer fluid approaches the downstream blade row from the suction side in the direction of secondary flows.

Turbine stage

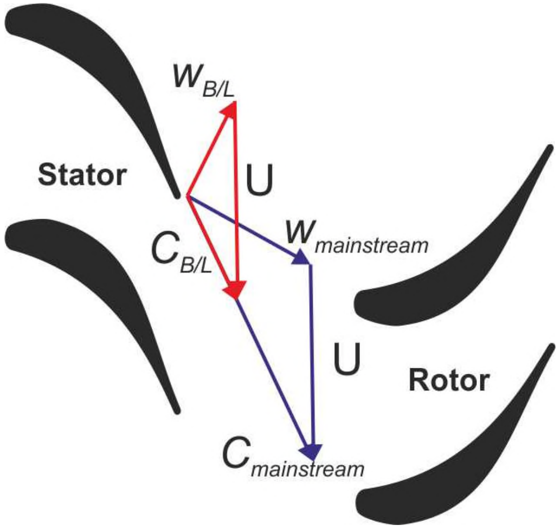


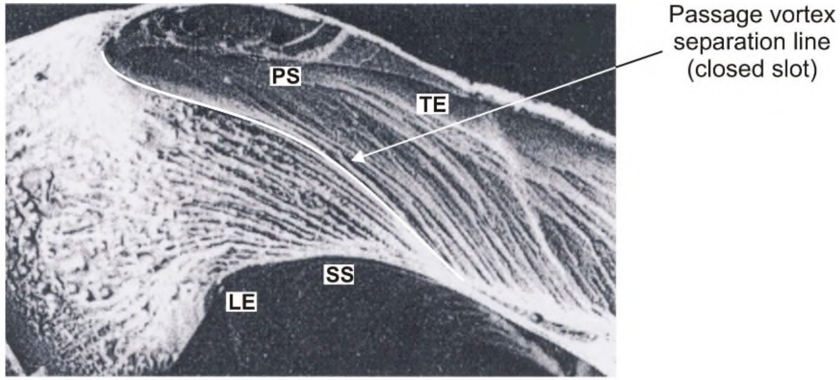
Compressor stage



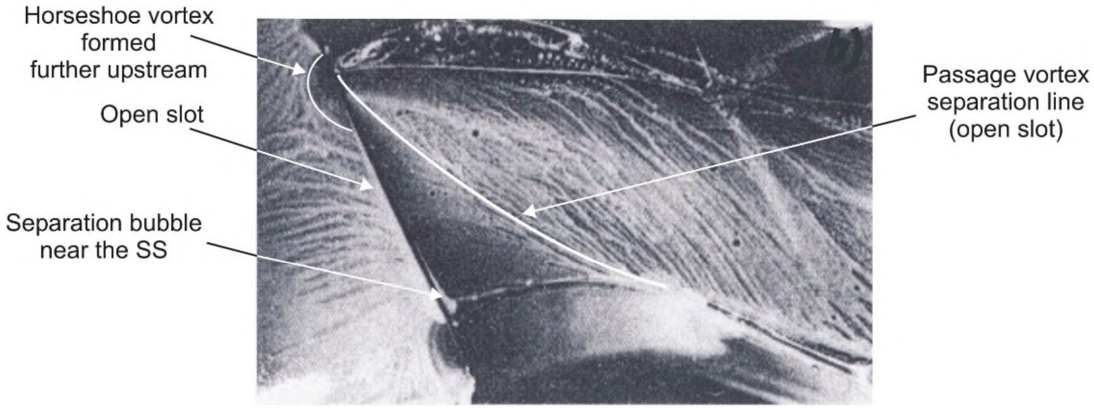
Effect of upstream boundary layer skew (caused by the endwall motion)

Flow visualisation of the endwall flowfield in a cascade with a skewed inlet boundary layer caused by moving the upstream endwall surface.

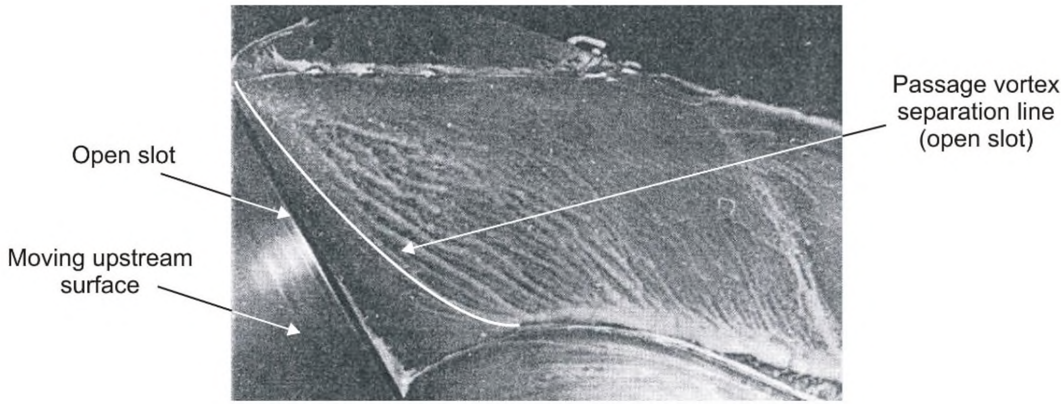




a) Closed hub slot - stationary upstream surface



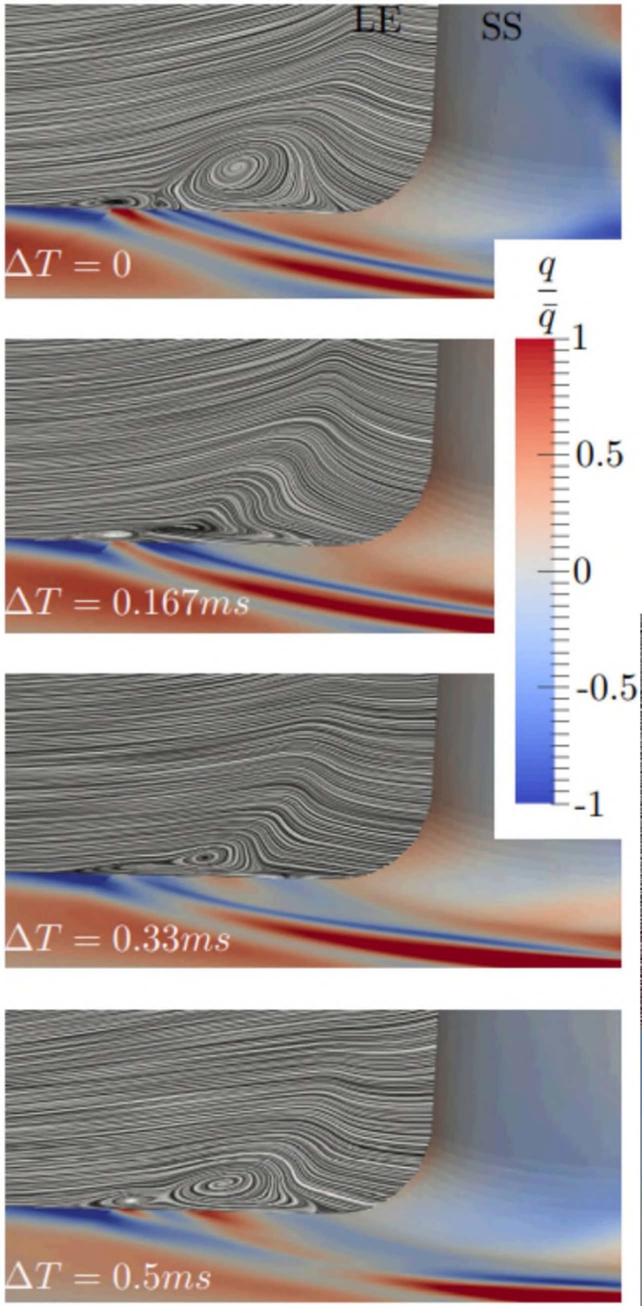
b) Open hub slot - stationary upstream surface



c) Open hub slot - moving upstream surface
(skewed inlet boundary layer)

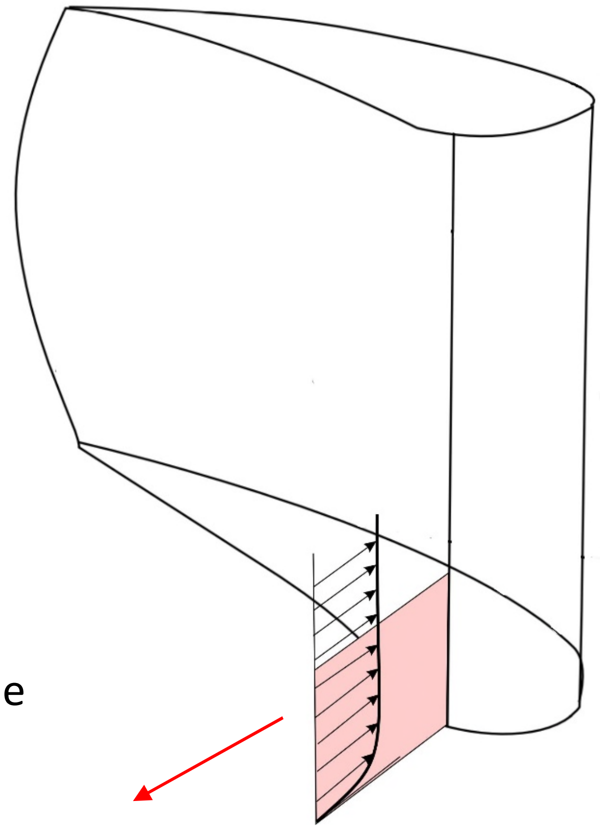
(Bindon)

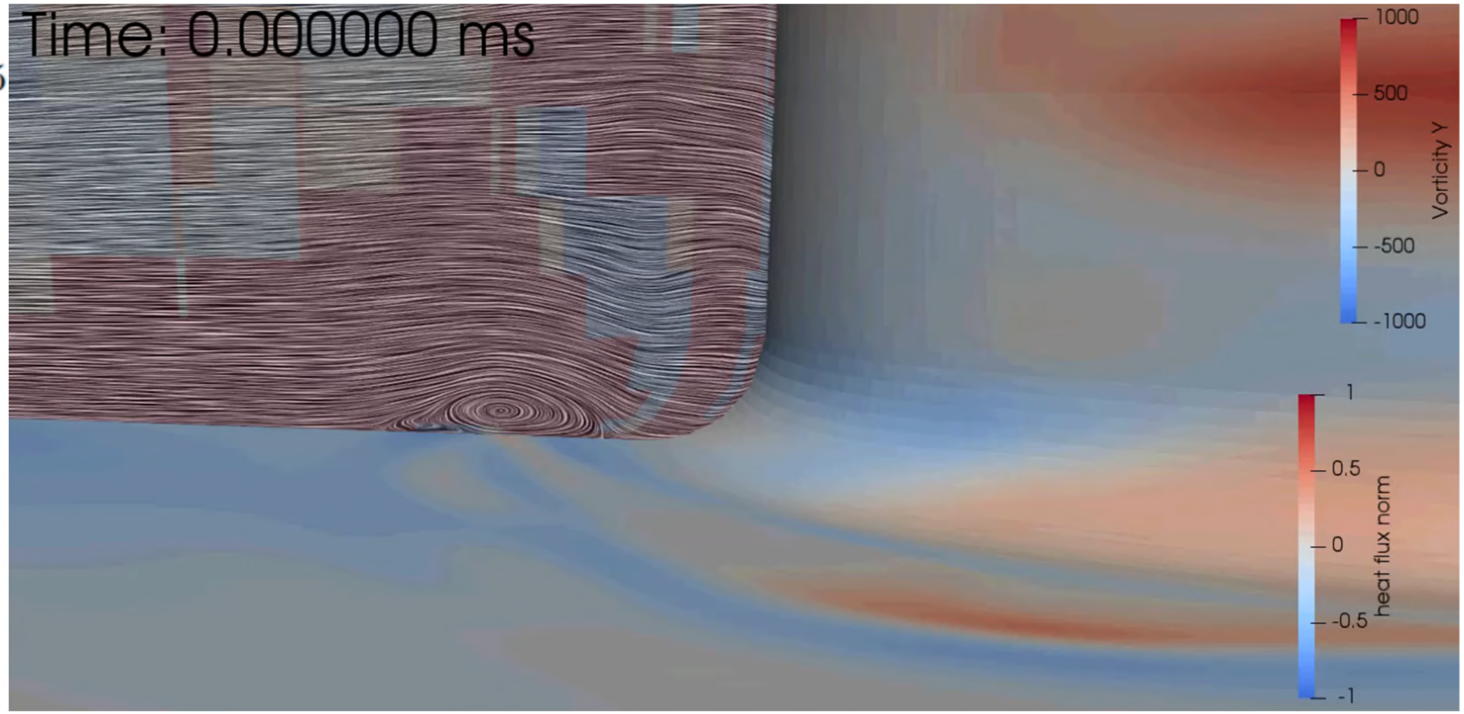
Unsteady nature of Horseshoe Vortex (HV) Formation at the Stator LE



LES simulations of behaviour of HV system at an NGV LE region in high Re flow with engine realistic incoming flow. (F. Shaikh, 2020)
velocities visualised using LIC, along with surface heat flux deviations.

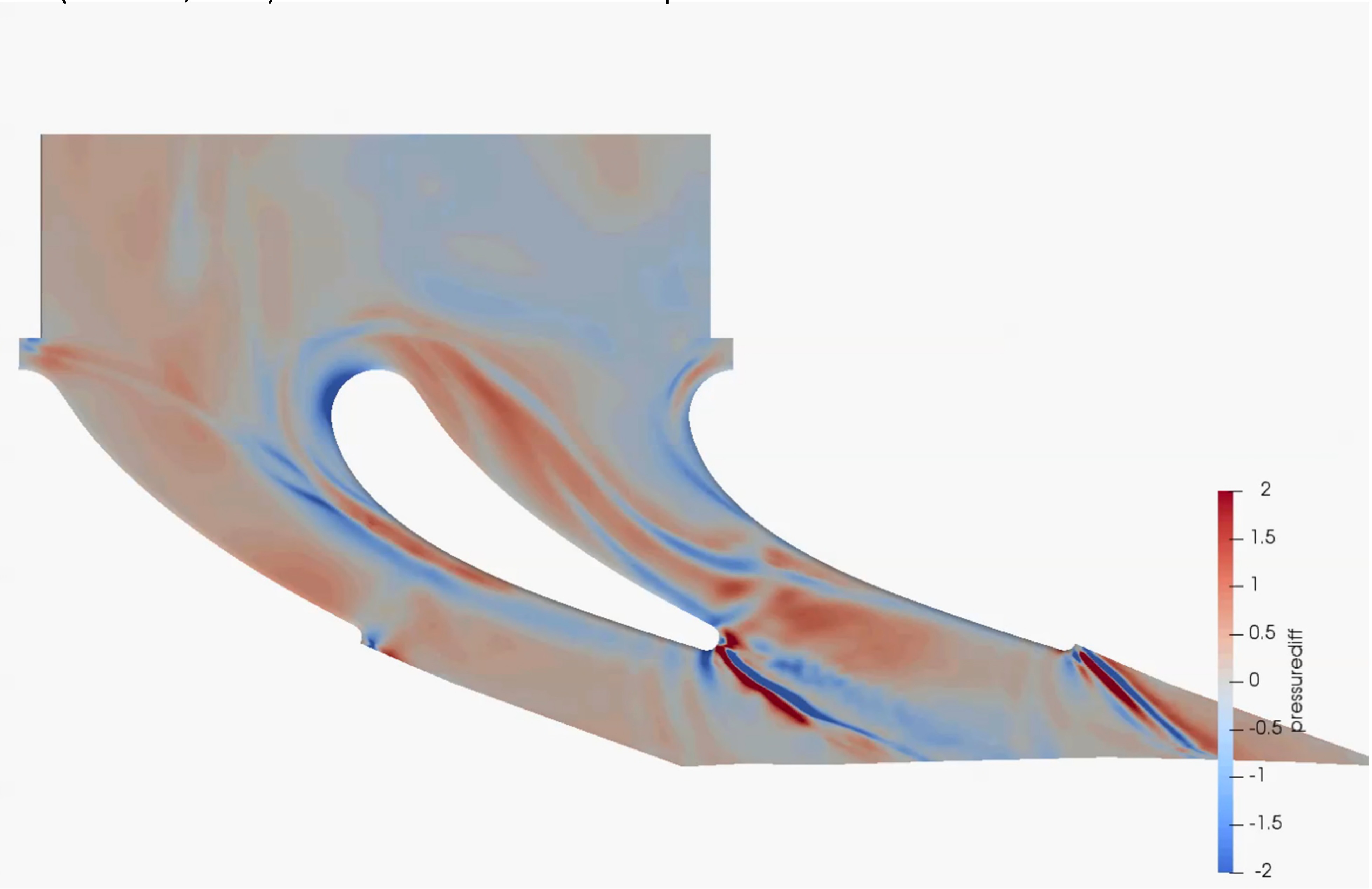
Line Integral Convolution (LIC): a technique for visualising vector field such as velocity





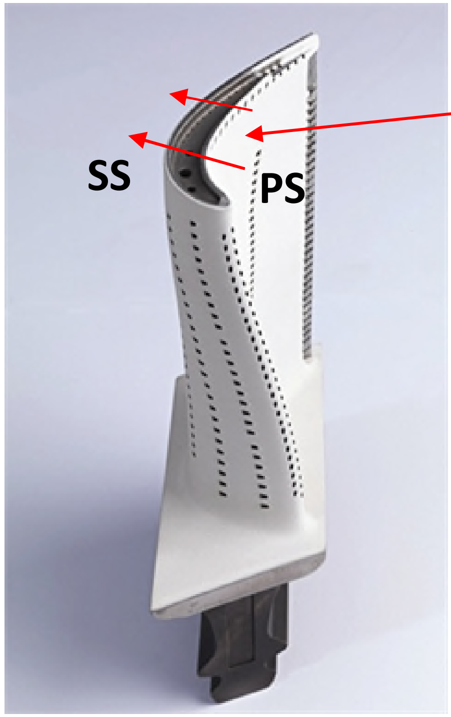
Unsteady nature of Passage Vortex and Endwall Flows

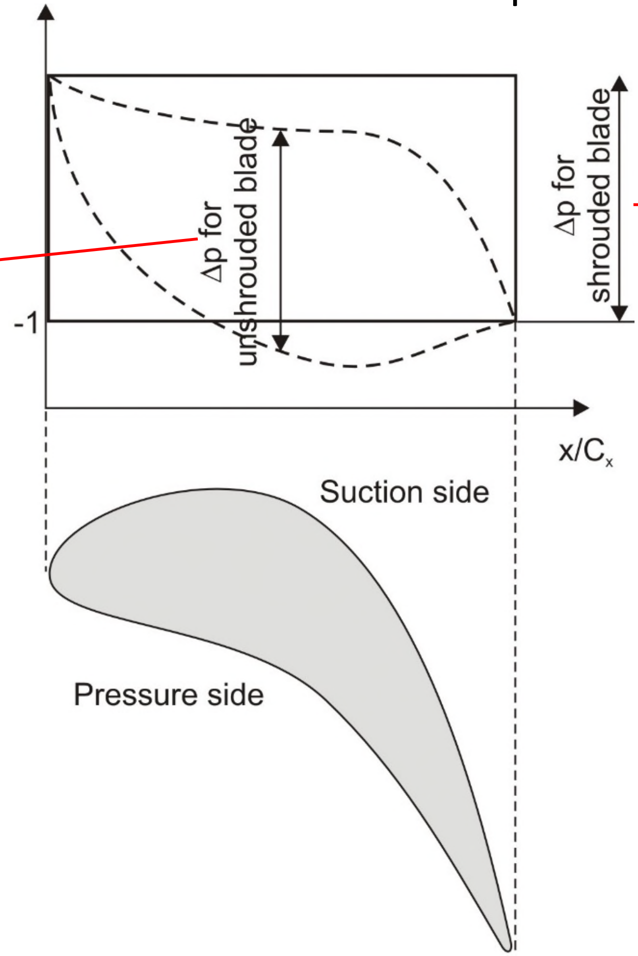
LES simulations of NGV endwall region in high Re flow with engine realistic incoming flow. (F. Shaikh, 2020) Flow visualised with surface pressure fluctuations



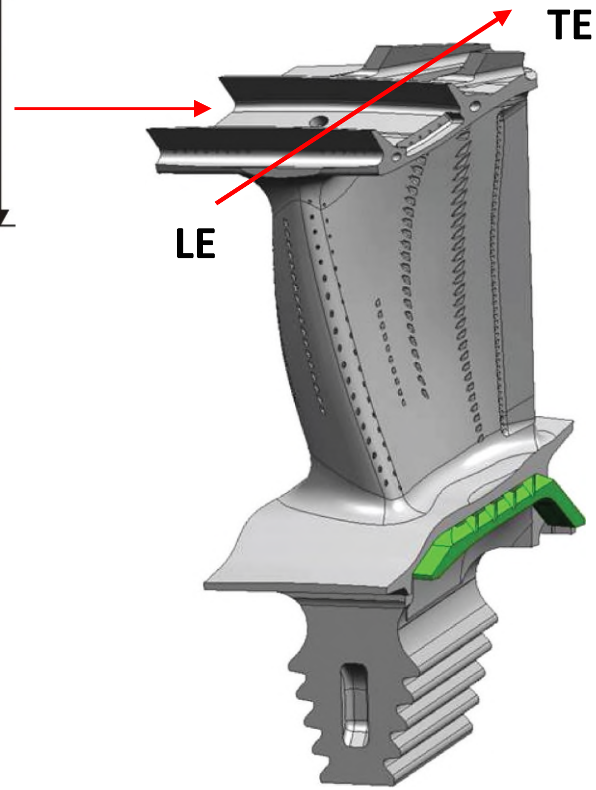
Tip leakage flows

Leakage flows are driven by the pressure difference across the blade tip (between pressure and suction side) through a gap between the rotor tip and the casing. The tip clearance is made as small as possible but mechanical limitations (vibrations and component thermal growth) usually mean that the clearance has to be of order 1- 2 % of the blade span. This allows a significant amount of fluid to leak over the blade tip from the pressure to the suction surface, which has a significant effect on the flow structure in the near tip region and loss. The structure of the tip leakage flow is very similar for both turbines and compressors.



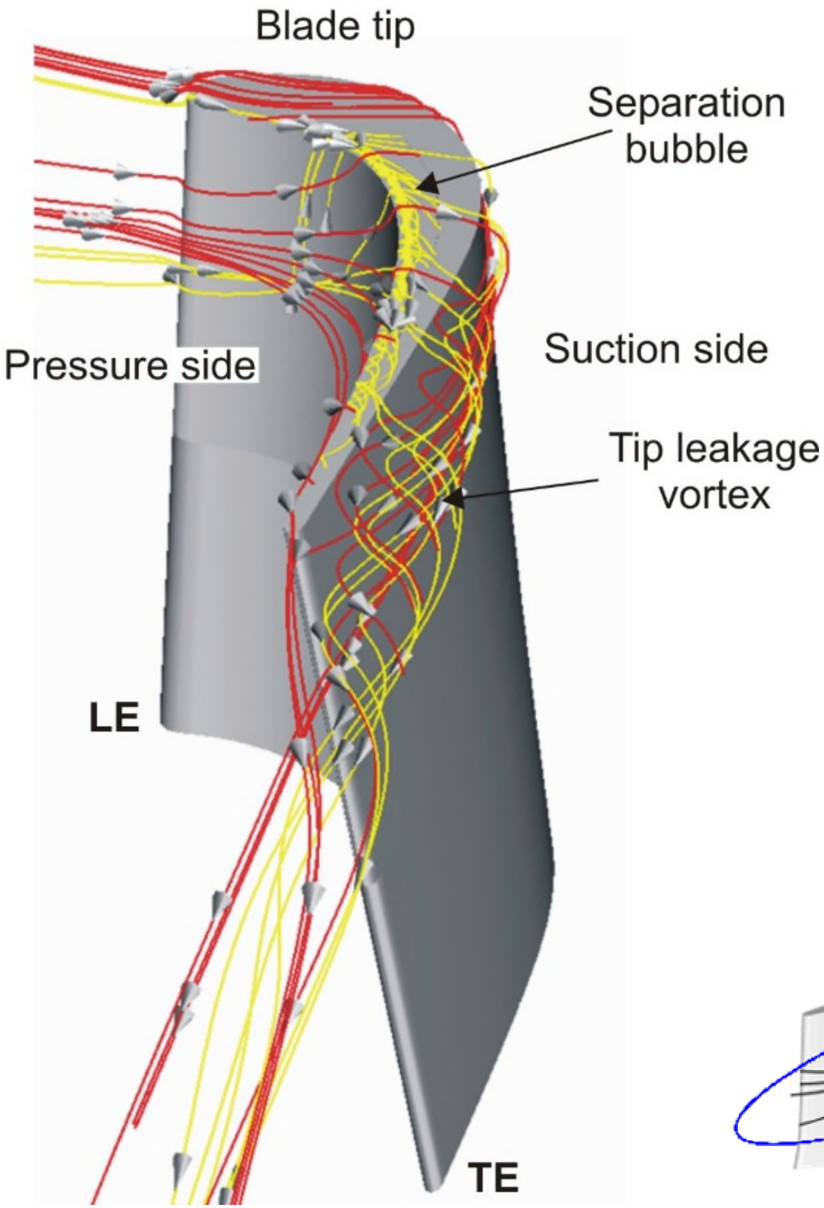


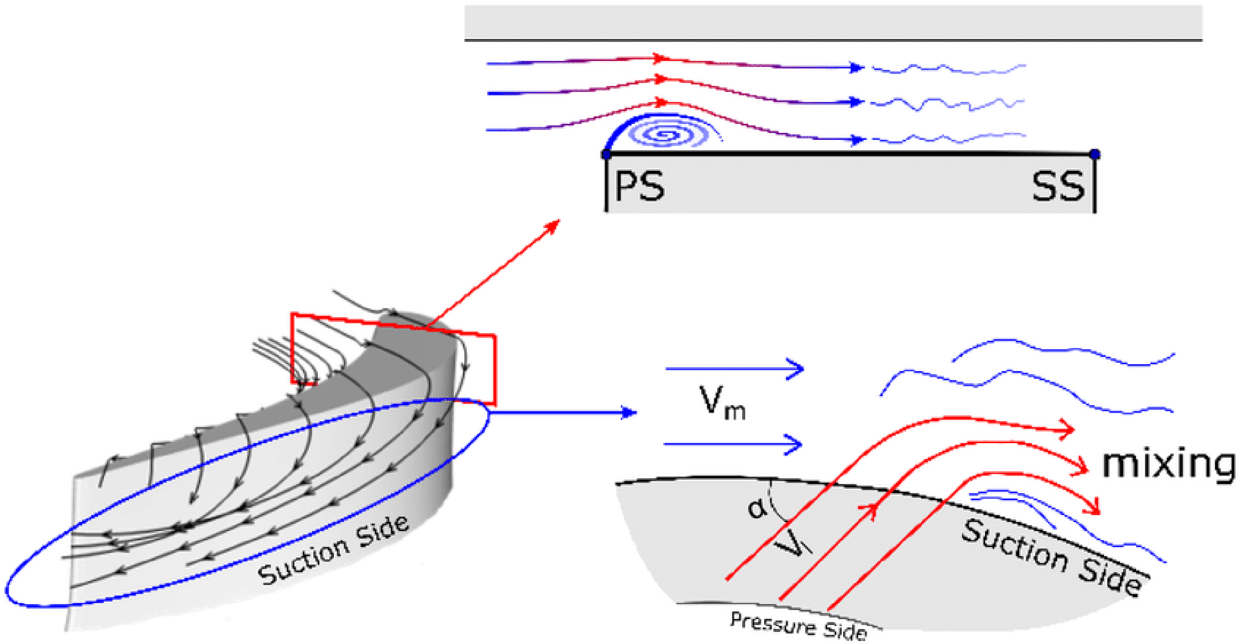
a) Leakage flow driving mechanism for shrouded and unshrouded blades



Tip leakage flows – unshrouded blades

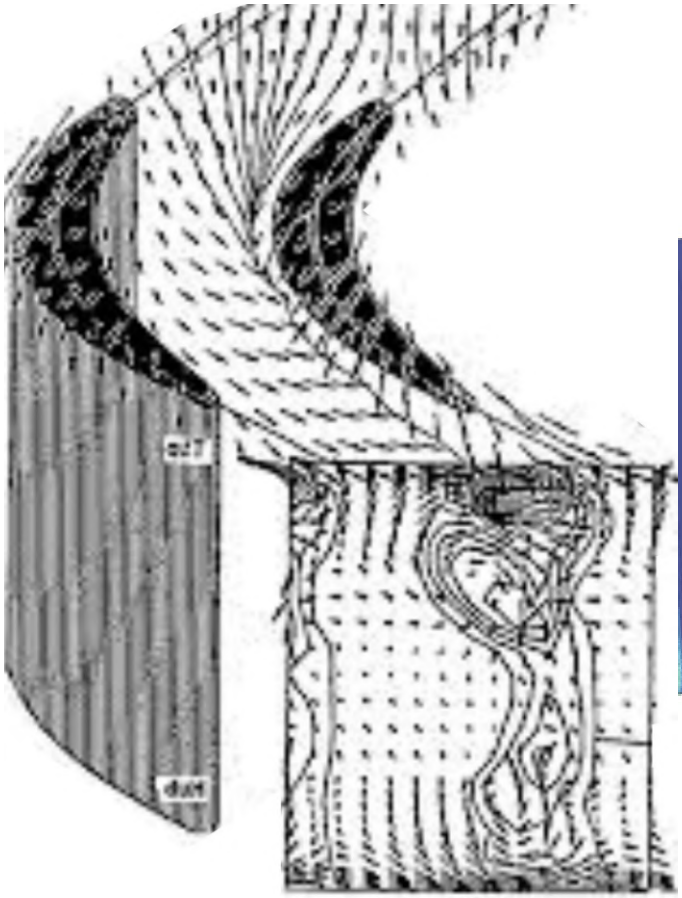
The leakage flow emerges on the suction side of the tip gap as a jet moving almost perpendicular to the blade surface and the mainstream flow. Discontinuity in velocity between the two flows constitutes a vortex sheet, which rolls up into a vortex adjacent to the suction surface.



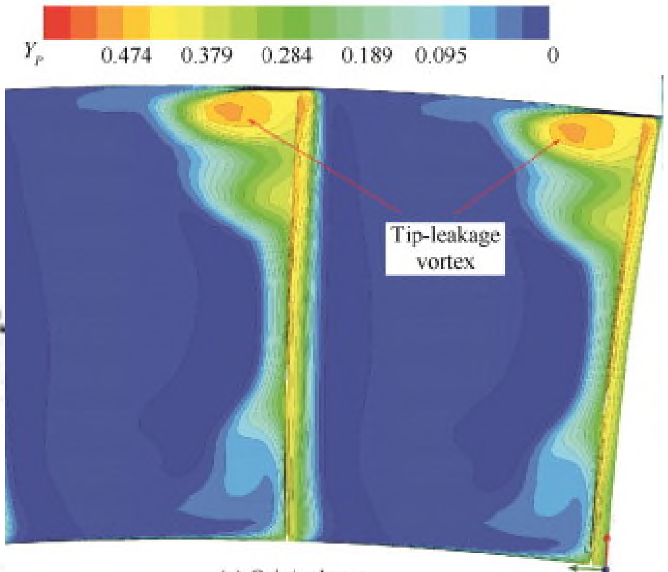


Tip leakage flows – unshrouded blades

The **tip vortex** gradually mixes out with the mainstream flow generating loss. Typically, leakage loss accounts for 1/3 of the total loss of efficiency of the machine.

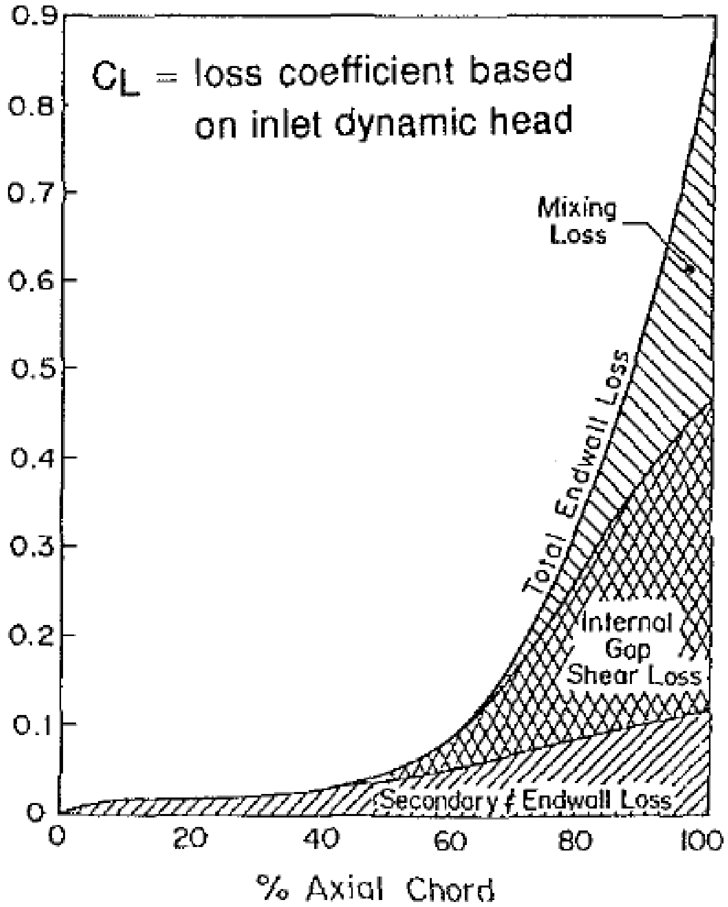


Losses of total pressure downstream of blade TE



(a) Original case

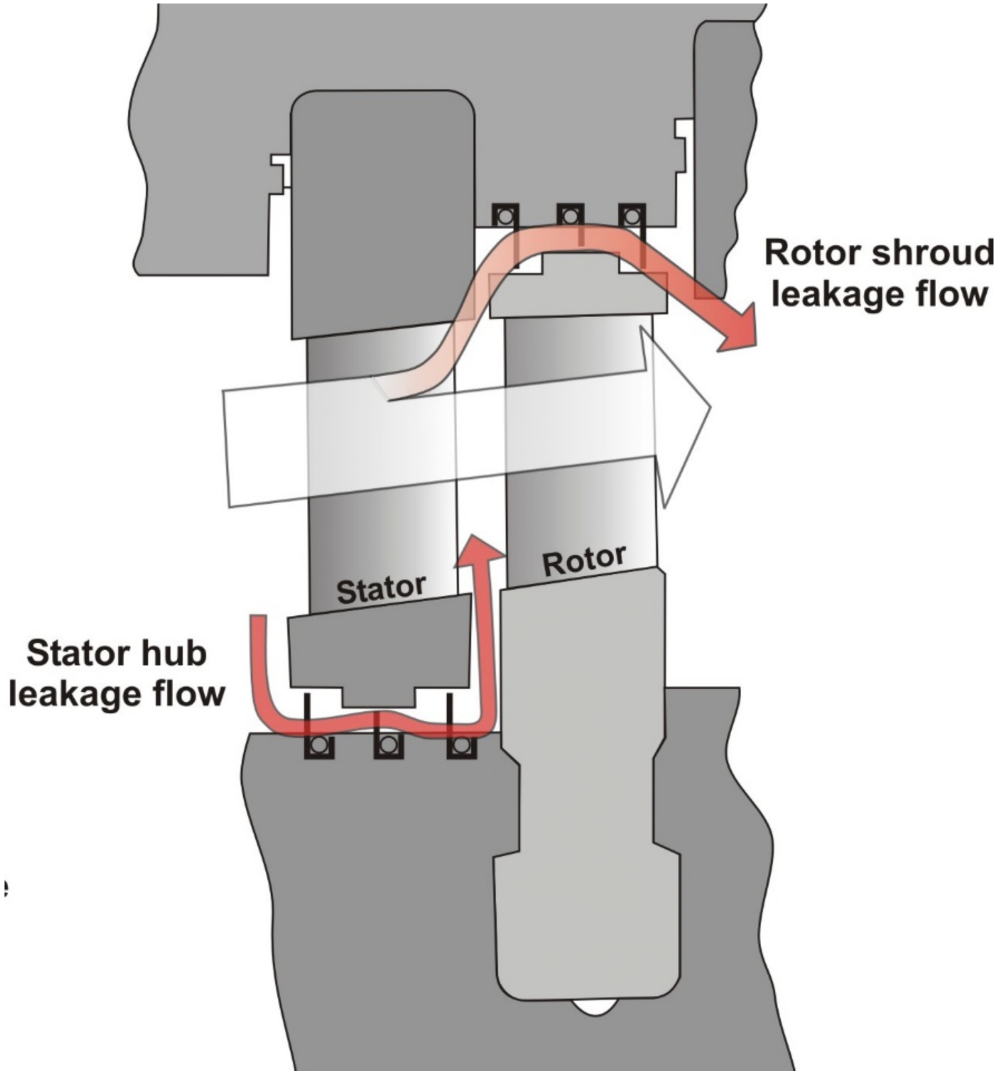
The growth of tip leakage loss through a turbine blade passage, from Bindon (1988)



Tip-leakage flow loss reduction in a two-stage turbine using axisymmetric casing contouring Author links open overlay panel, Wei, et.al.

Tip leakage flows – shrouded blades

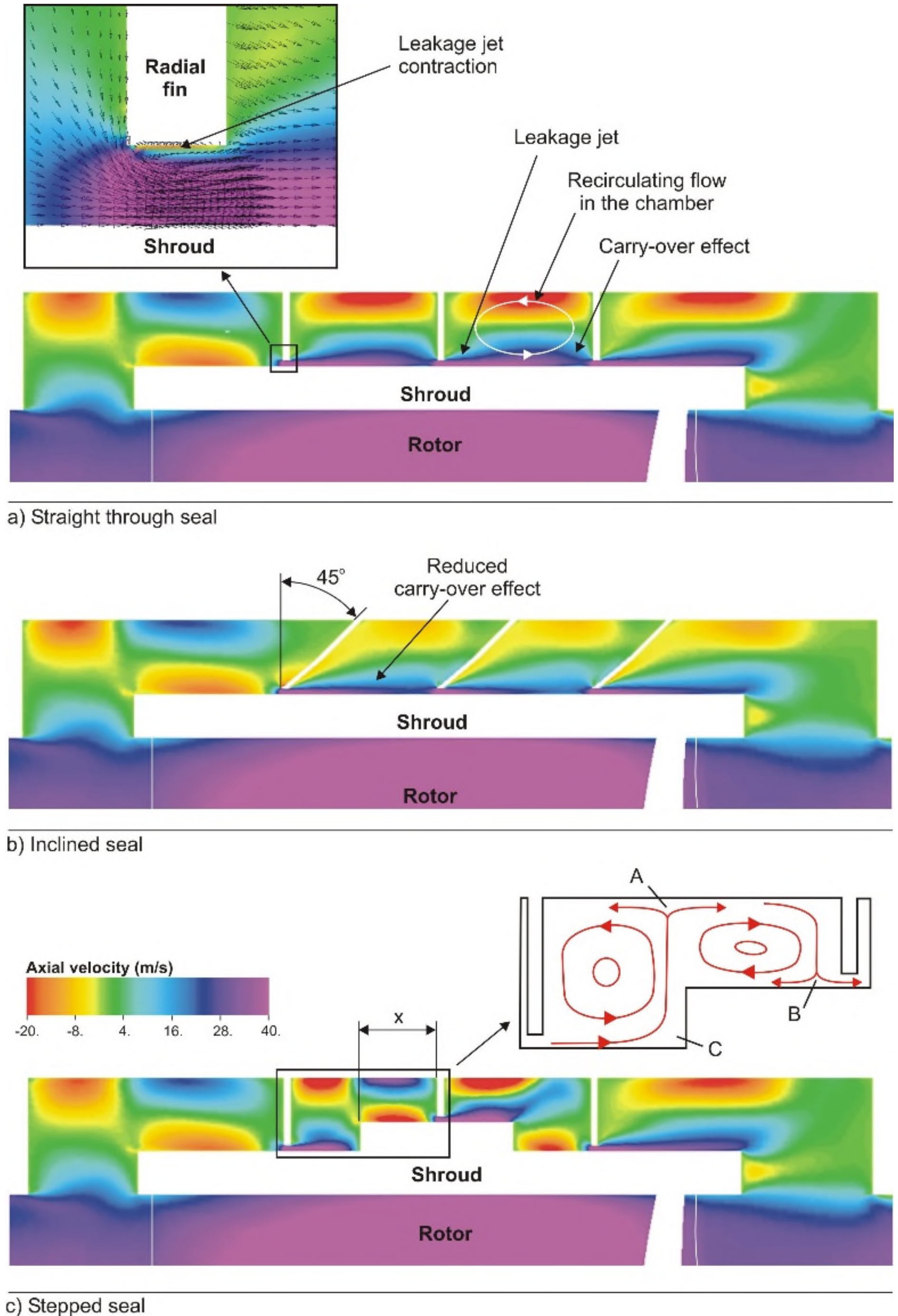
A shroud is an outer band around the rotor tip or stator blade hub that blocks any leakage flow over the blade tip from the pressure to the suction side. In this case the leakage flow is driven by the pressure difference across the blade row. Although the value of the pressure difference between the blade surfaces is comparable to that of the pressure drop across the blade row, the main advantage of using the shrouded blades over the unshrouded blades is that the leakage flow can significantly be reduced, by using the shroud in combination with multiple labyrinth seals.



Tip leakage flows – shrouded blades

Different rotor shroud and labyrinth seal geometries

A labyrinth seal includes a series of constriction and expansion chambers, through which the flow successively accelerates and decelerates, dissipating its kinetic energy through turbulent mixing.

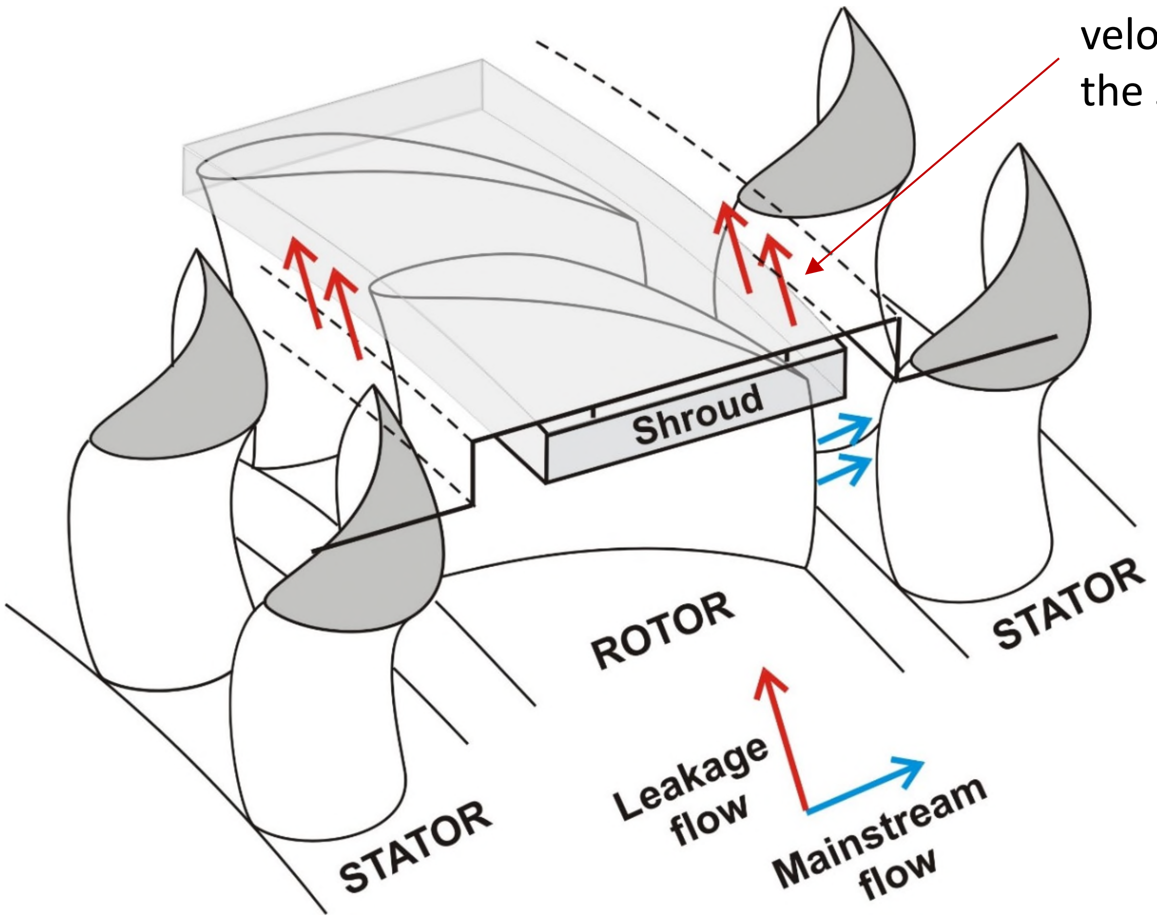


velocity contours in the shroud cavity

In low aspect ratio (high pressure) turbines with shrouded blades, leakage losses contribute significantly to overall losses. Leakage flow reduces turbine performance primarily by reducing extracted work in the rotor blades. Along with this, there are other loss-generating mechanisms through which the shroud leakage flows affect turbine performance. They are:

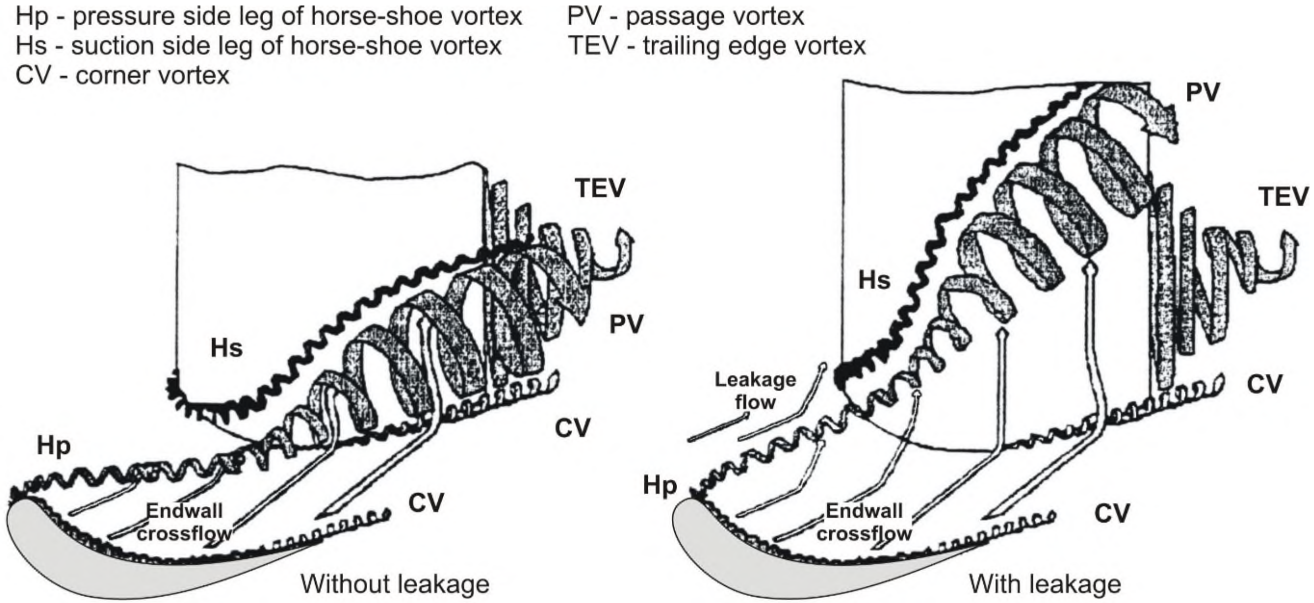
- due to mixing in the shroud cavity,
- mixing through the labyrinth seal,
- mixing downstream of the rotor due to the velocity difference between the leakage flow and the mainstream flow, and
- non-ideal incidence onto the downstream blade row.

Leakage fluid unturned by the rotor blade maintains the swirl velocity component et the exit of the shroud cavity

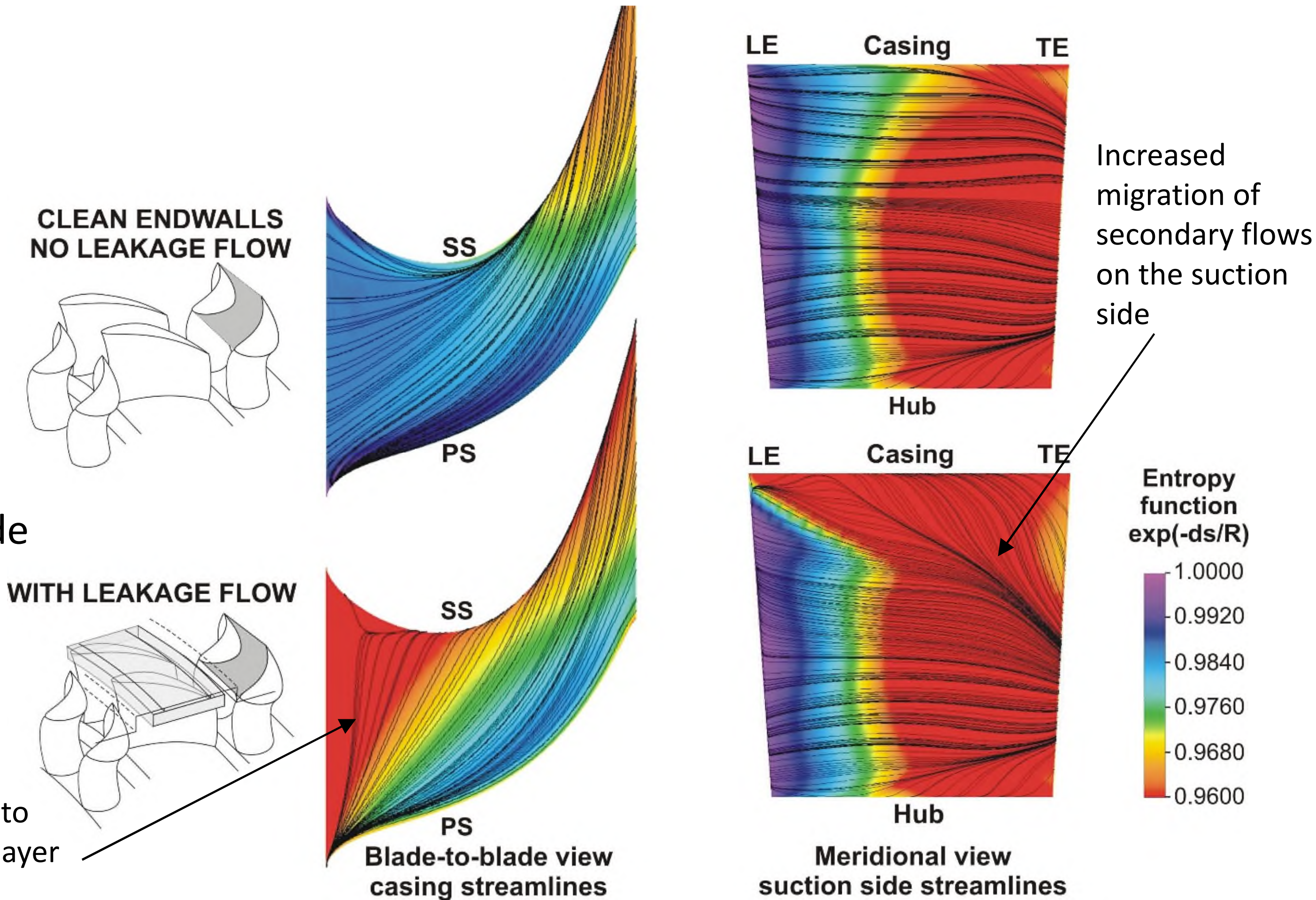


Effect of unturned rotor shroud leakage flow on downstream stator secondary flows

Schematic of secondary flow structures without the upstream leakage and with leakage

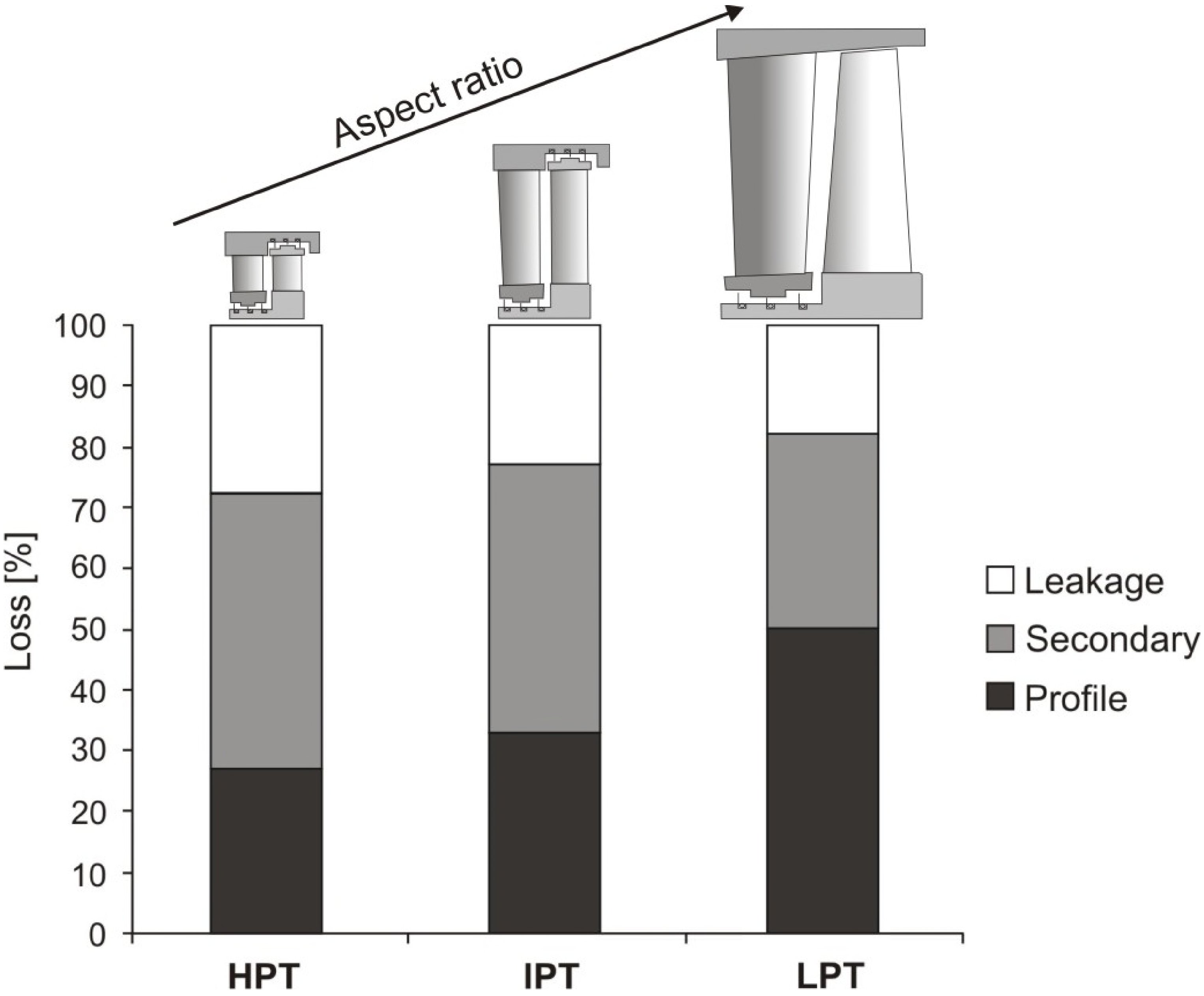


Numerical simulation of streamlines and entropy (loss) contours on the downstream stator tip endwall and suction side



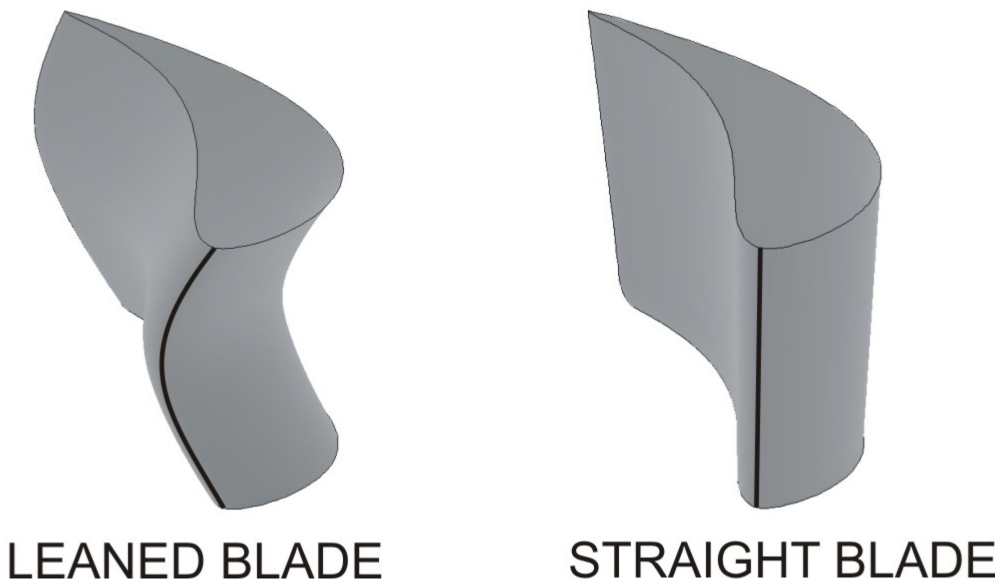
Enhanced enwall cross-flow due to skew in the upstream boundary layer

Typical loss breakdown for different aspect ratio turbine bladings



Blade Lean

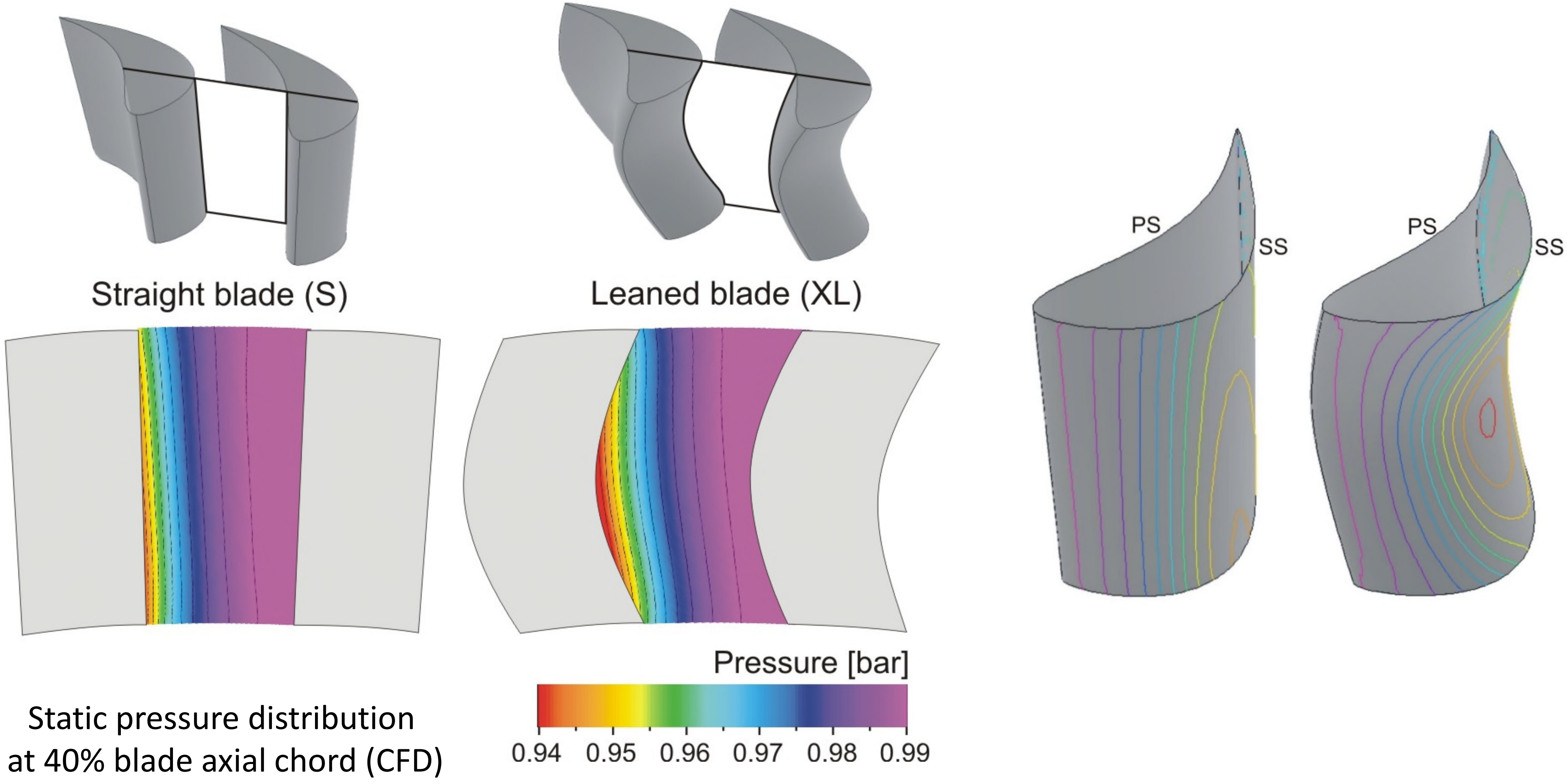
A blade is leaned if a line through the centroids of the blade sections is not a radial line.
The effects of blade lean, i.e. non-radial blade stacking, on the blade loading can be very powerful.



Blade lean has been successfully used:
In high aspect ratio LP steam turbines to increase the root reaction.
In compressors ("end-bend") where the unloading of the endwalls can be used to:
- reduce tip leakage flow;
- suppress blade-endwall corner separation (improve the efficiency & surge margin).

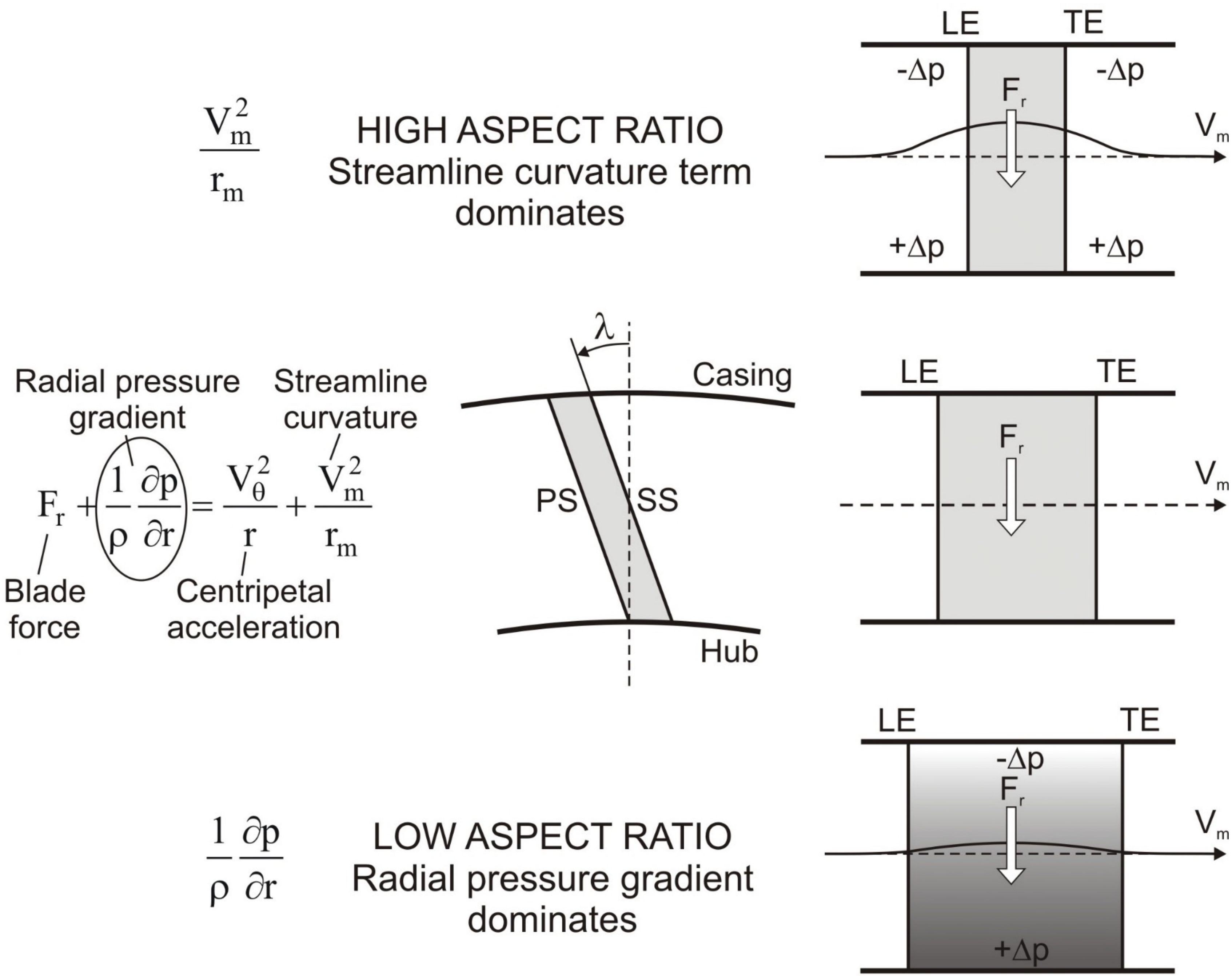
Despite the large amount of work the influence of blade lean on HP turbine performance still not well understood.

In the low aspect ratio blading, with high hub to casing radius ratio, the radius of curvature on the blade to blade plane is much greater than hub and casing radii. Therefore, the pressure gradients perpendicular to the hub and casing are much smaller than the pressure gradient on the blade to blade stream surface, i.e. $c_{rel}^2/r_{c,blade} \gg c_\theta^2/r$ and $c_m^2/r_{c,merid}$ where $r_{c,blade}$ is the streamline curvature in the blade to blade plane, $r_{c,merid}$ is that in meridional plane and r is the local stream surface radius. The dominant effect is that the contour lines of constant pressure are almost radial. Therefore, with the blade lean it appears that the blade is moved tangentially within an almost 'frozen pressure field'

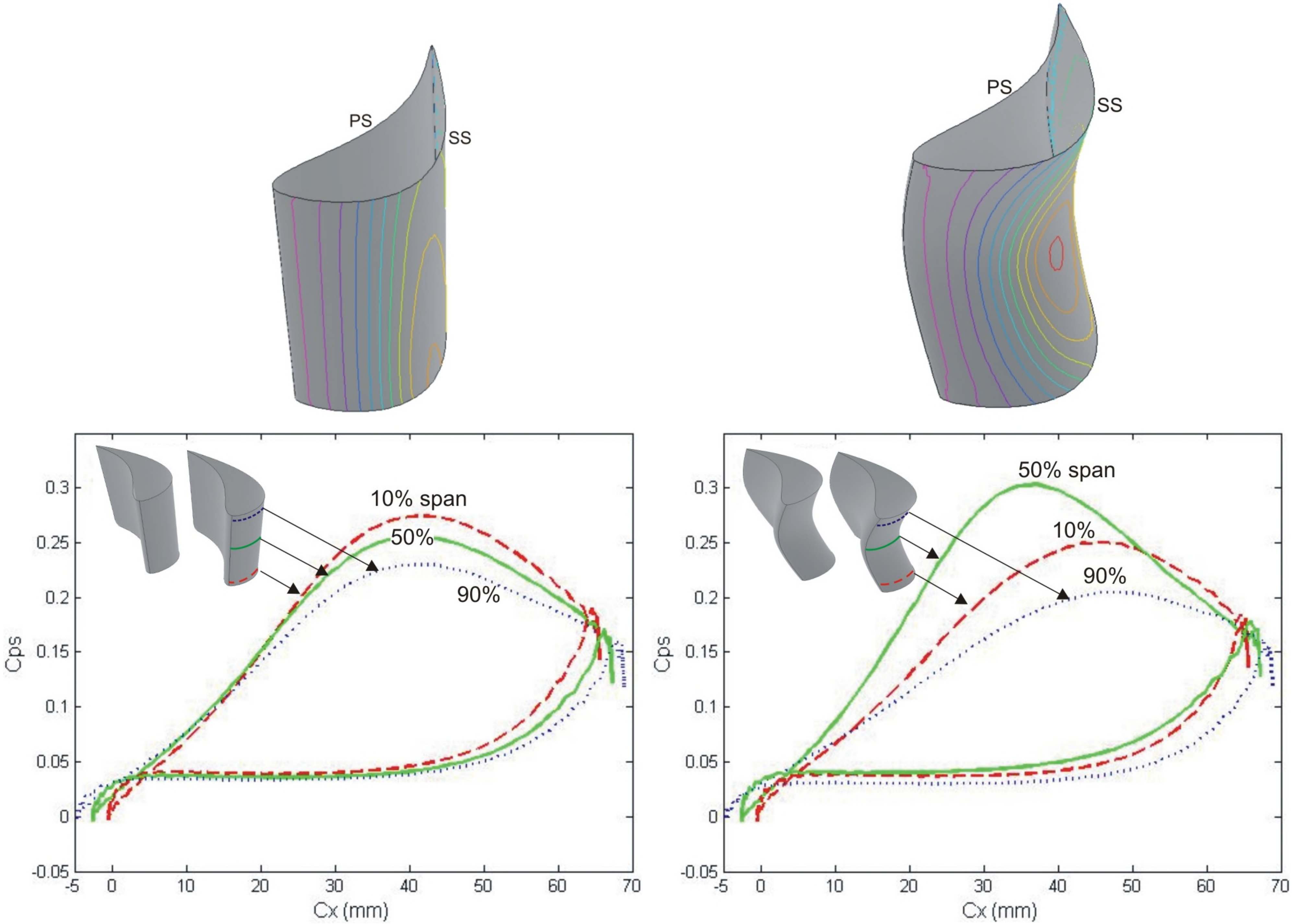


Static pressure distribution
at 40% blade axial chord (CFD)

An interpretation of blade lean (non-radial stacking)

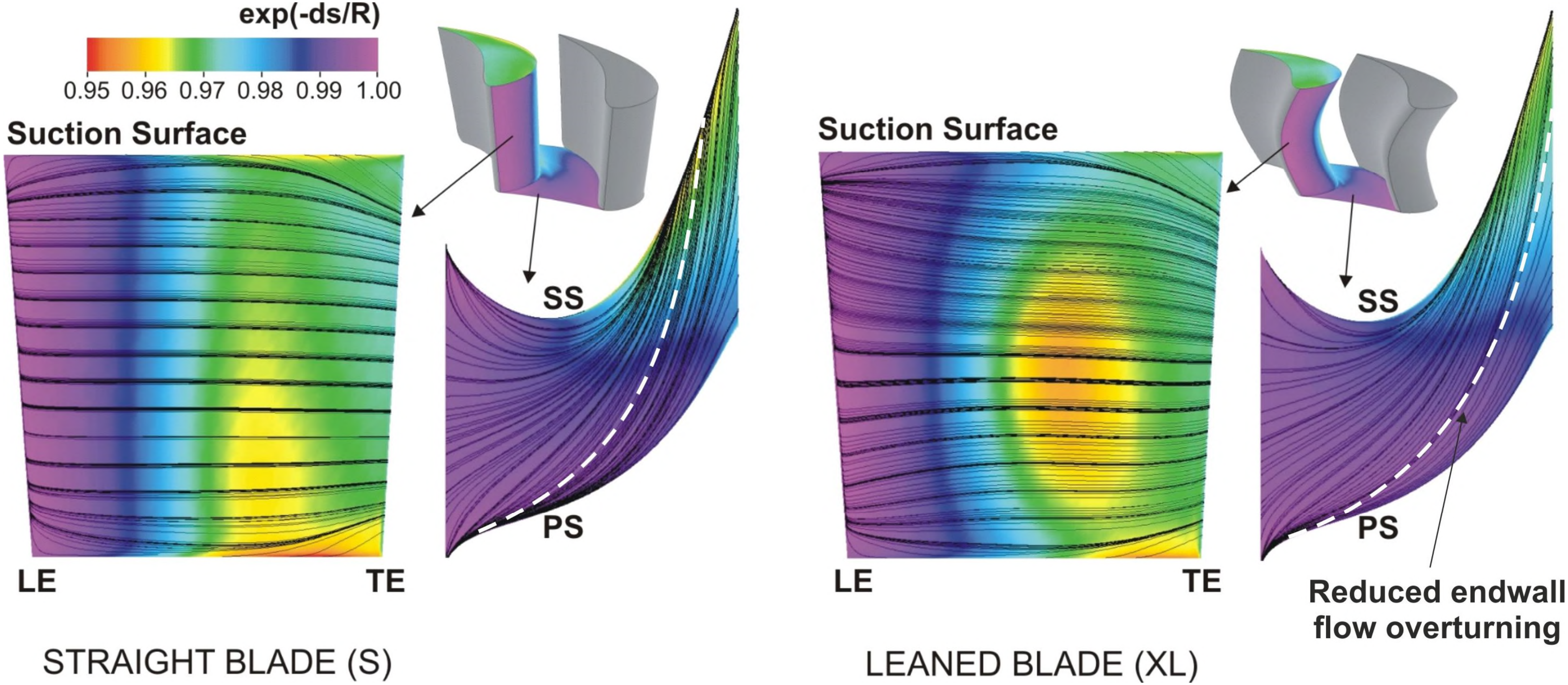


Pressure distribution for straight and lean turbine blade



Blade lean used for control of secondary flows

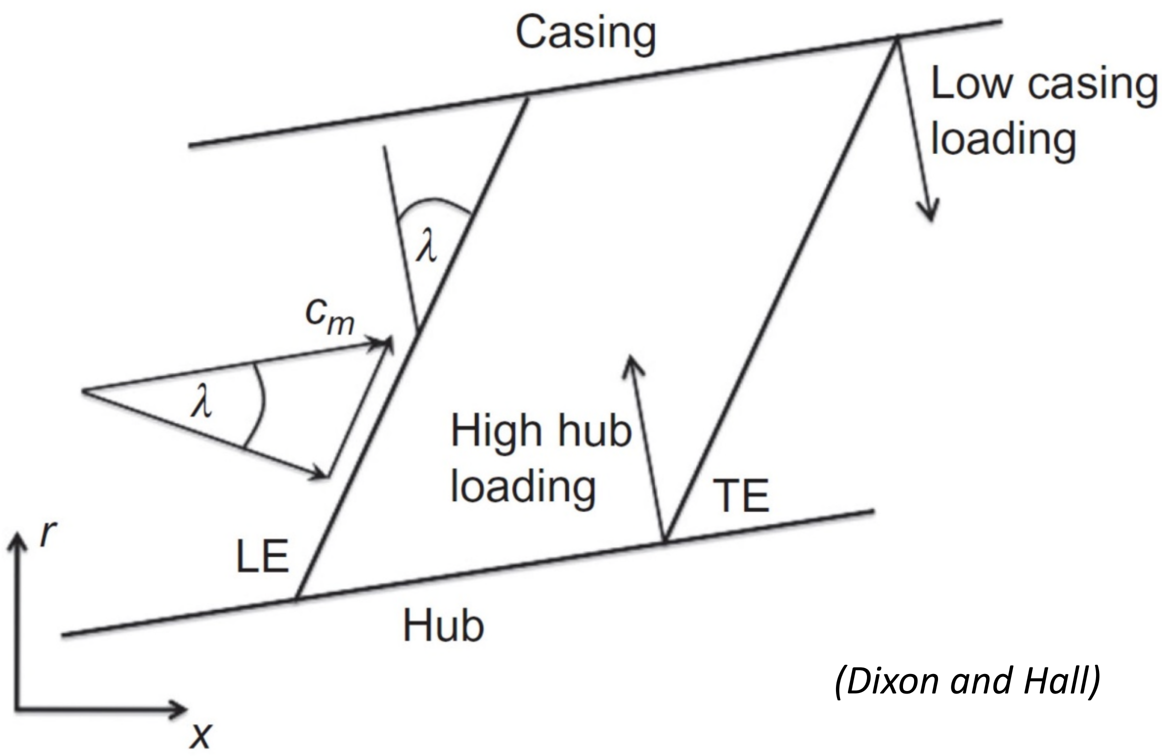
Blade suction side and hub endwall streamlines with entropy contours



Blade Sweep

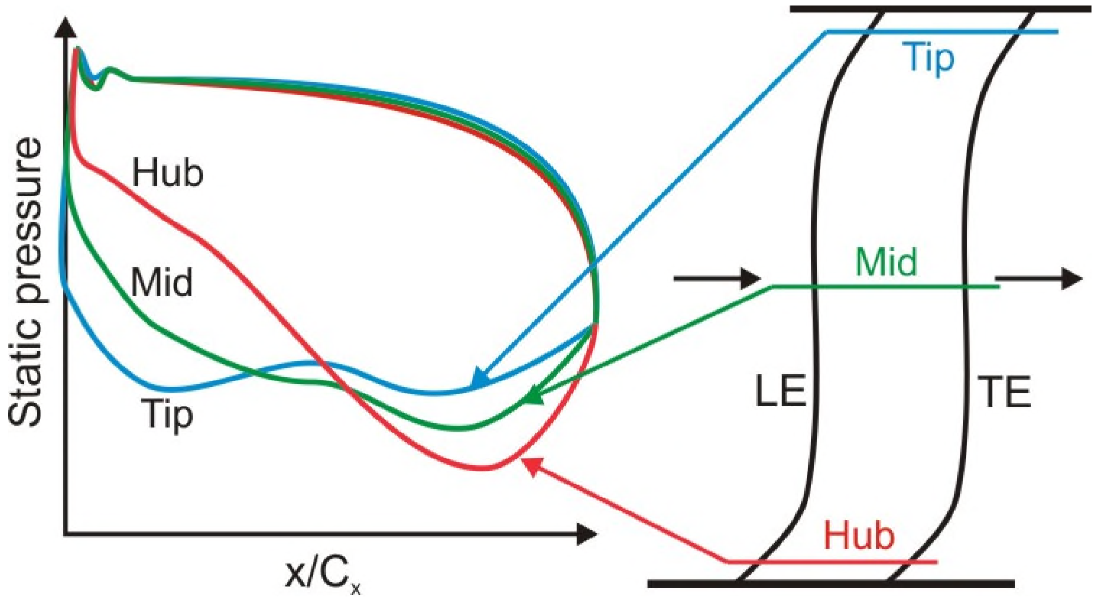
A blade is swept when the line of the leading edge is not perpendicular to the incident flow or if the line of the trailing edge is not perpendicular to the leaving flow (analogous to a swept wing).

Effect of sweep is to reduce effective velocity perpendicular to the blade surface and thus reduce the local blade loading and surface Mach number. If the leading edge sweep angle is λ, the perpendicular velocity reduces from c_m to $c_m cos\lambda$.

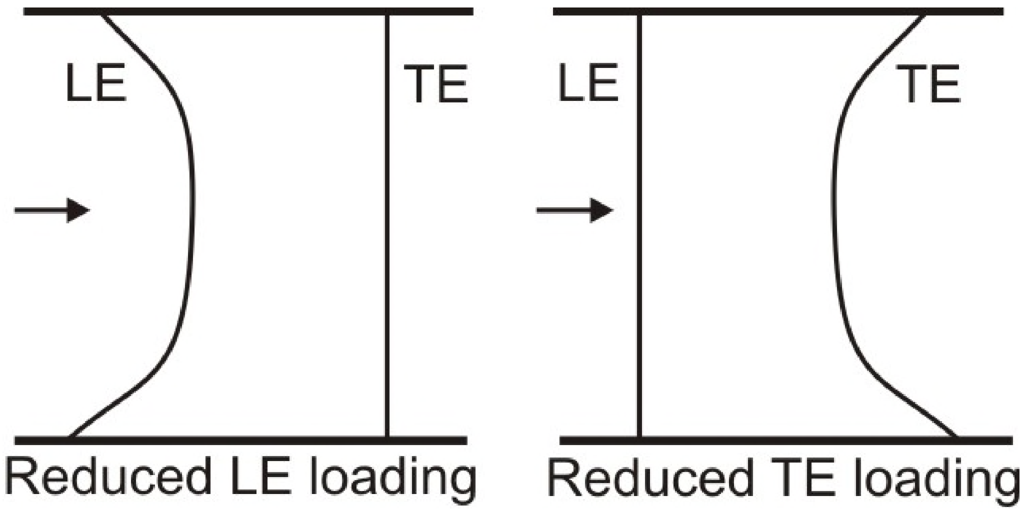


(Dixon and Hall)

Blade Sweep



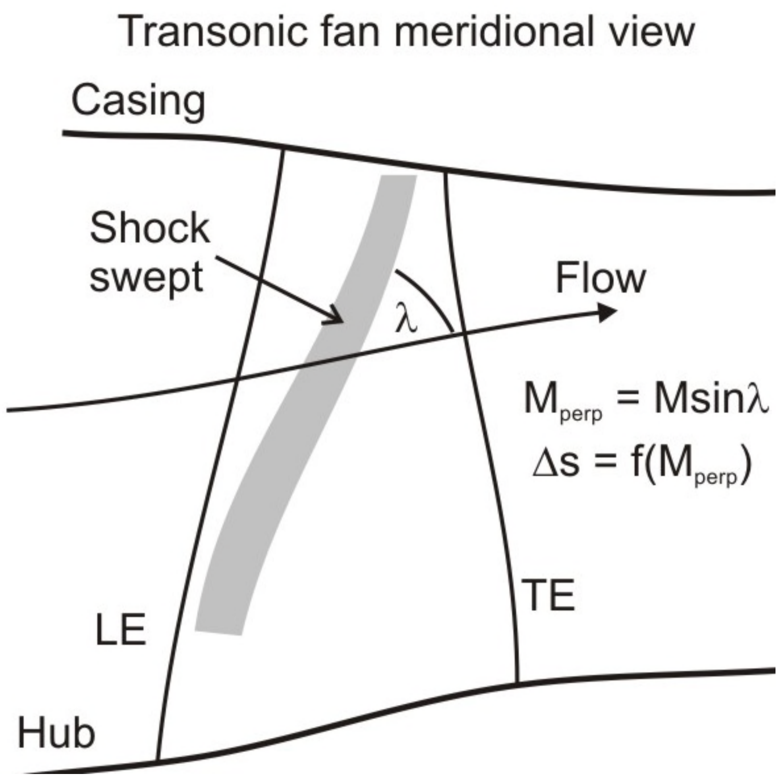
To illustrate the effect of the blade sweep on the spanwise loading distribution, a turbine blade on the following figure is swept forward at the hub and backwards close to the tip. The blade pressure distribution is significantly modified near both endwalls (different from midspan pressure distribution). Close to the hub loading is reduced at the leading edge and increased at the trailing edge.
Conversely, at the tip loading is increased at the leading edge and reduced at the trailing edge region.



Blade sweep is usually used in the design of subsonic blade rows to reduce loading at the leading and trailing edge as is shown in this figure. In compressors forward leading edge sweep is used to reduce loading and make leading edge more tolerant of the changes in inlet angle due to skew near the endwalls.

Sweep in transonic fans

Important effect of sweep is on the shock losses of a transonic fan. Figure shows a typical shock structure at mid-pitch. The shock is swept in meridional plane. The shock stagnation pressure loss is a strong function of the Mach number component perpendicular to the shock. This component can be significantly reduced by sweep, in exactly the same way as can the drag of a transonic aircraft wing.



Modern fan blades for large jet engines typically have a combination of both rearward and forward sweep above mid-span.

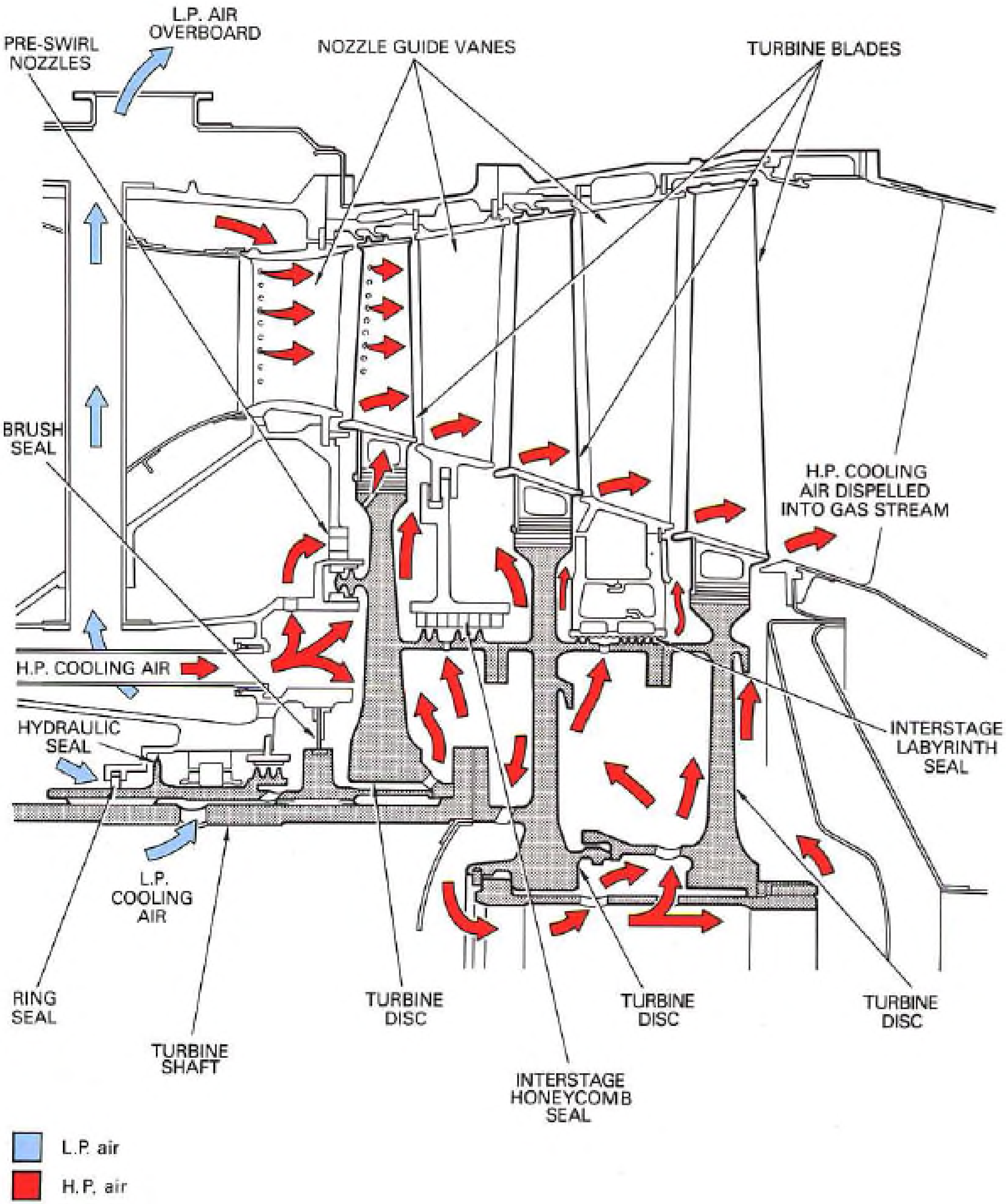
Secondary Air System (*The Jet Engine, R&R*)

Airflows which do not directly contribute to the engine thrust.

The system has several important functions to perform for the safe and efficient operation of the engine:

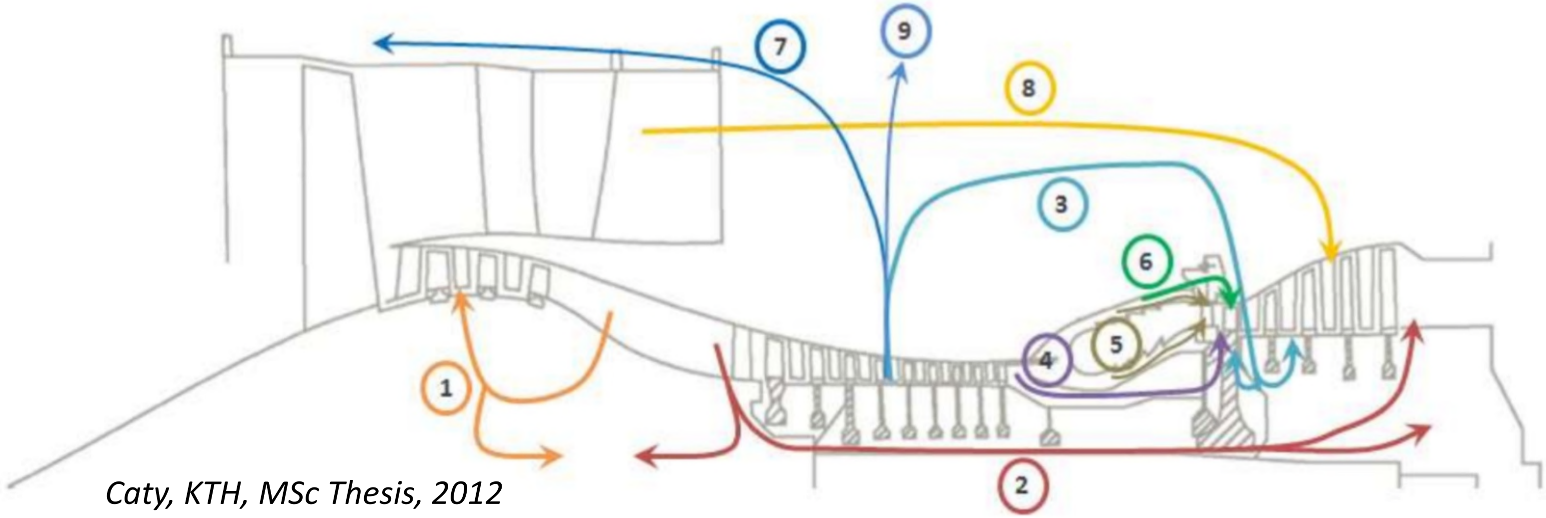
- internal engine and accessory unit cooling,
- bearing chamber sealing prevention of hot gas ingestion into the turbine disc cavities,
- control of bearing axial loads, etc.

Up to 20 % of the total engine core mass flow may be used for these various functions.



Secondary Air System (SAS)

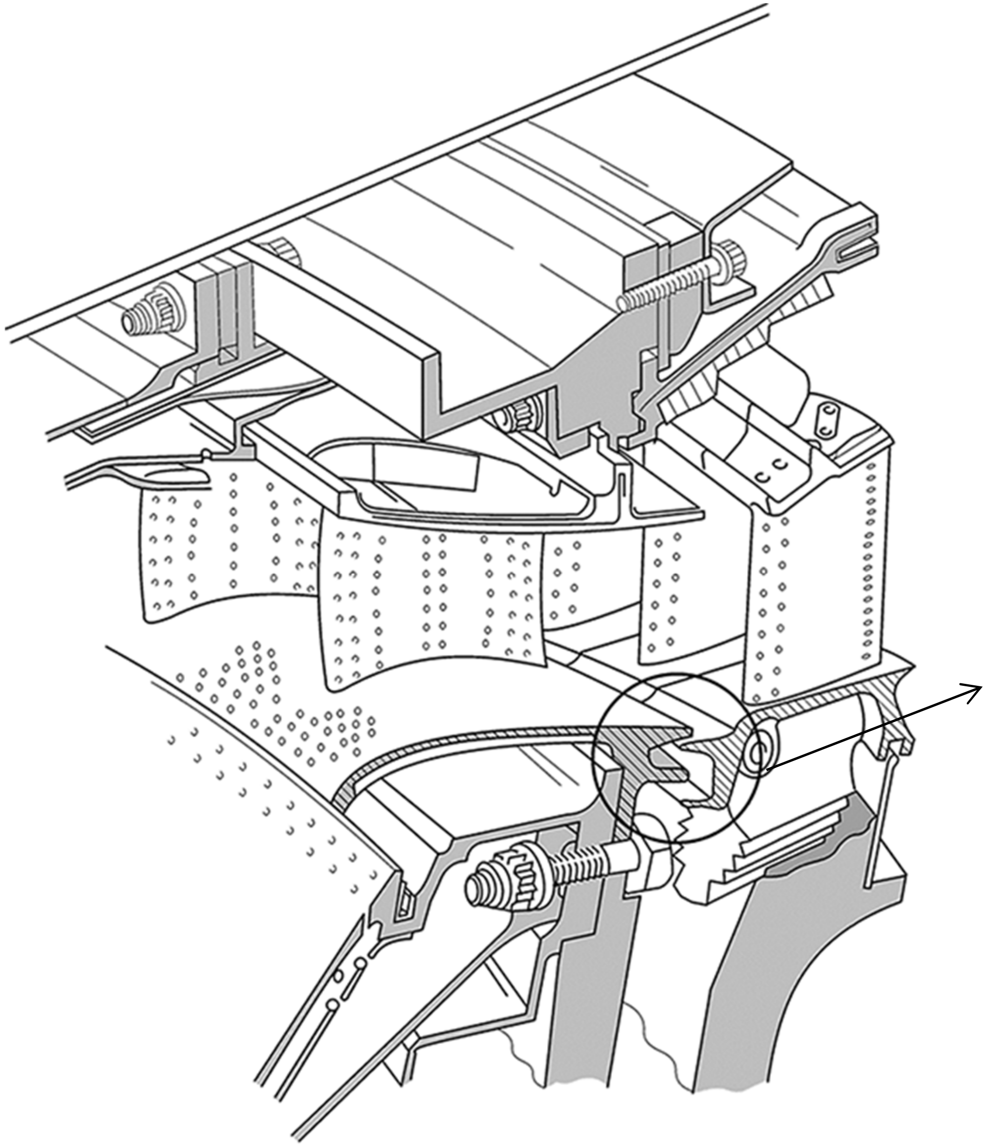
Summary of the different functions of a typical SAS architecture for a double spool jet engine



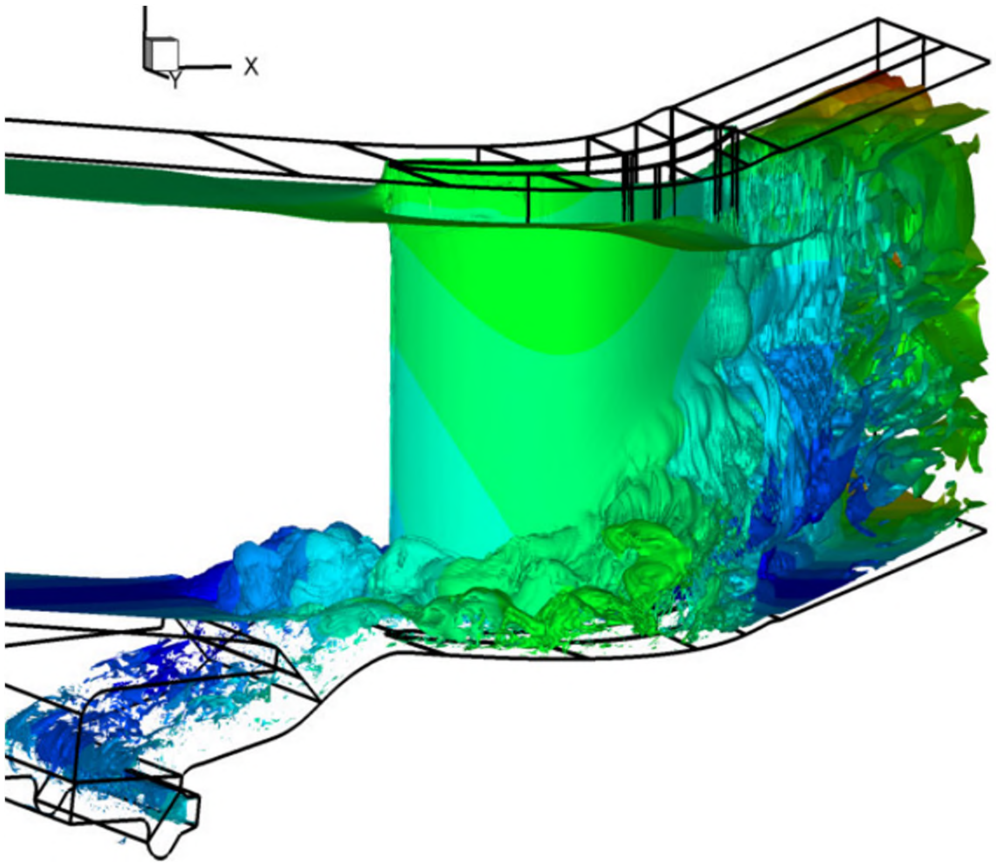
Caty, KTH, MSc Thesis, 2012

Circuit Number	Main Functions
1	LPC rotor cooling Front bearing chamber pressurization (front)
2	Front bearing chamber pressurization (rear) HPC, HPT and LPT disk cooling (last stage) Rear bearing chamber pressurization LPT rear cavity purge
3	HPT rear cavity cooling and purge LPT nozzle cooling LPT front cavity cooling and purge
4	HPT front cavity purge HPT rotor blade cooling
5	HPT nozzle and HPT lower part cooling
6	HPT upper part cooling
7	Nacelle anti icing
8	LPT active clearance control
9	Customer bleed and wing anti icing

Secondary Air System (SAS)



C Sangan, J. Turbomach. 135(2), 021013



Influence of the rim seal geometry on the main passage flow. Rim seal is used to minimise ingestion of hot gas into the wheel-space of a gas turbine. (Vorticity magnitude isosurfaces for the included cavity geometry, *GT2013-94416*)