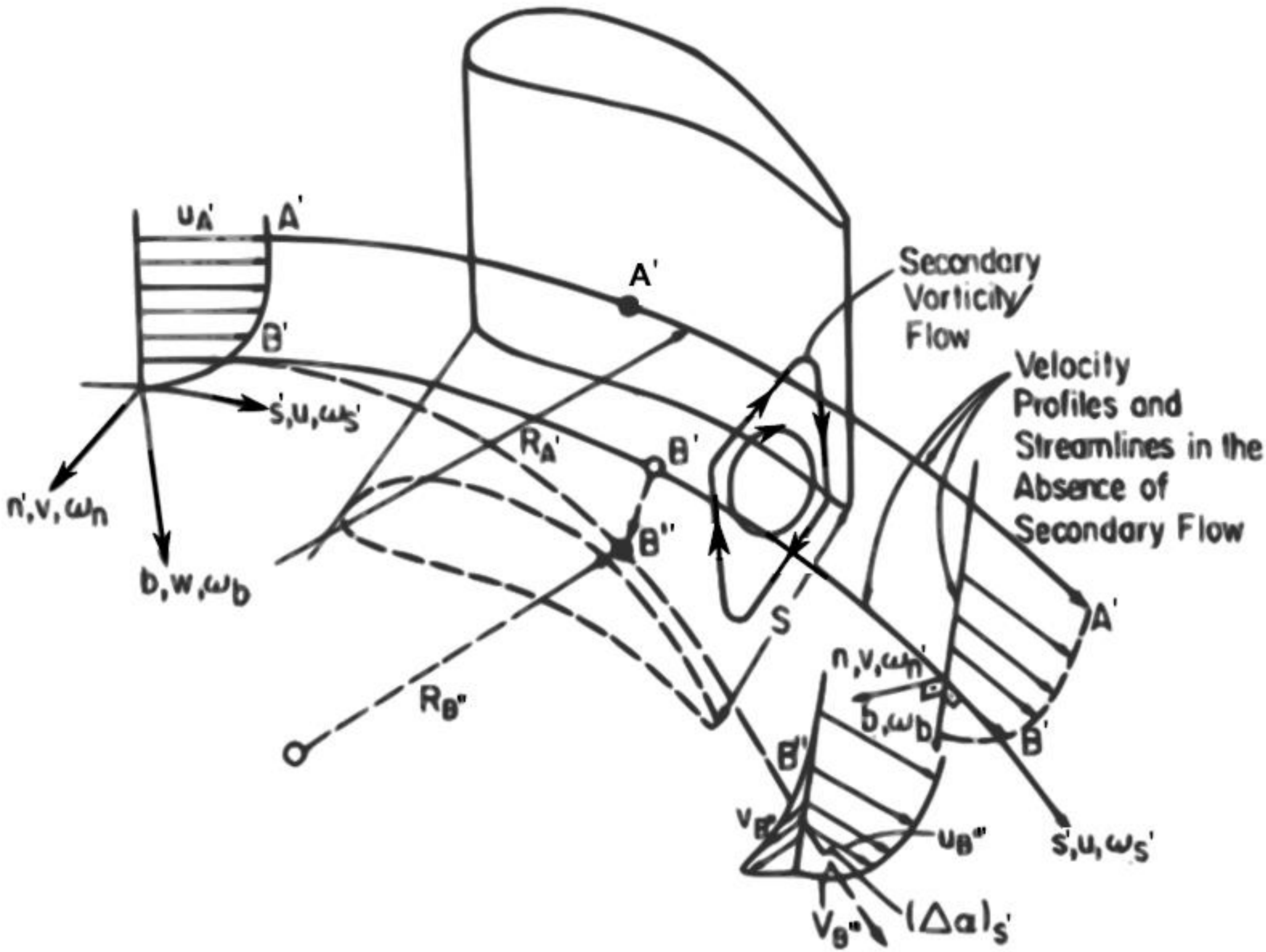
- Recap: Lecture 8: 11th August 2015, 1530-1655 hrs.
  - 3-D losses in an axial compressor
    - Axi-symmetric versus non-axisymmetric analysis
    - Secondary flows
      - Physics of secondary flows
      - Inviscid and viscous theories

- Secondary flows
  - Occur in flow through curvatures.
  - Flow through curved diffusers, compressor, turbine blade passages.
  - Flow in a direction perpendicular to the primary flow.
  - Usually appears as a pair of counter-rotating vortices.
  - Due to imbalance between the radial pressure gradient and the centripetal forces.
  - Different analytical methods for understanding secondary flows: inviscid analysis: gyroscope analogy, viscous analysis.
  - Tip leakage flows and secondary flows are often indistinguishable.



Secondary flow development (Hawthorne, 1955)

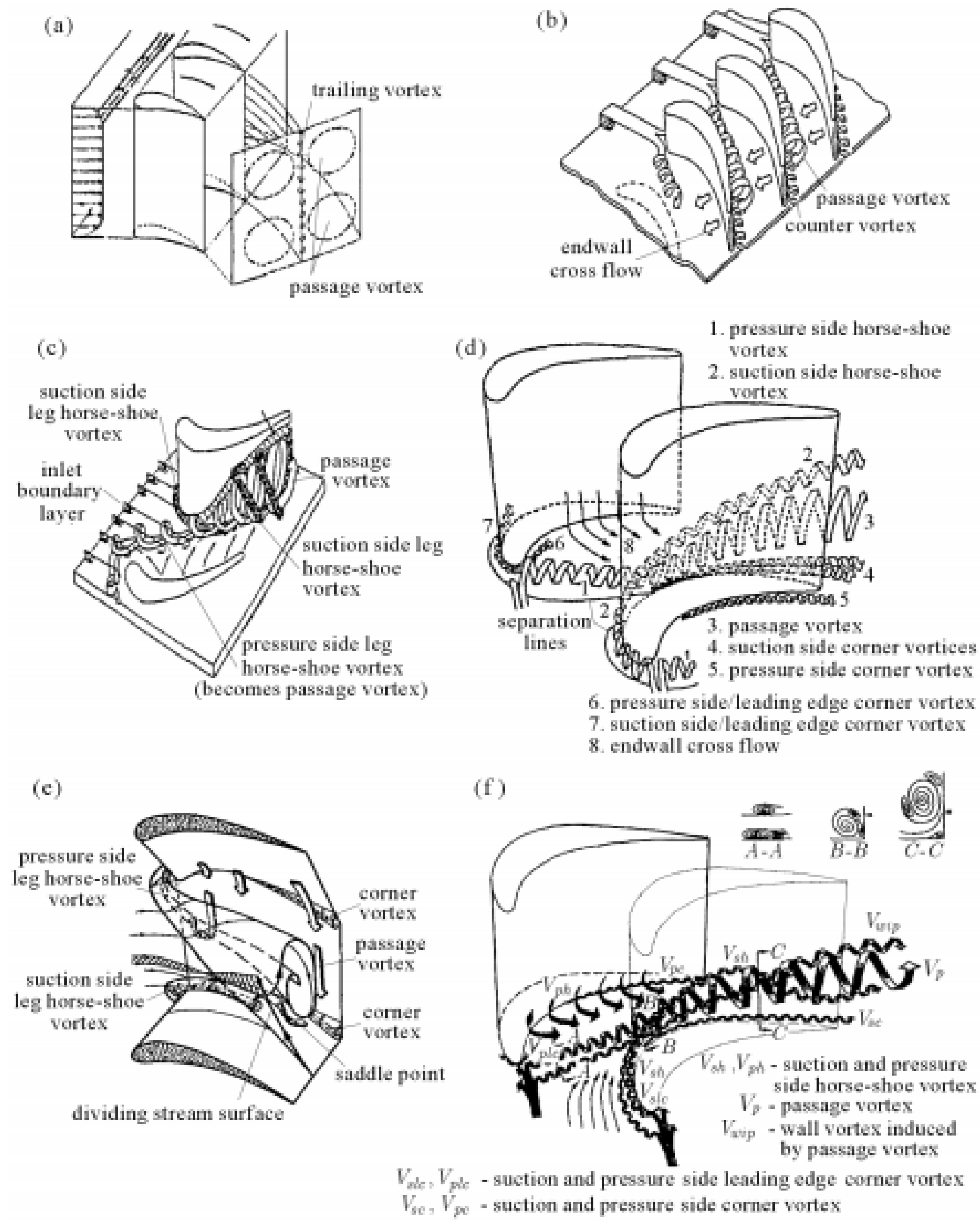
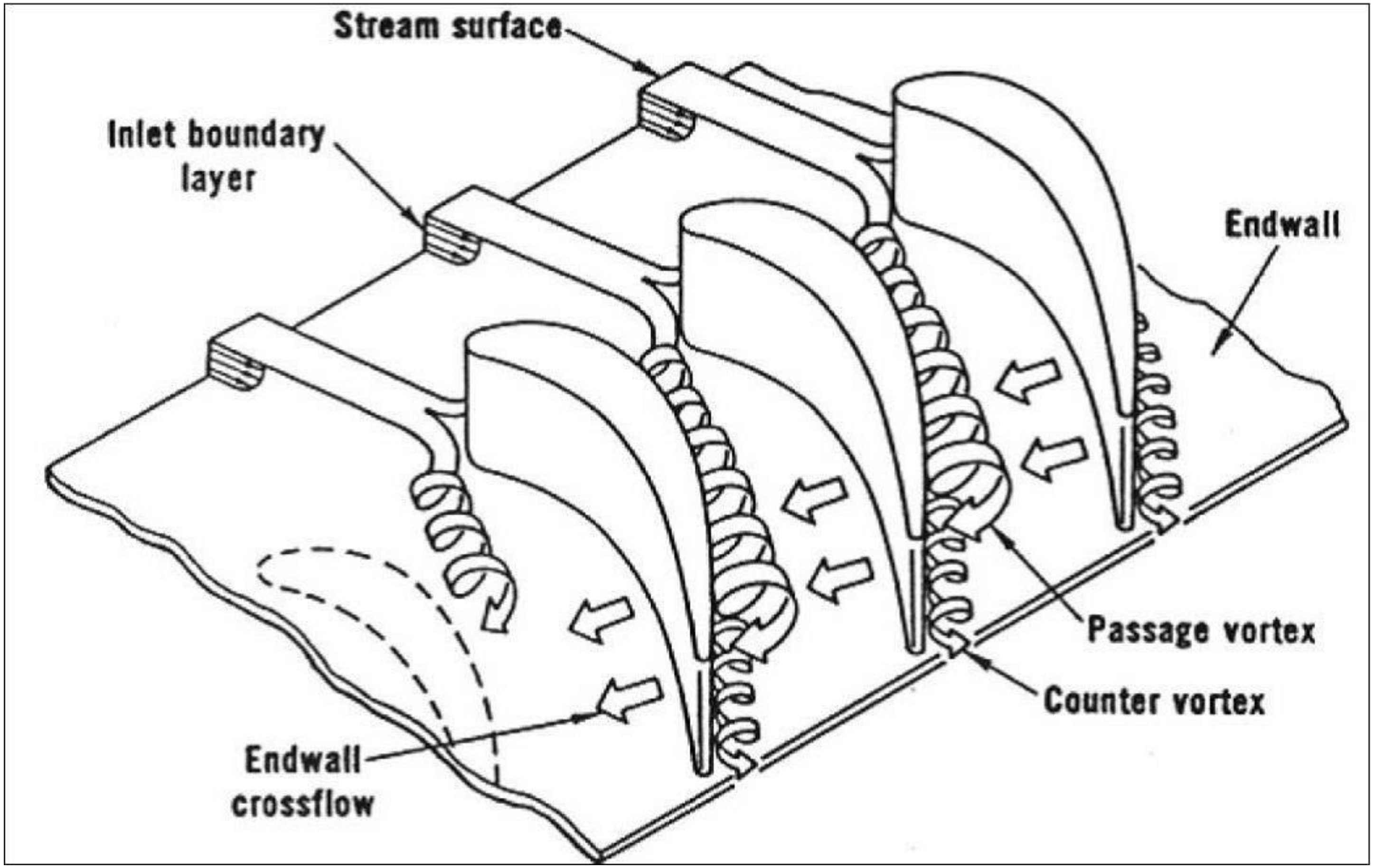
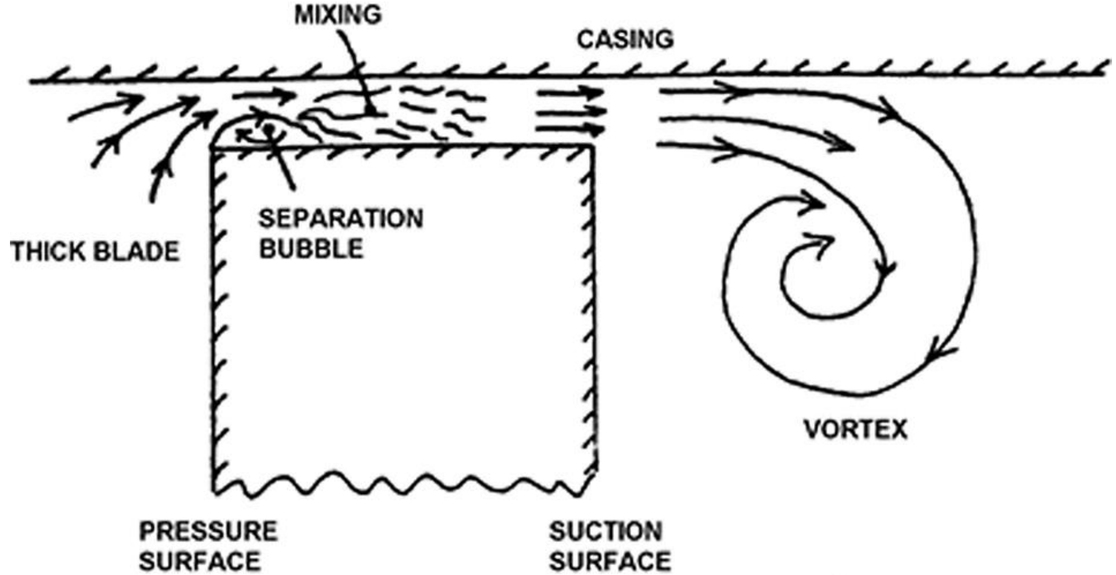


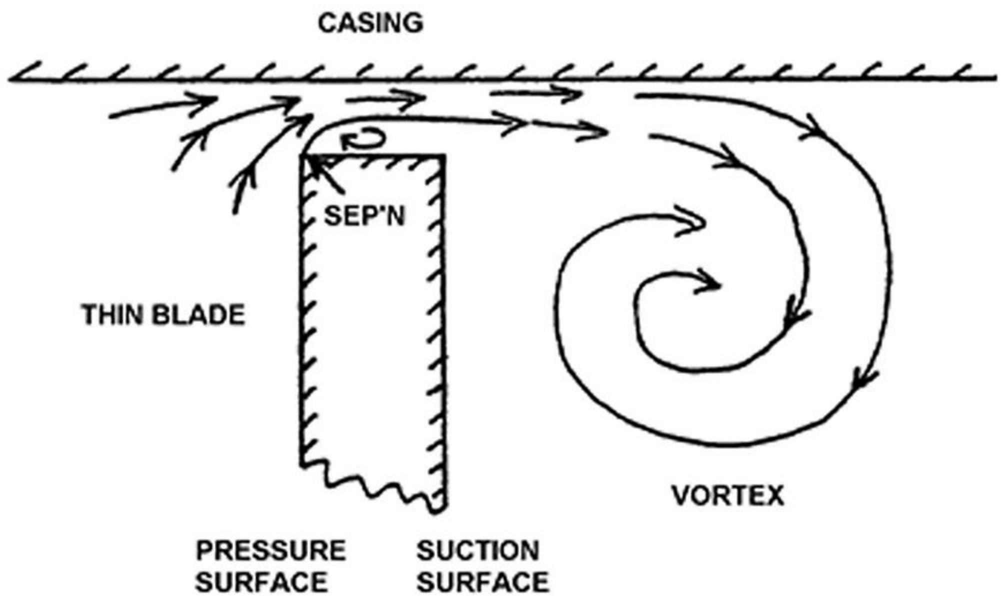
Fig. 1. Secondary flow models in turbine cascades: (a) – model of Hawthorne (1955), (b) – model of Langston (1980), (c) – model of Sharma and Butler (1987), (d) – model of Goldstein and Spores (1988), (e) – model of Doerffer and Amecke (1994), (f) – model of Wang *et al.* (1997)



Langston's secondary flow development model for turbines

- Tip leakage flows and losses
  - Tip clearance is a mechanical requirement.
  - Account for about 30% of the total losses in compressors and turbines.
  - Tip leakage caused due to difference between the pressure surface and the suction surface.
  - Tip leakage flow when interacts with the primary flow, results in a vortex.
  - This vortex causes total pressure losses.
  - Interaction of this vortex with the stator downstream also causes losses in the stator.


MIXING
CASING
SEPARATION
BUBBLE
THICK BLADE
VORTEX
PRESSURE
SURFACE
SUCTION
SURFACE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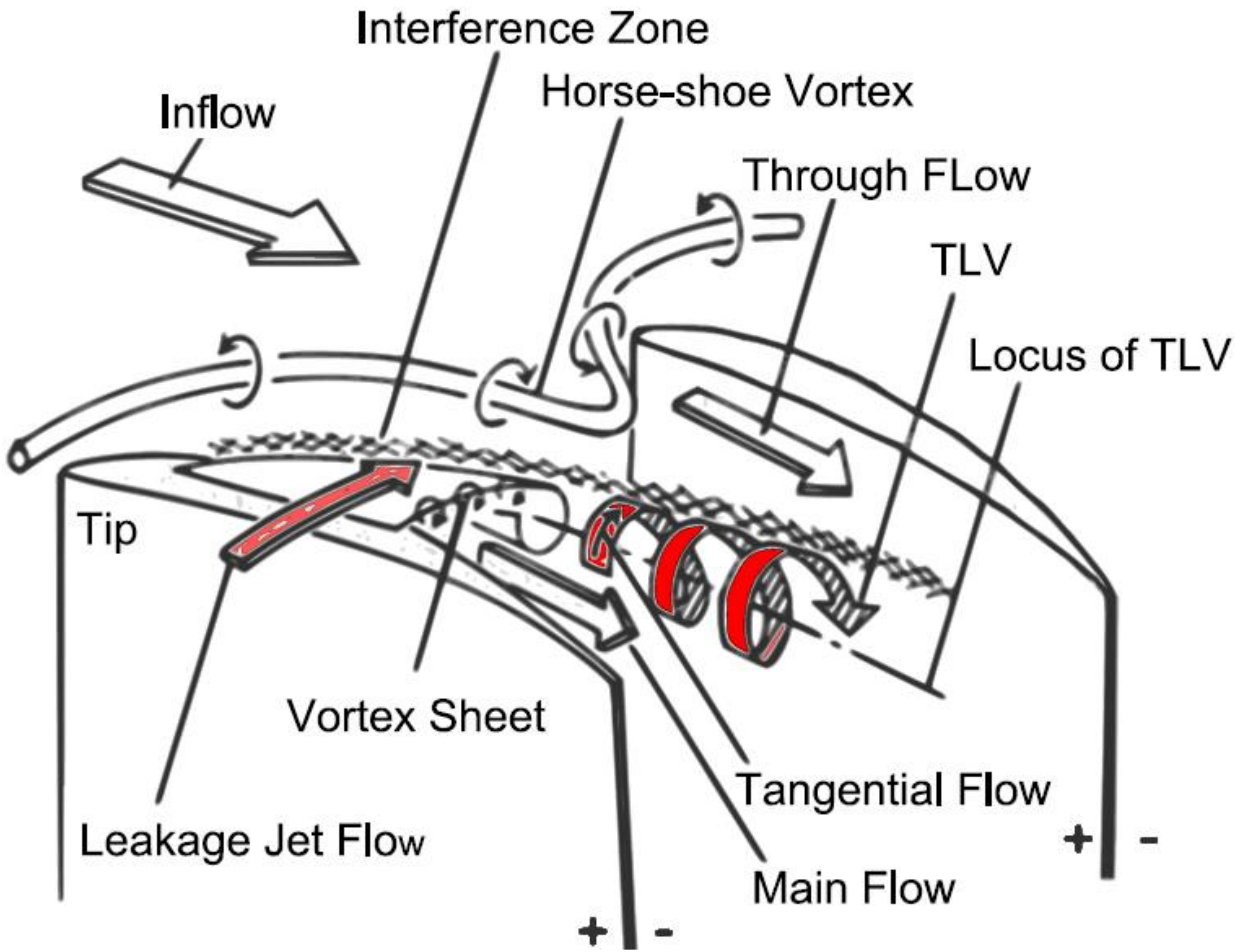
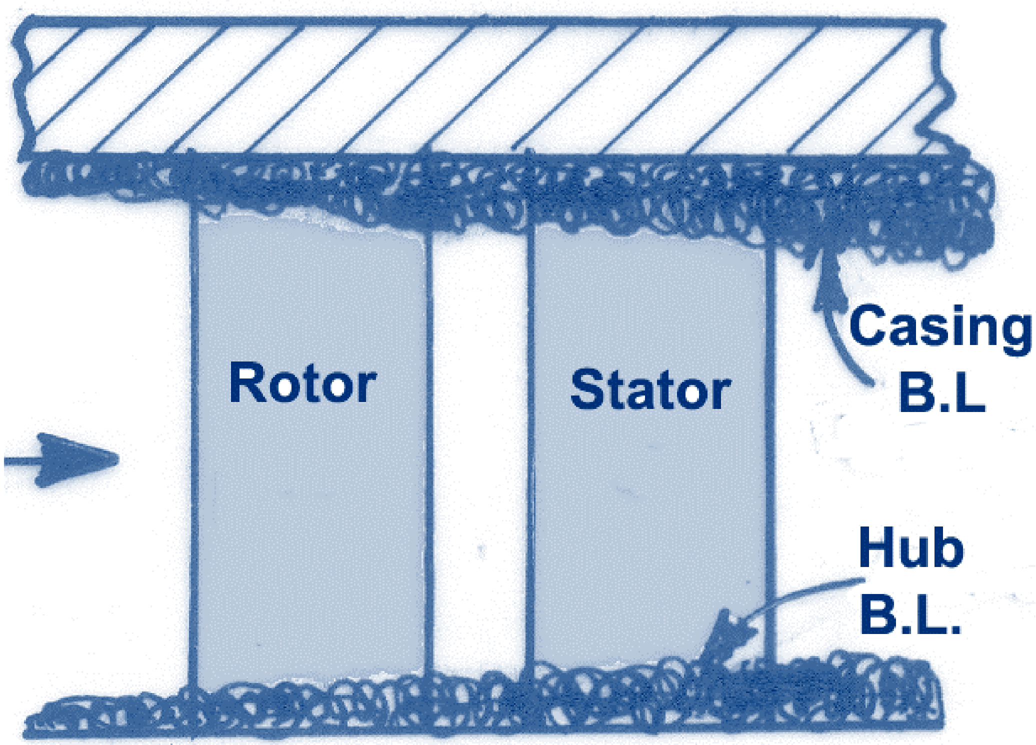


Interaction between the tip leakage flow with the primary flow

- Tip leakage flows and losses
  - Tip clearance varies with operation.
  - Usually increases due to differential expansion of the casing and the blades.
  - Increase in tip clearance results in a corresponding increase in losses.
  - Compressor blades operating at off-design conditions suffer increased losses due to interaction of the tip leakage flow with the thick boundary layer on the blade suction surface.

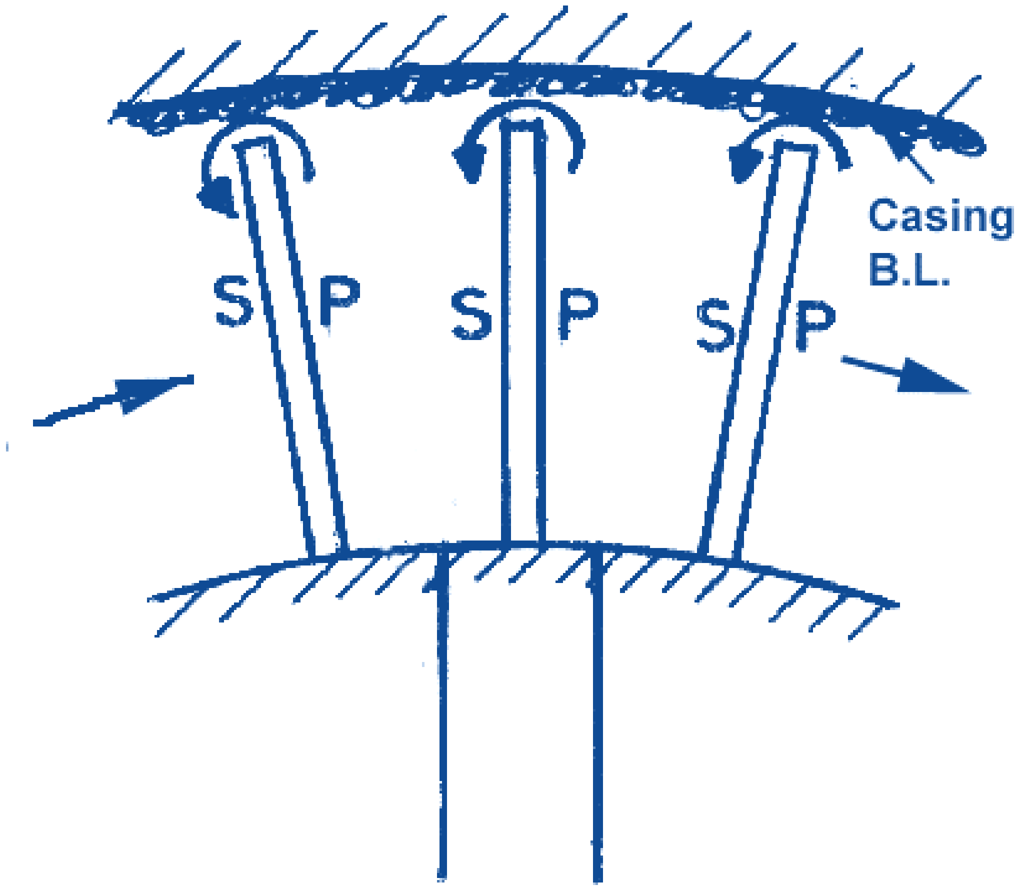
3-D flow in axial compressors



Boundary layer development at casing and hub (due to adverse pressure gradient of main flow) further contributes to 3-D flow development

End-wall Boundary layer development

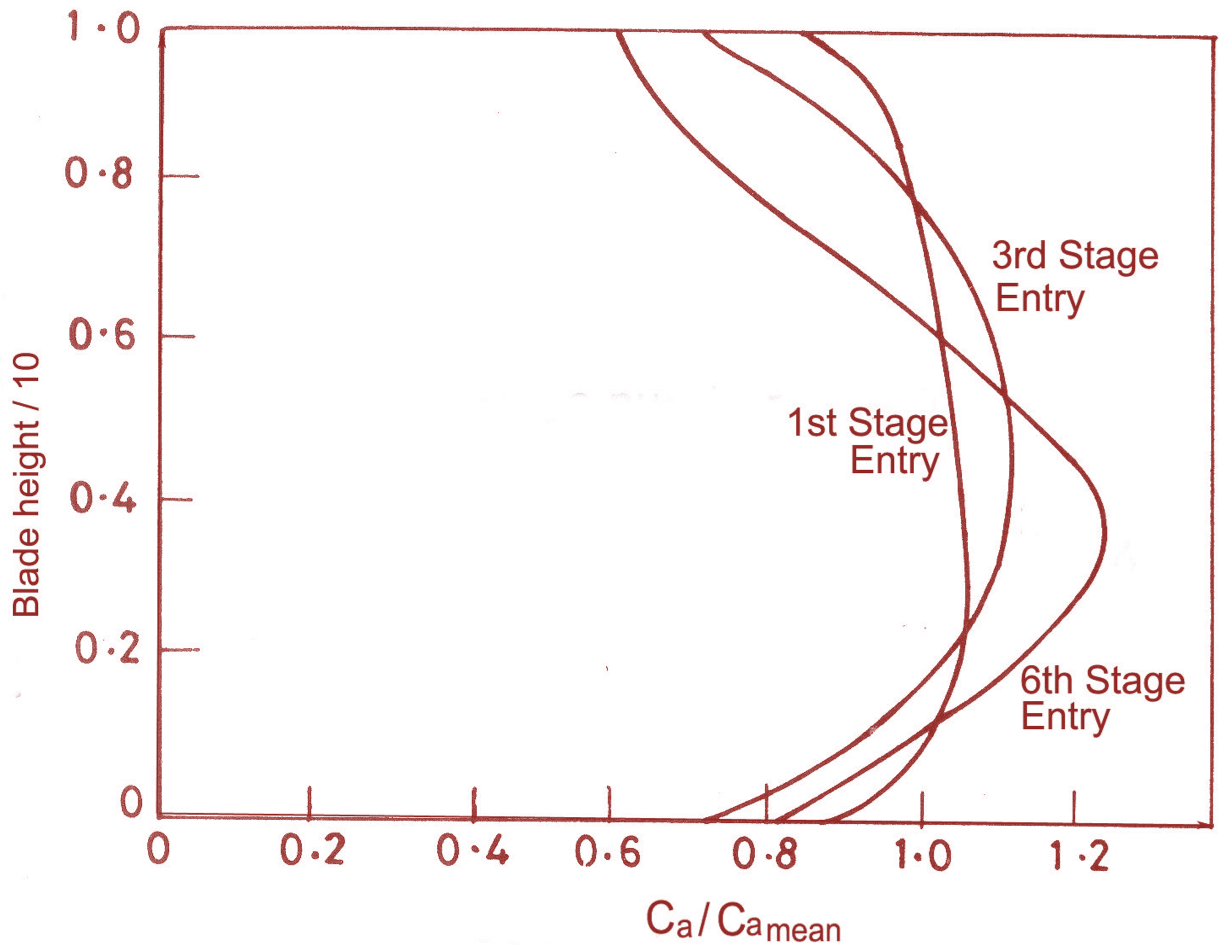
3-D flow in axial compressors



Scrubbing

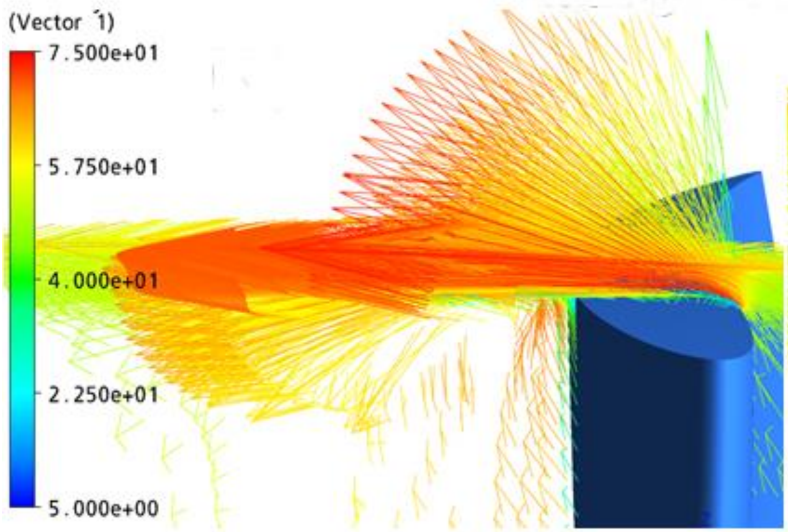
- Tip cross flow is opposite in motion to the rotation of the rotor blades
- Blade tip scrubs through casing boundary layer

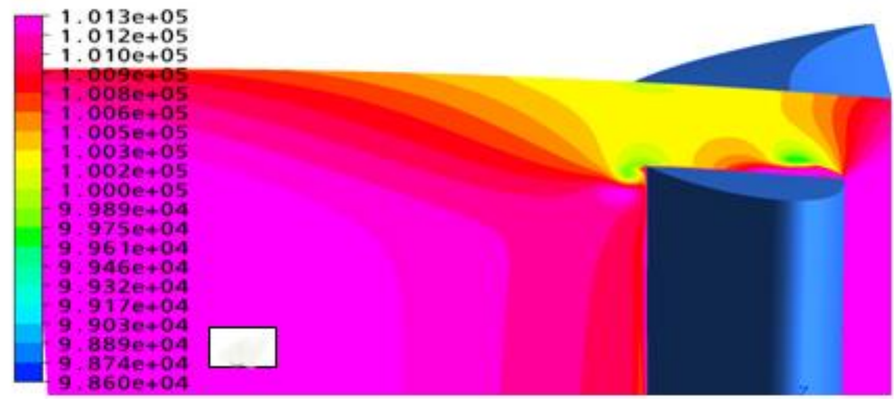
3-D flow in axial compressors

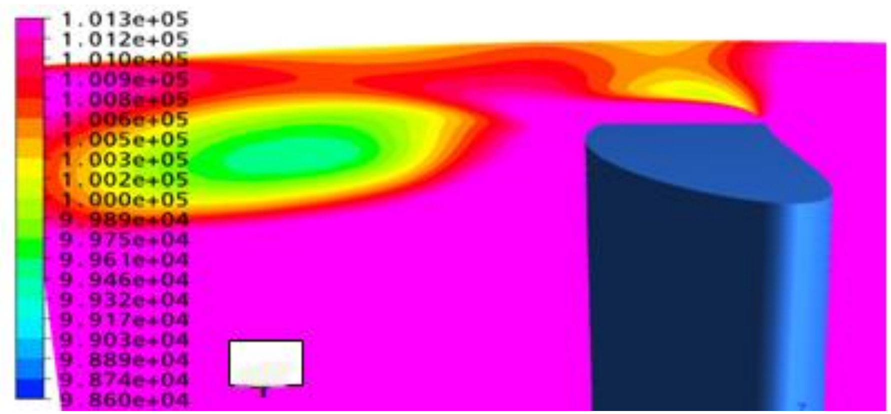


Change of inlet velocity profile through stages

3-D flow in axial compressors

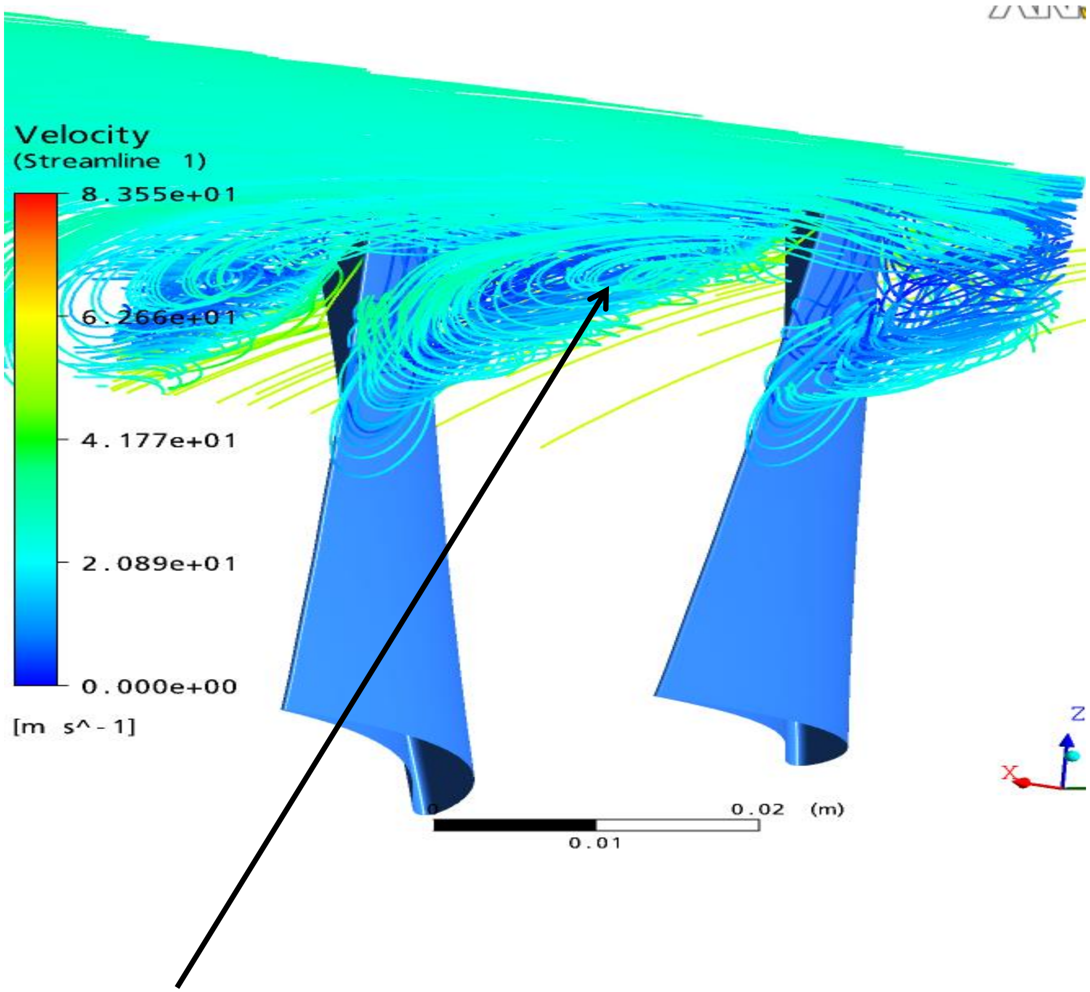






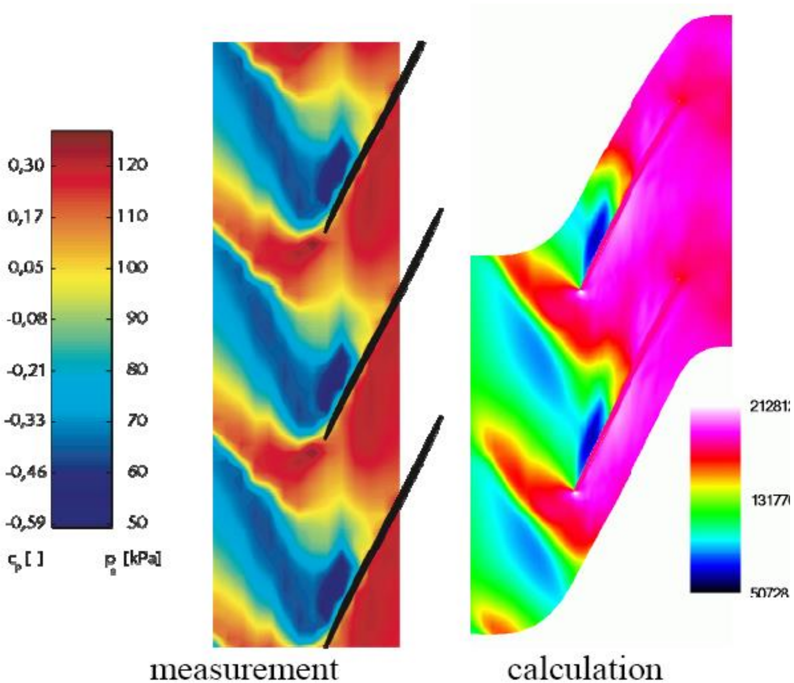
Flow across blade tip

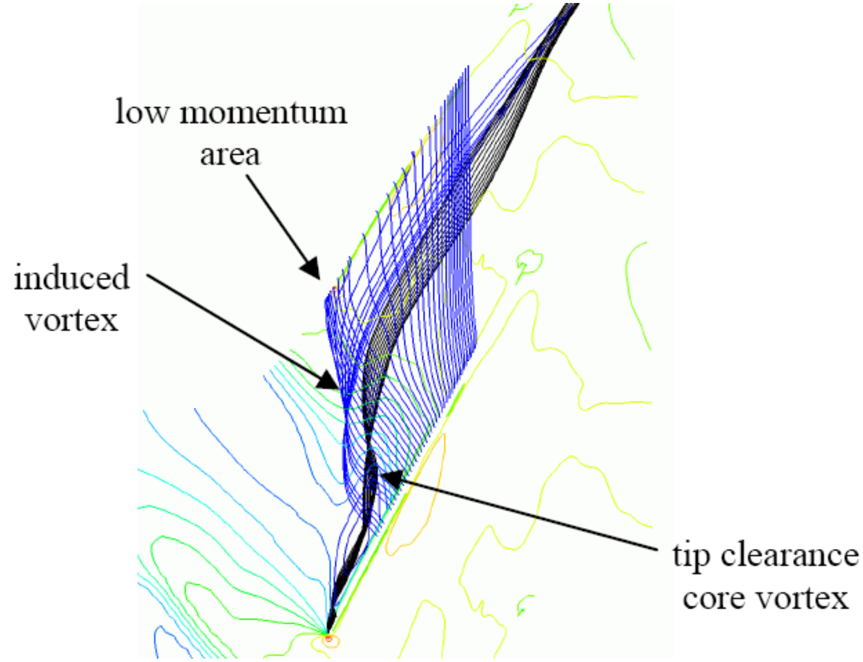
3-D flow in axial compressors



Passage vortex development across blade passage

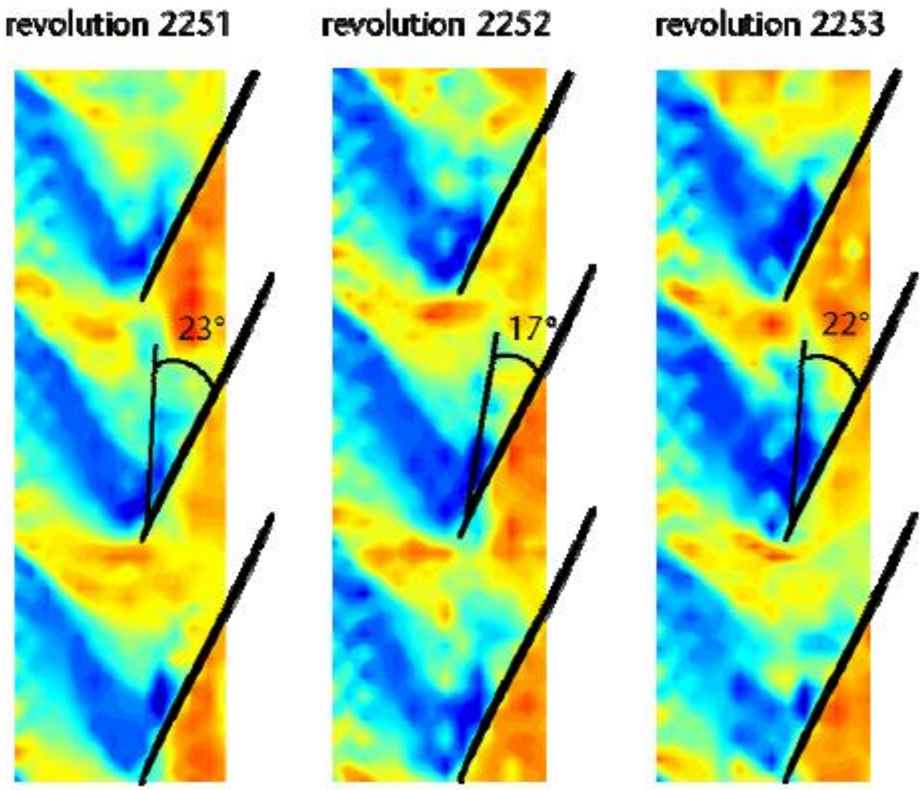
Tip leakage flows





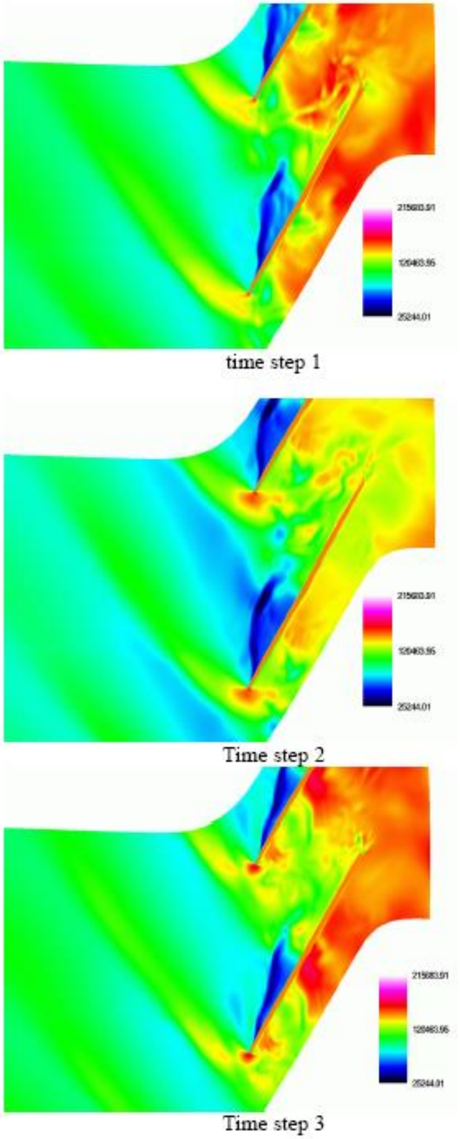
Casing static pressure distribution and particle traces near stall (Hah et al. (2008)

2008 ASME TURBO EXPO Conference, Berlin, Germany



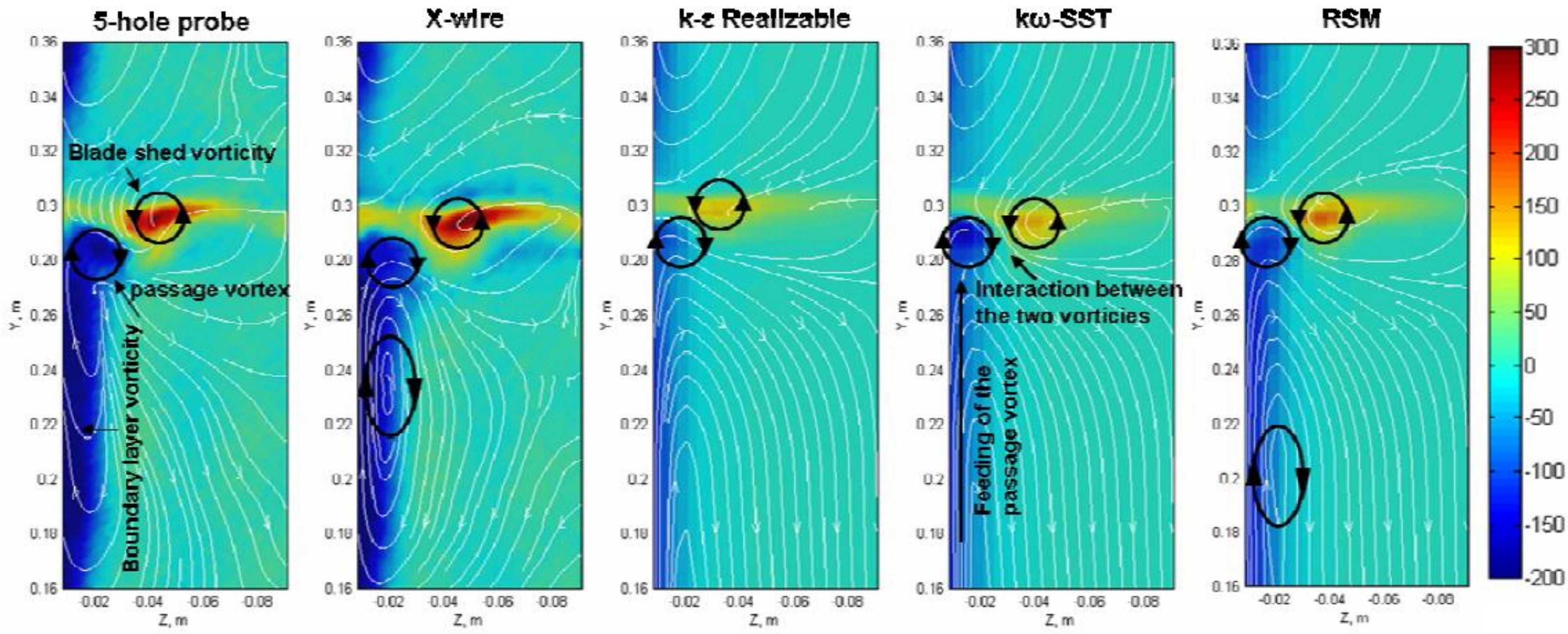
Measured

Vortex fluctuations close to stall (Hah et al. 2008)



Computed

Passage vortex



Streamwise vorticity at downstream location of 0.5C of the blade (Hjarne et al. 2007)

2007 ASME TURBO EXPO Conference, Montreal, Canada

Radial equilibrium analysis

- Account for radial variations in
  - Blade speed
  - Axial velocity
  - Tangential velocity
  - Static pressure
- Large variations in these parameters can occur as the flow passes through a rotor.