Design Optimization of A Small Scale High Expansion Ratio Organic Vapour Turbo Expander for Automotive Application

Presenter: Qiyu YING

Co-writer: Weilin ZHUGE, Yangjun ZHANG, Lei ZHANG

2017.09.14

清華大學
Tsinghua University

Content

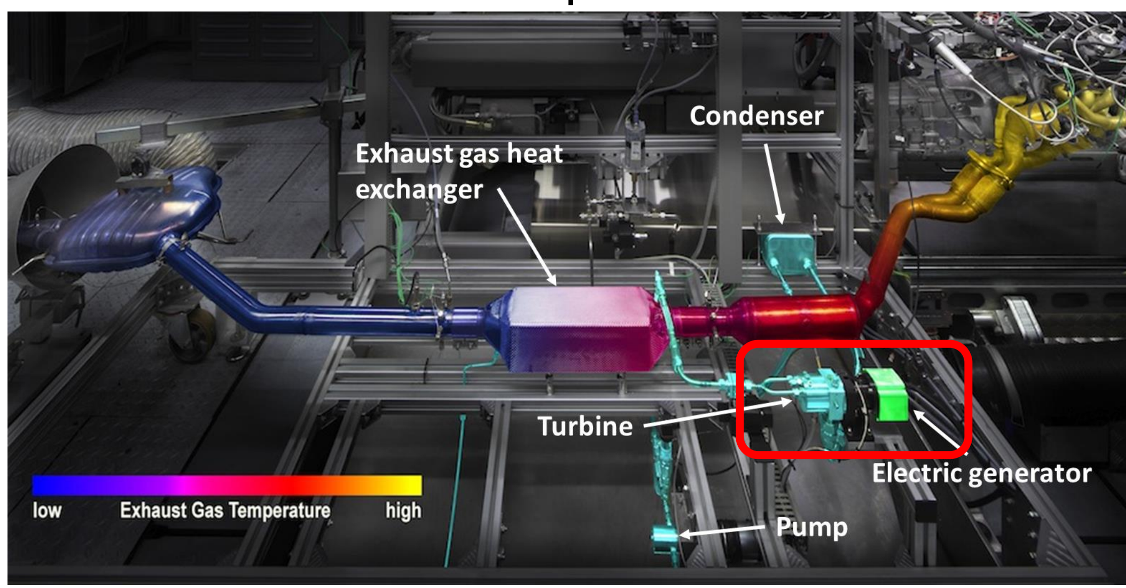
- Introduction
- Numerical methods
- Simulation and optimization
- Conclusions

Introduction

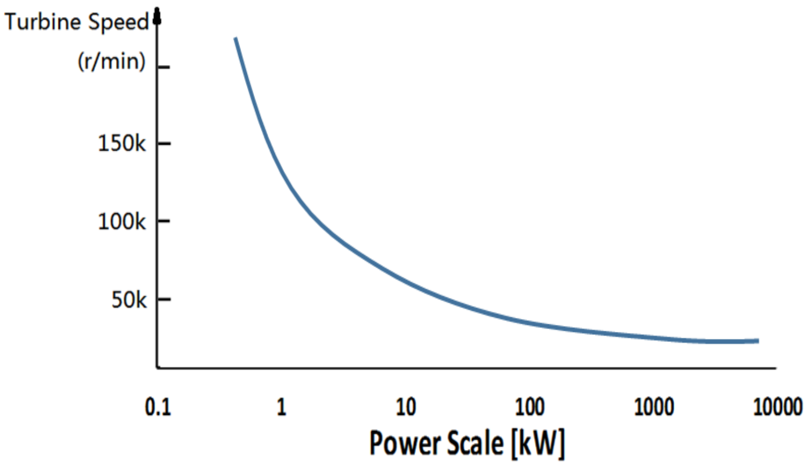
- Problems within ICE waste heat recovery
  1. Low-grade energy, fluctuation conditions
  2. Space requirements
  3. Shock resistance
  4. Safety
  5. Coupled with ICE

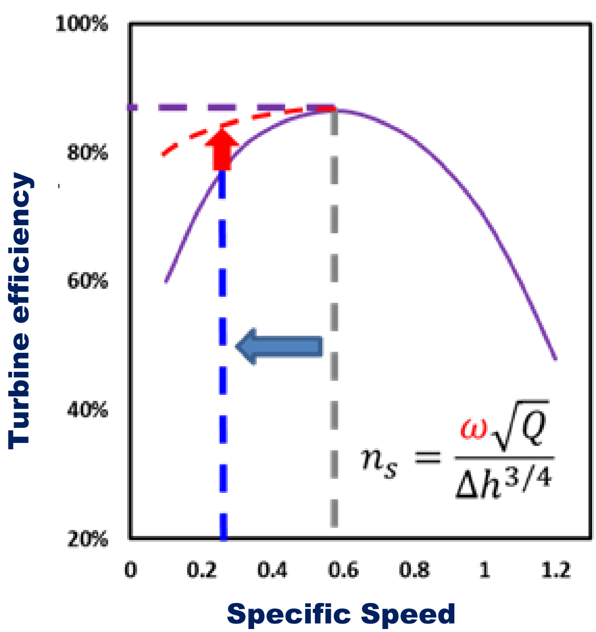
- Organic Rankine Cycle
  + Efficiency
  + Stability
  + Compact configuration
  + Low temperature range performance

★ Expander is the most significant component since it affects the system directly

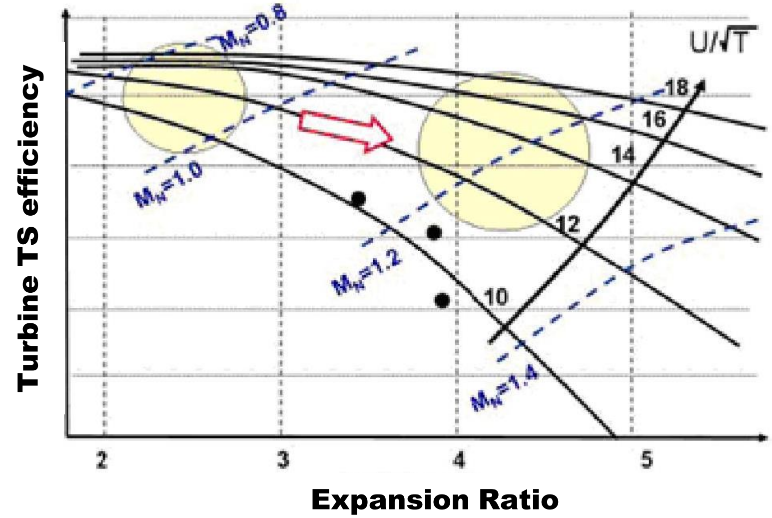


Introduction





$$\eta_{cycle} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_{\text{out}}}{T_{\text{in}}} = 1 - (\frac{p_{out}}{p_{in}})^{\frac{k-1}{k}}$$



★ Improve expansion ratio helps increase system efficiency and turbine load

★ **Difficulty 1**: Small power leads to high rotation speed

★ **Difficulty 2**: High expansion ratio as well as organic substance leads to high Mach number

Radial-inflow Turbine

Design specifications and operating point conditions

Part	Parameters	Values (Unit)	Part	Parameters	Values (Unit)
Design Working Condition	Working fluid	R245fa	Vane	Outlet radius	81（°）
	Total inlet temperature	473 (K)		Blade height	2（mm）
	Total inlet pressure	3200 (kPa)		TE thickness	1（mm）
	Static outlet pressure	400 (kPa)		Blade number	11
	Specific speed	0.3	Rotor	Inlet radius	38（mm）
	Mass flow rate	0.66 (kg/s)		Inlet blade height	2（mm）
	Power	25 (kW)		Exit tip radius	20（mm）
	Rotation speed	40500 (rpm)		Exit hub radius	11（mm）
Volute	Throat radius	60（mm）		Axial length	25（mm）
	Throat area	120（mm^2）		Exit angle	-60（°）
Vane	Inlet radius	48（mm）		Blade number	9
	Inlet angle	75（°）		TE thickness	1（mm）
	Outlet radius	40（mm）		Tip clearance	0.2（mm）

Content

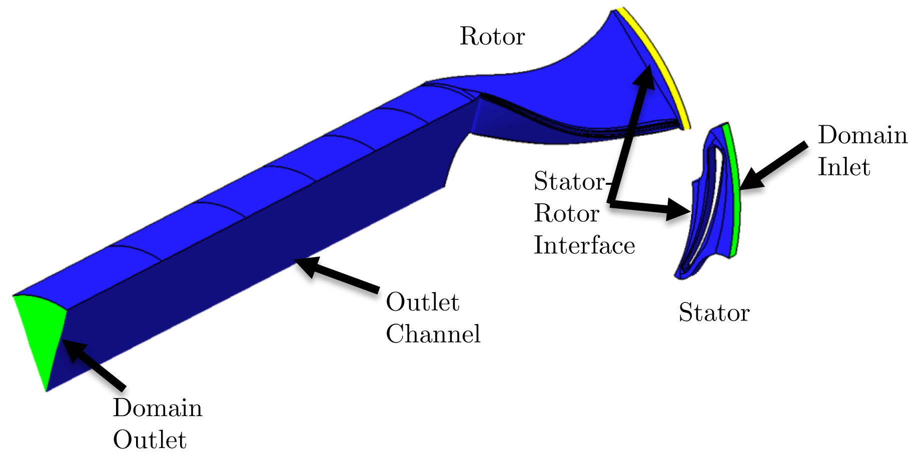
- Introduction
- Numerical methods
- Simulation and optimization
- Conclusions

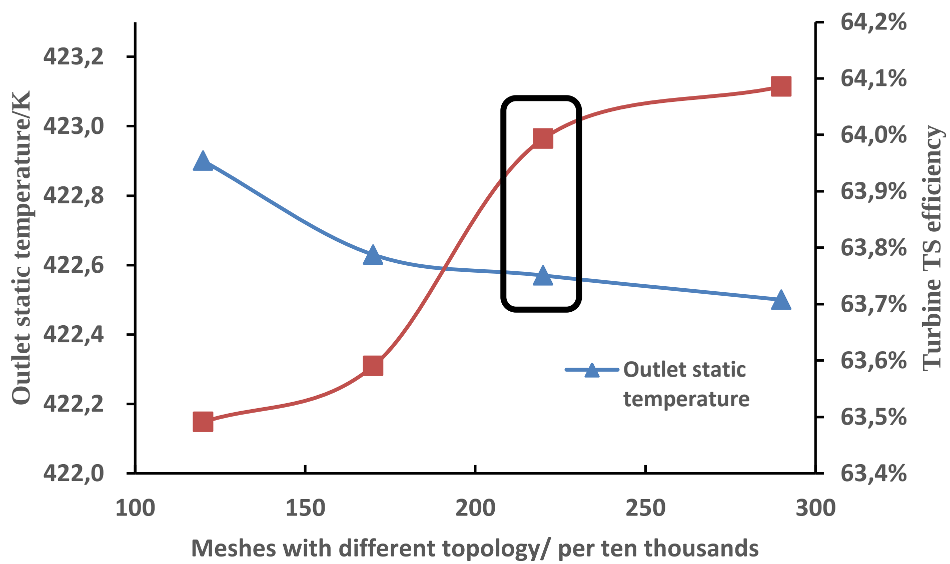
Numerical Method

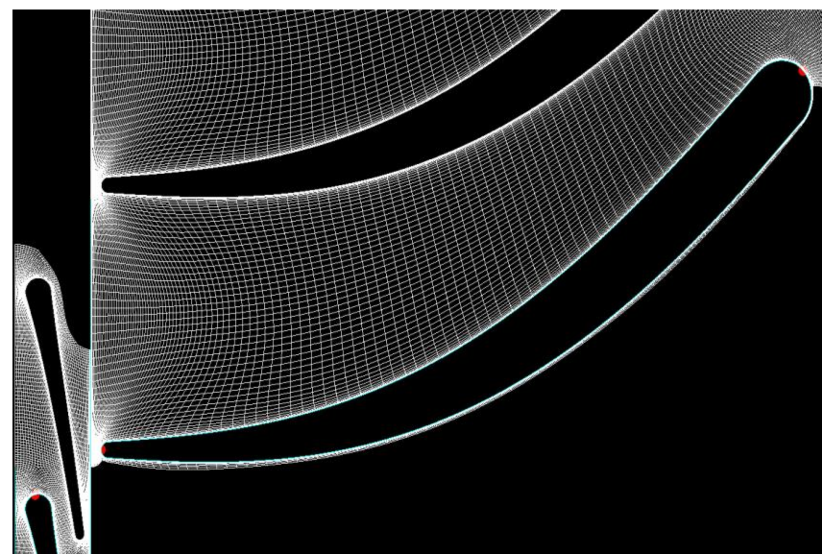
- CFD Software : NUMECA Fine/Turbo
- Simulation with steady condition
- RANS
- SST turbulence model
- Spatial Discretization : Finite volume method
- Time Discretization : Multistage Runge-Kutta
- Rotor-Stator interface : Full non matching mixing plane
- Boundary Condition
  - ▲ Inlet: Total temperature and total pressure
  - ▲ Outlet: Static Pressure

Grid Independence

- Single Channel
- Blade geometries are modified, so that different **topologies** instead of specific grids are tested here







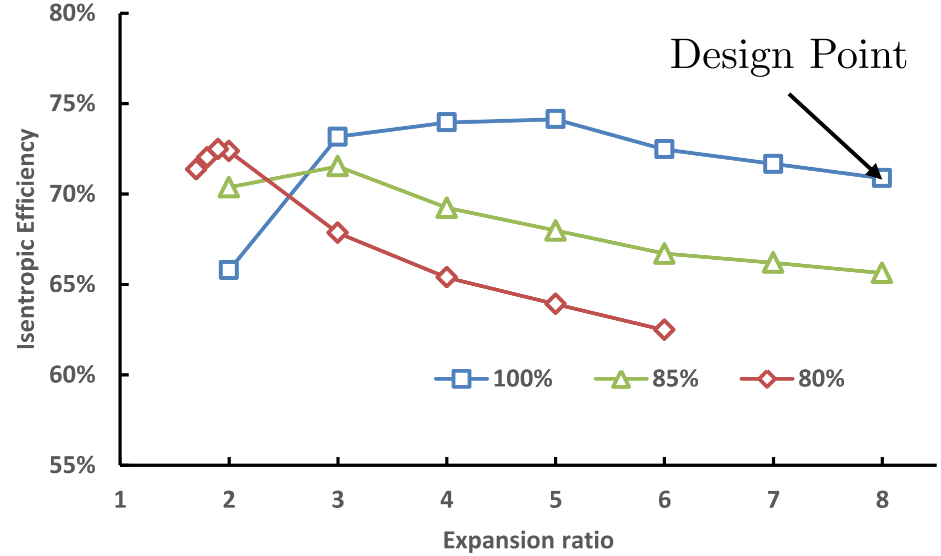
Content

- Introduction
- Preliminary turbine design numerical methods
- Results and discussions
- Conclusions

CFD Simulation

Radial Turbine Simulation

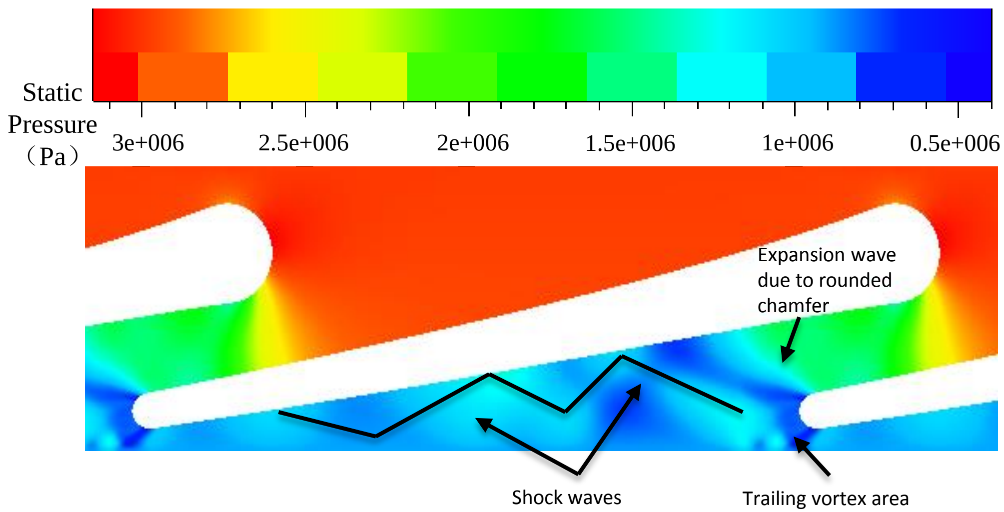
- ✓ Single channel domain without volute
- ✓ Initial conditions are determined from 1D simulation
- ✓ Rotation speed is determined by corrected speed

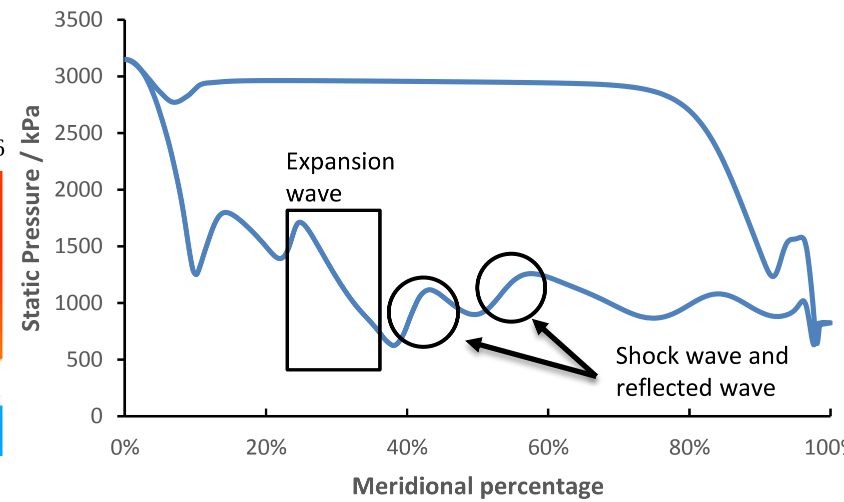


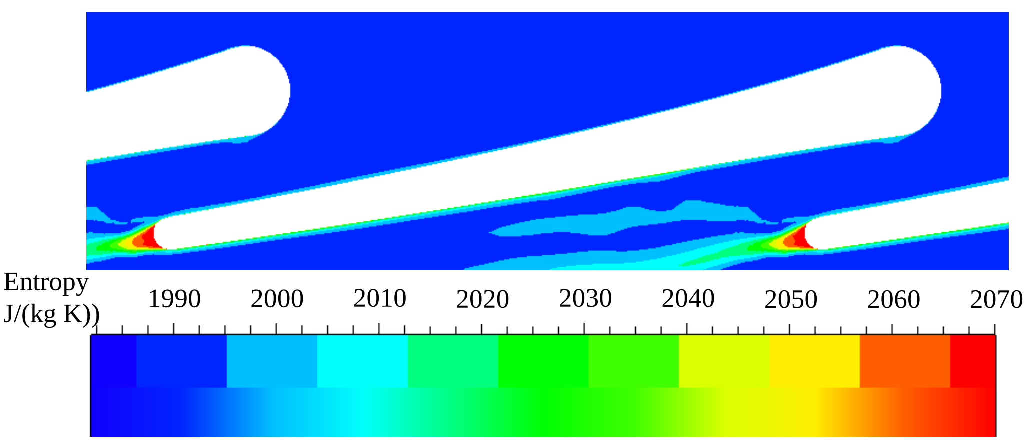
- ◆ Preliminary design point has low efficiency with high expansion ratio conditions
- ◆ Efficiencies are generally lower than 75% within whole working conditions

Parameter	Value
Inlet Total Pressure	3200 (kPa)
Mass Flow Rate	0.65 (kg/s)
Output Power	22.4 (kW)
Isentropic Efficiency	70.88 (%)

Vane Loss Analysis



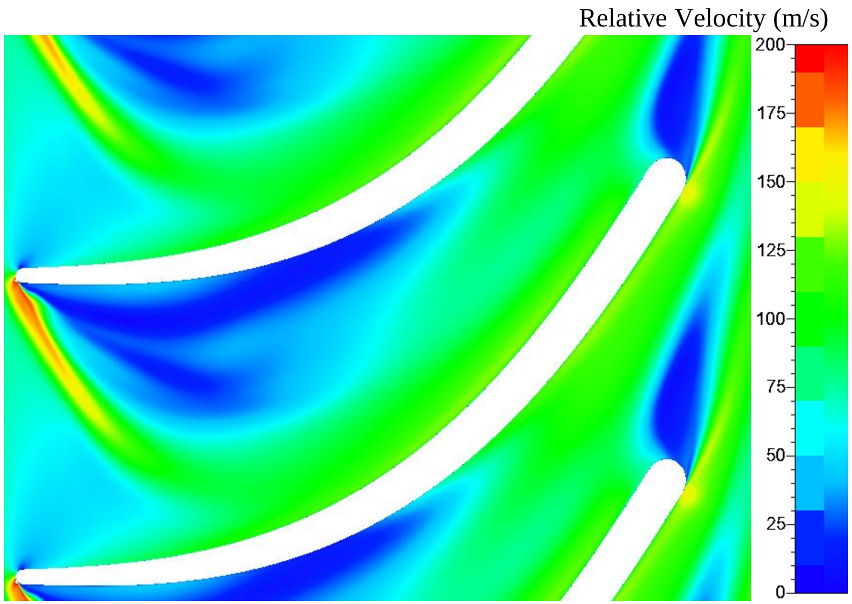


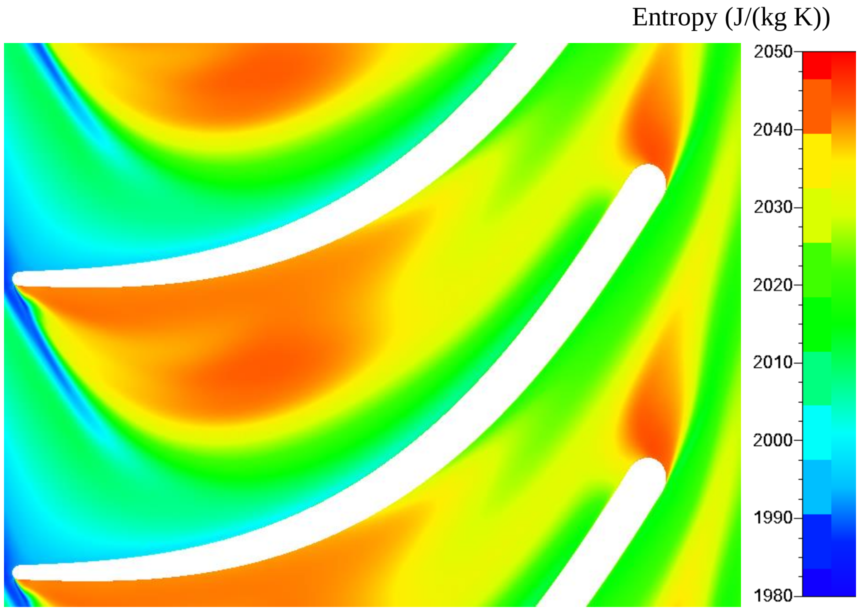


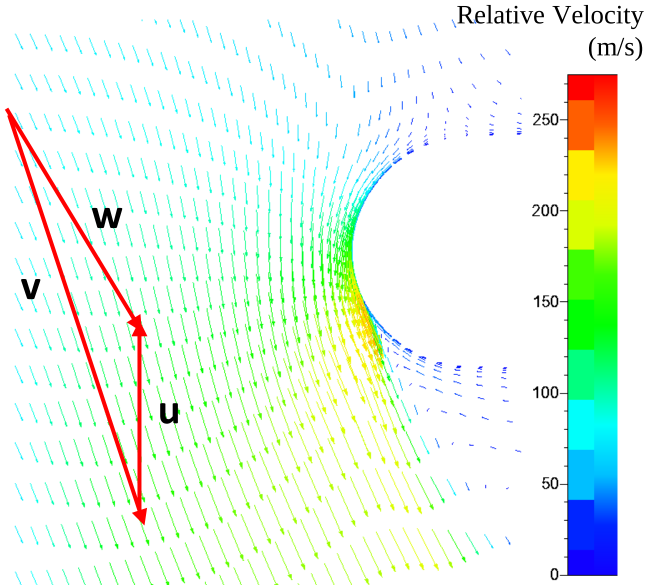
Main Loss in Stator

- Loss raised by shear flow in the trailing edge
- Shock wave loss and interaction between shock wave and boundary layer
- Influence factor: inlet & outlet angle, blade shape

Rotor Loss Analysis





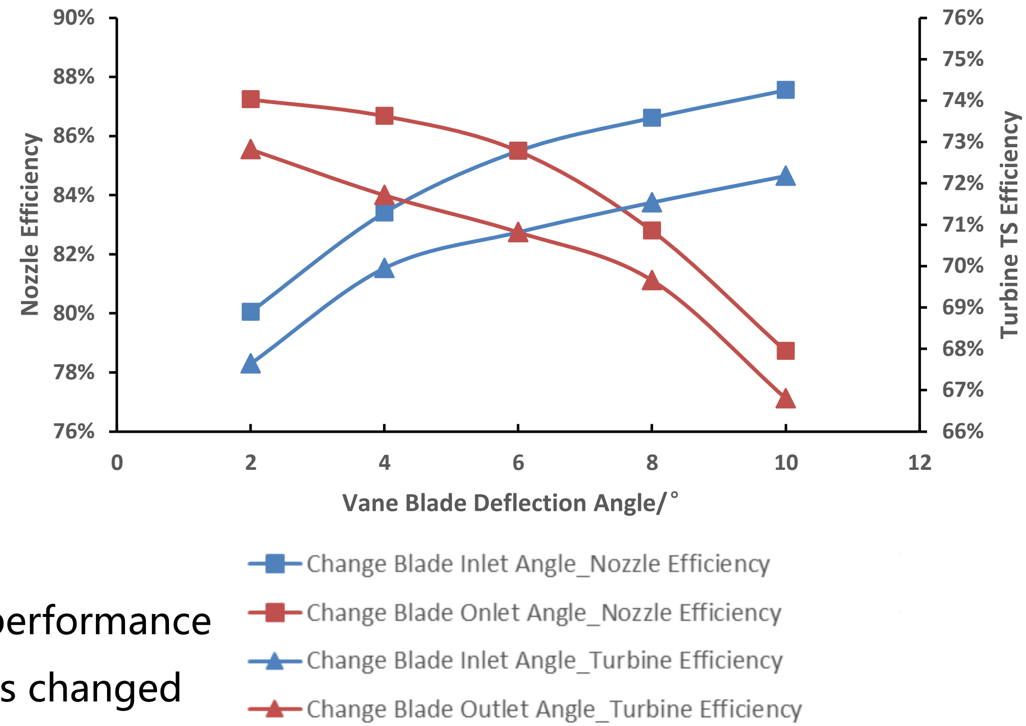


- Main Loss in Rotor
  - High incident angle leads to flow separation in leading edge
  - Shear flow and trailing vortex
  - Influence factor: inlet blade angle, leading edge, trailing edge thickness

Effects of Vane Blade Angle

☐ Effect of vane blade inlet and out angle

- Original inlet blade angle is 75°
- Original Outlet blade angle is 81°
- Blade deflection angle is the difference between inlet and outlet angle, which is 6° initially

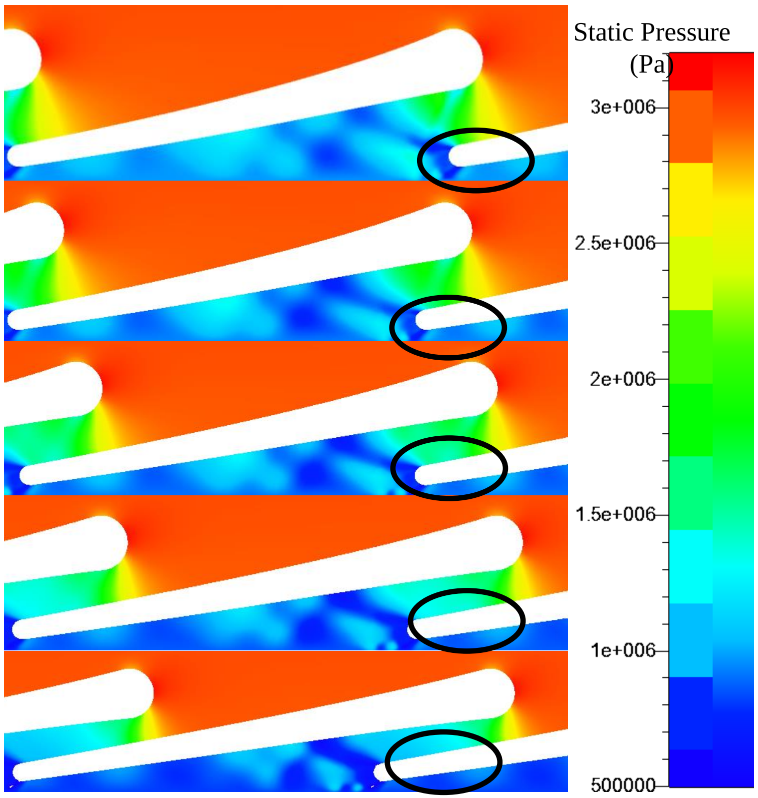


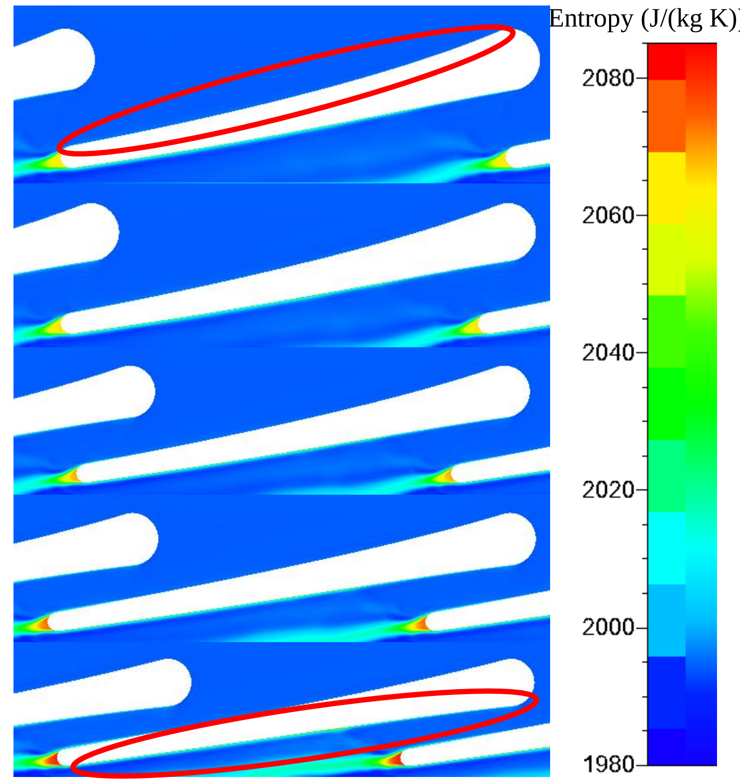
☐ Results Analysis

- ✓ Nozzle performance and turbine performance have similar trend as blade angle is changed
- ✓ Similar turbine efficiency trend can be seen when inlet and outlet angle is changed
- ✓ Increasing blade outlet angle improves more

Effects of Vane Blade Angle

◻ Vane Blade Inlet Angle





◻ Geometry

- ➢ The throat is receding and expansion section prolongs
- ➢ Blade shape varies asymmetrically

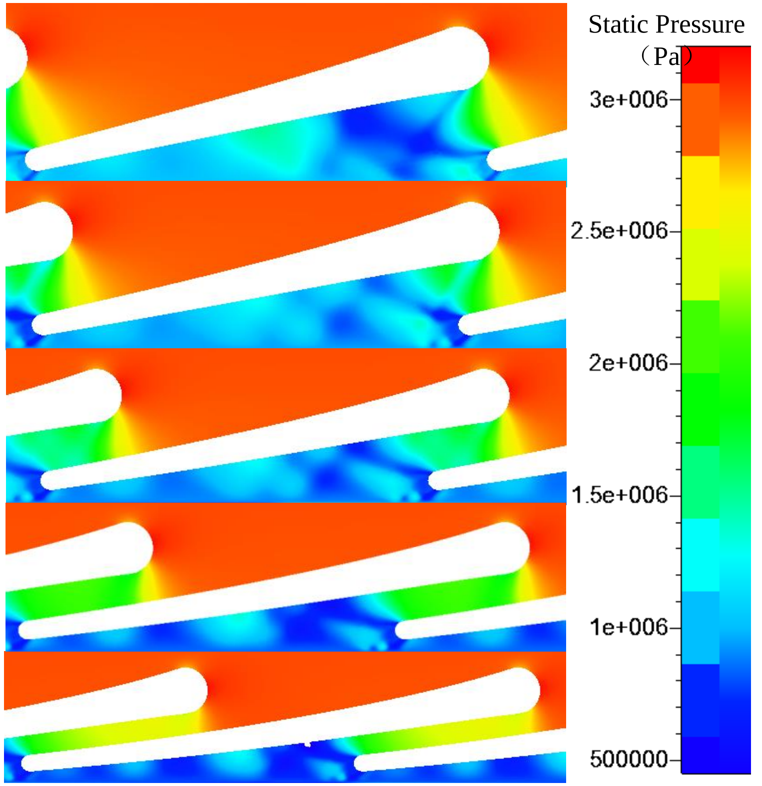
◻ Loss

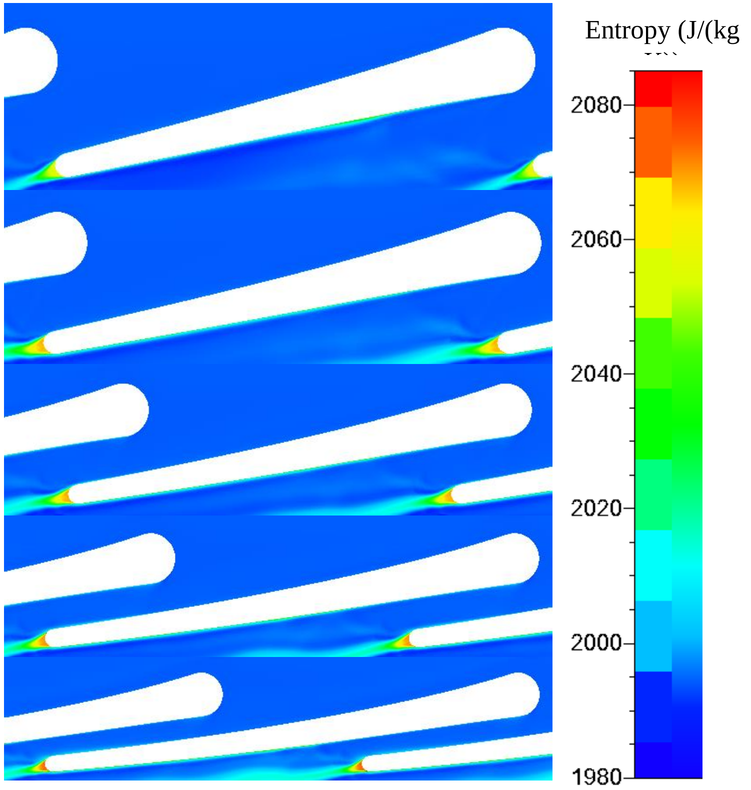
- ➢ Trailing edge loss increases as shear flow enhanced

清華大學 Tsinghua University

Effects of Vane Blade Angle

□ Vane Blade Outlet Angle



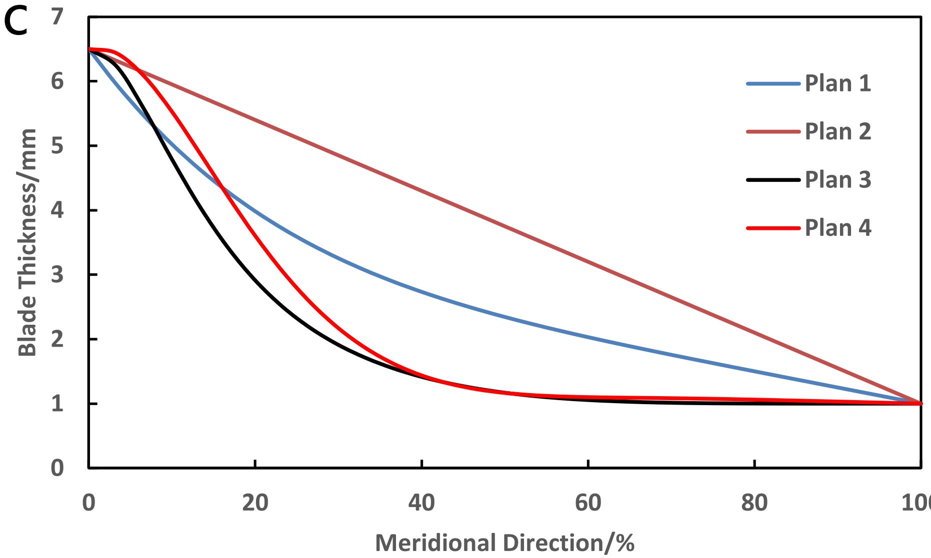


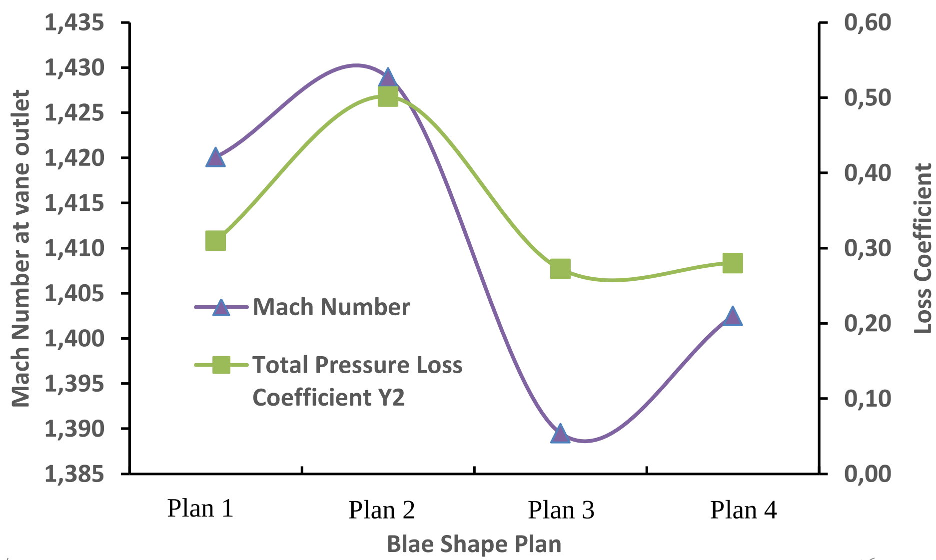
- ✓ Similar Geometry Variation
- ✓ Similar Loss Development

Effects of Vane Blade Shape

◻ Vane Blade Shape at Supersonic Section

Blade Shape Plan	Description
Plan 1	Preliminarily designed shape
Plan 2	Original blade shape with straight expansion section
Plan 3	Parabola shape
Plan 4	MOC shape



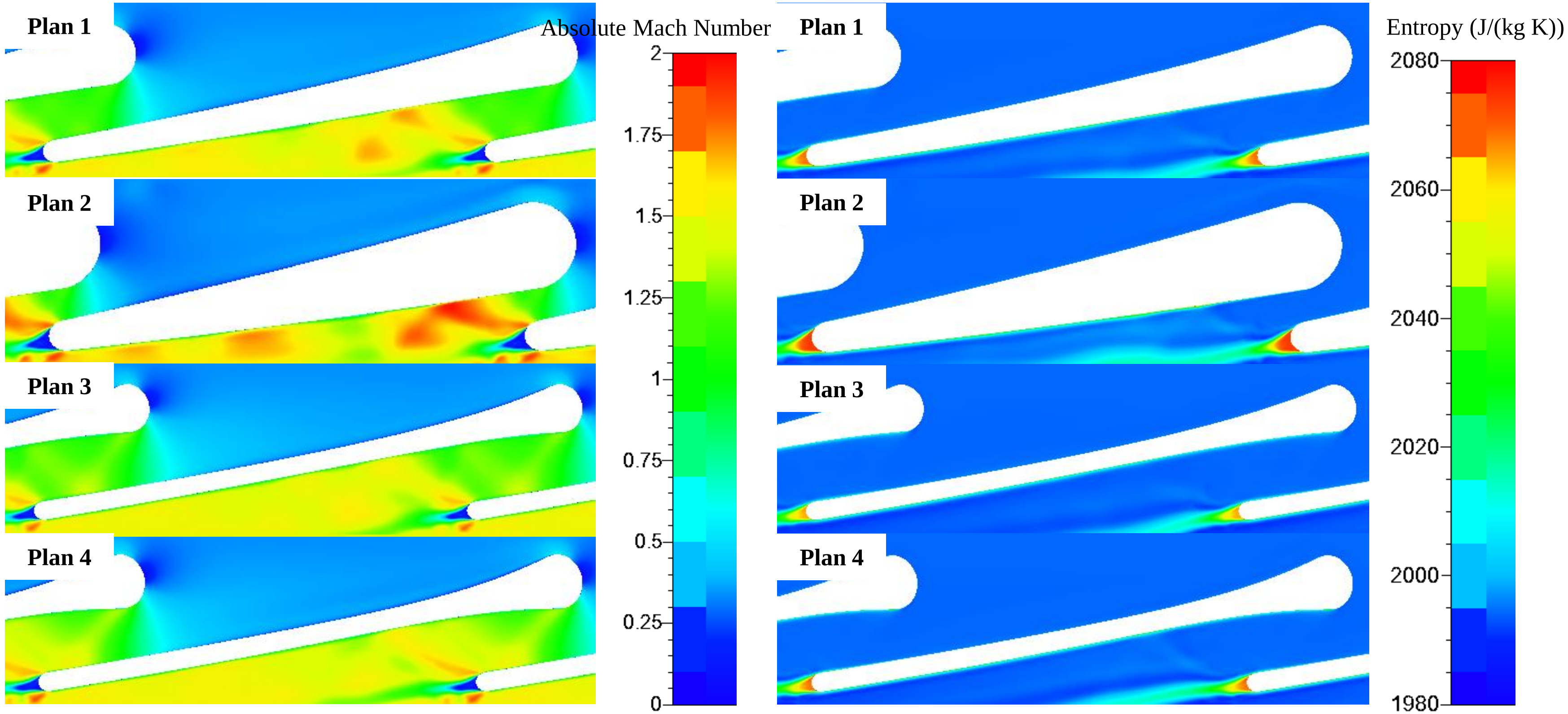


◻ Results Analysis

- ✓ Original blade is easily machined but has poor performance
- ✓ Parabola shape and MOC shape has similar improvement

Effects of Vane Blade Shape

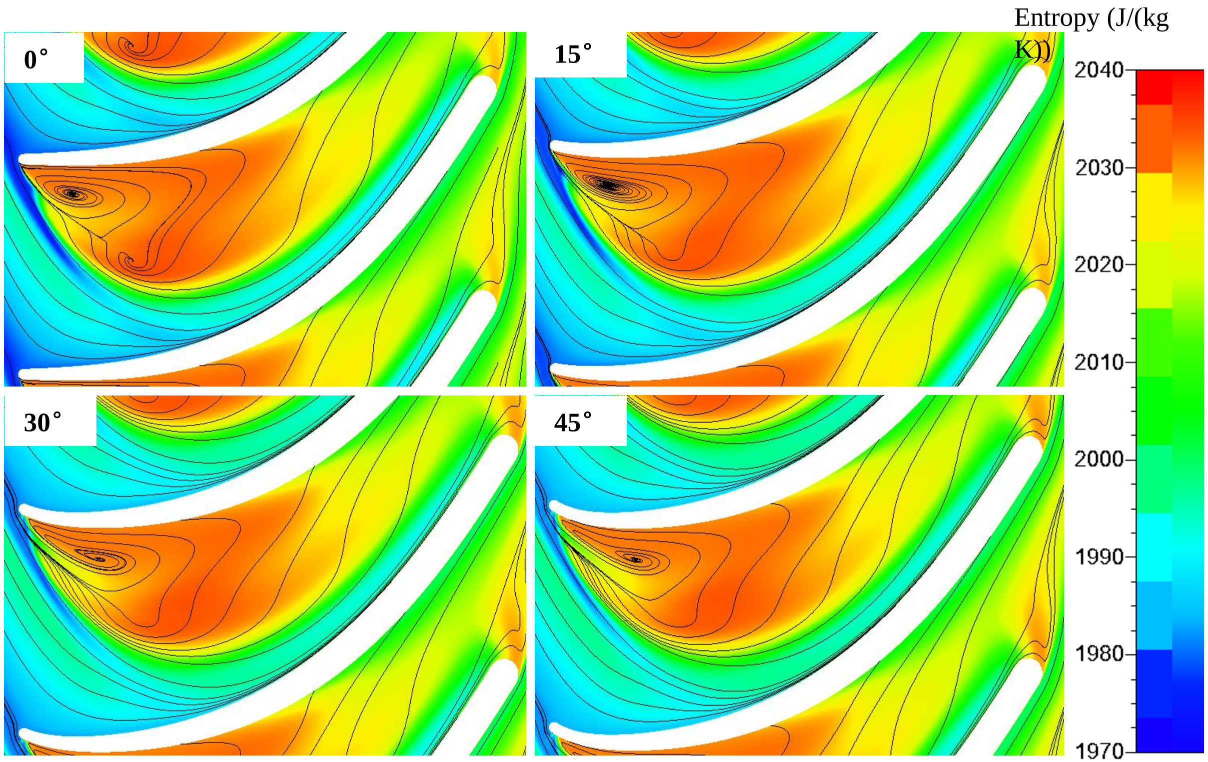
☐ Effect of Vane Blade Shape at Supersonic Section



- Plan 2 with straight shape has stronger wave phenomena and larger entropy production at trailing vortex area
- Parabola shape and MOC shape suppress shock wave at nozzle outlet

Rotor Blade Leading Edge

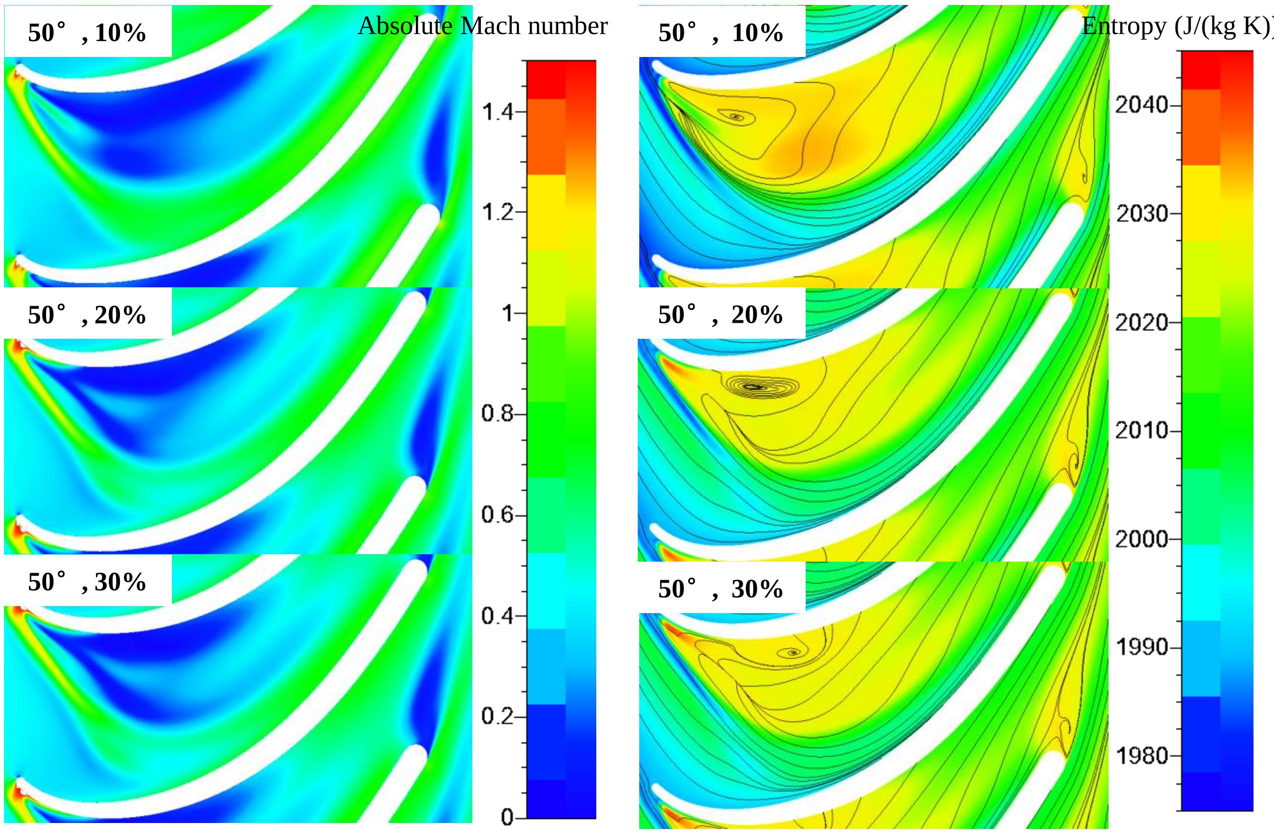
☐ Effect of Rotor Blade Inlet Angle



- ➢ Rotor blade inlet angle has direct connection with incident angle
- ➢ Flow separation can be observed as flow slows down as a result of increasing inlet blade angle
- ➢ Entropy production is smaller with larger blade angle

Rotor Blade Leading Edge

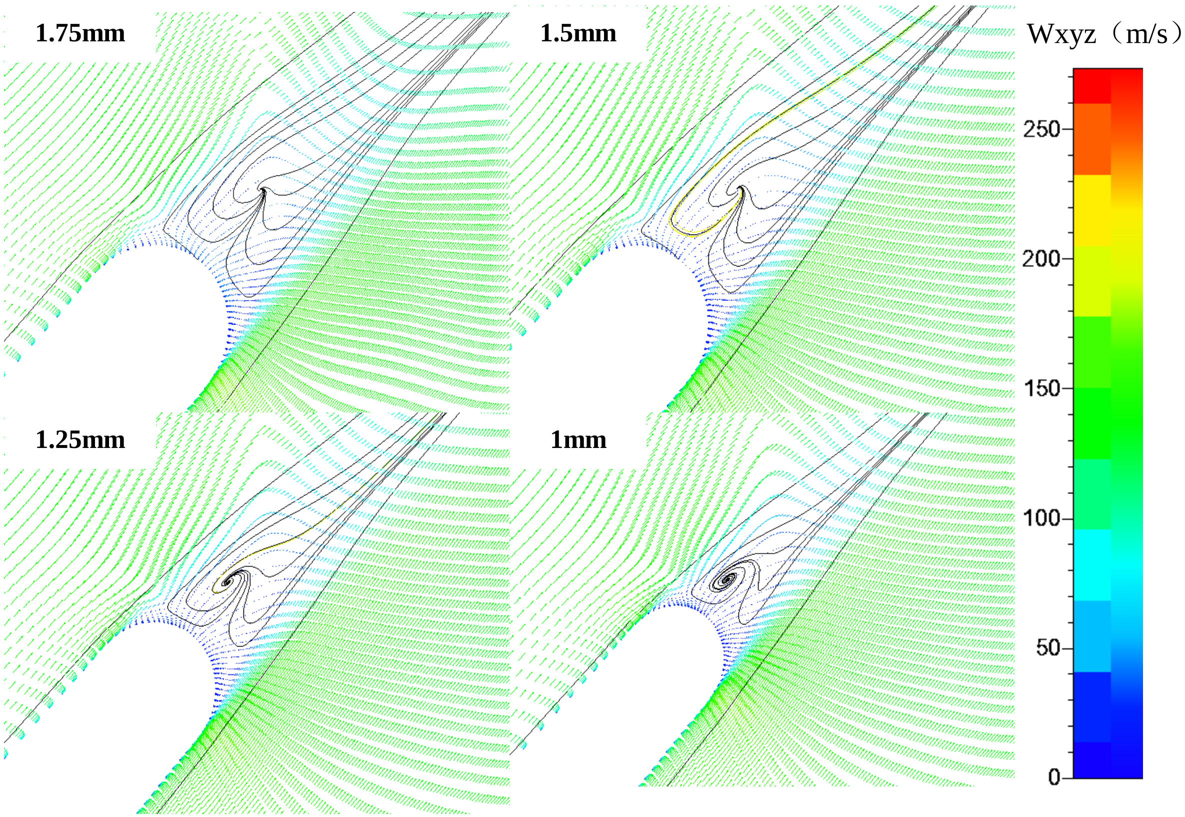
Effect of Leading Edge Bending



- Curvature radius of blade leading edge changed with increasing blade bending and inlet flow accelerated
- Flow deflection in the passage reduced, separation vortex shrank and receded
- Flow separation in the leading edge was further suppressed

Rotor Blade Trailing Edge

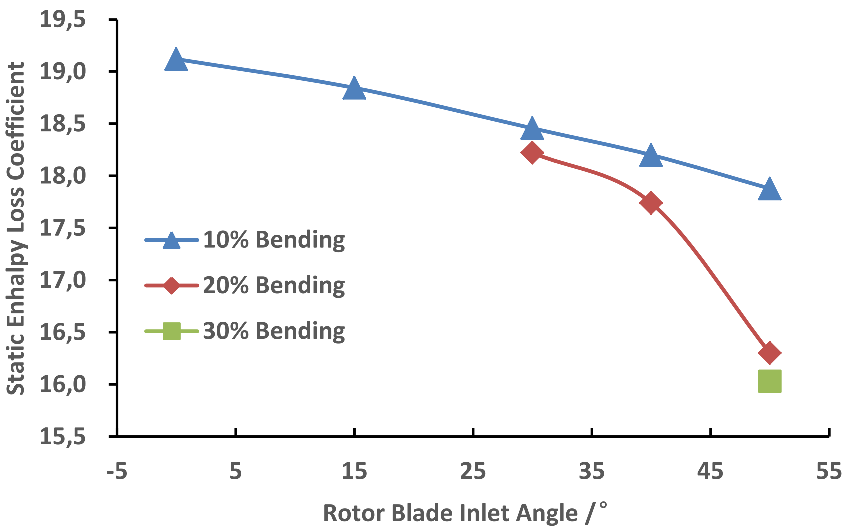
☐ Effect of Trailing Edge Thickness



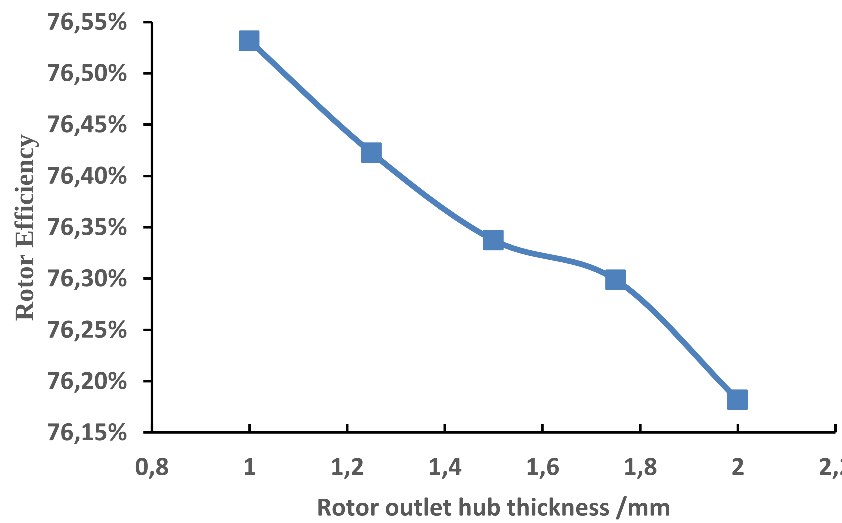
- Vortex area shrank with smaller trailing edge thickness
- Velocity gradient on both sides decreased and shear flow diminished
- Center part in vortex enlarged obviously and streaming enhanced

Rotor Blade Effect

Rotor Blade Leading Edge



Rotor Blade Trailing Edge



Results Analysis

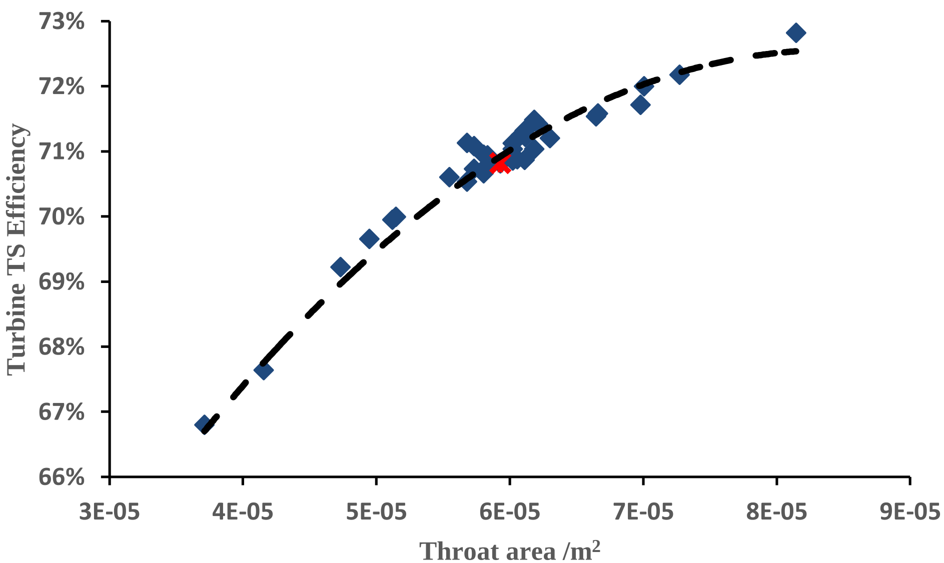
- ✓ Increasing rotor blade inlet angle helps diminish loss
- ✓ Increasing rotor bending in leading edge improves turbine performance

Results Analysis

- ✓ Reduce blade thickness in trailing edge part improves efficiency
- ✓ Only changes hub thickness has limited help

Nozzle Optimization

- Optimization is carried out based on the abovementioned parameters and analysis
- Turbine flow capacity is constrained by heat recovery system, thus throat area is the constraint condition of optimization



Optimization Method

1. Establish polynomial function between blade parameters and nozzle and turbine performance:

$$P_i = f_{i1}(S_i) \quad \eta_i = f_{i2}(S_i)$$

2. Turbine efficiency is the objective function:

$$\eta = \frac{\sum_{i=1}^{6} \eta_i}{6} = \frac{\sum_{i=1}^{6} f_{i2}(S_i)}{6}$$

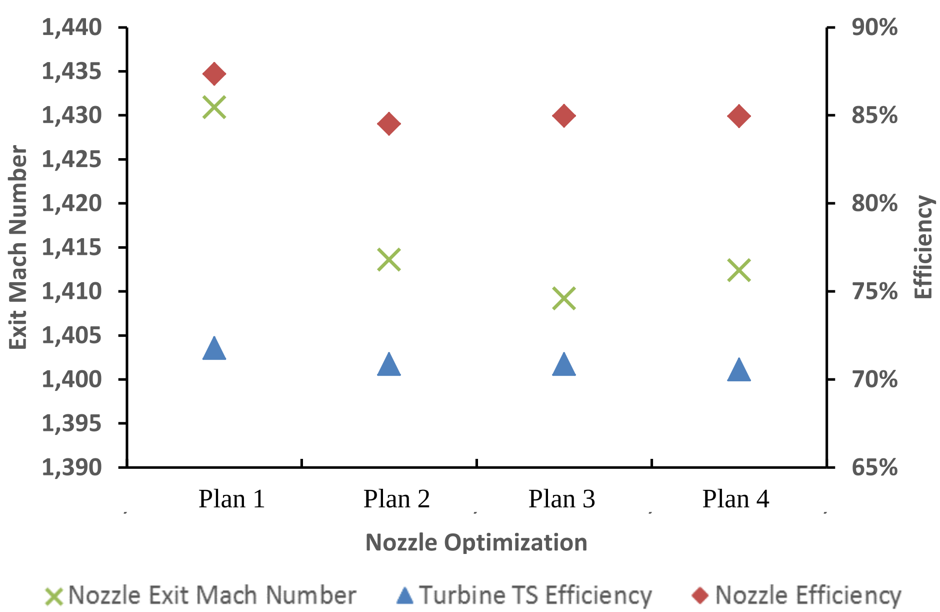
3. Boundary condition and constraint condition:

$$S_{i,min} \le S_i \le S_{i,max}$$

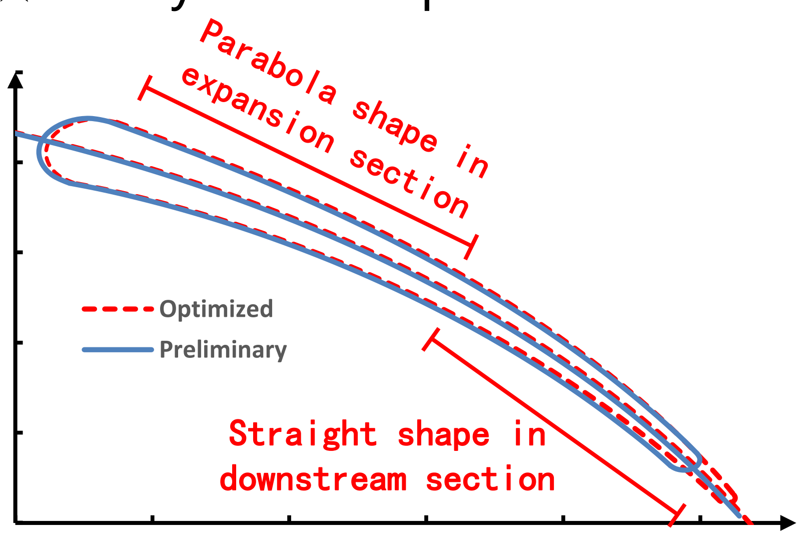
$$\sum_{i=1}^{6} S_i = 6 * S_0$$

Nozzle Optimization

Nozzle Optimization	Blade Inlet Variation (°)	Blade Outlet Variation (°)	Thickness in TE (mm)	Blade Shape in Expansion Section
Plan 1	0.149	0.103	-0.589	Shape 3
Plan 2	1.189	0.974	-0.346	Shape 3
Plan 3	1.184	0.967	-0.257	Shape 3
Plan 4	0.788	0.63	-0.367	Shape 4

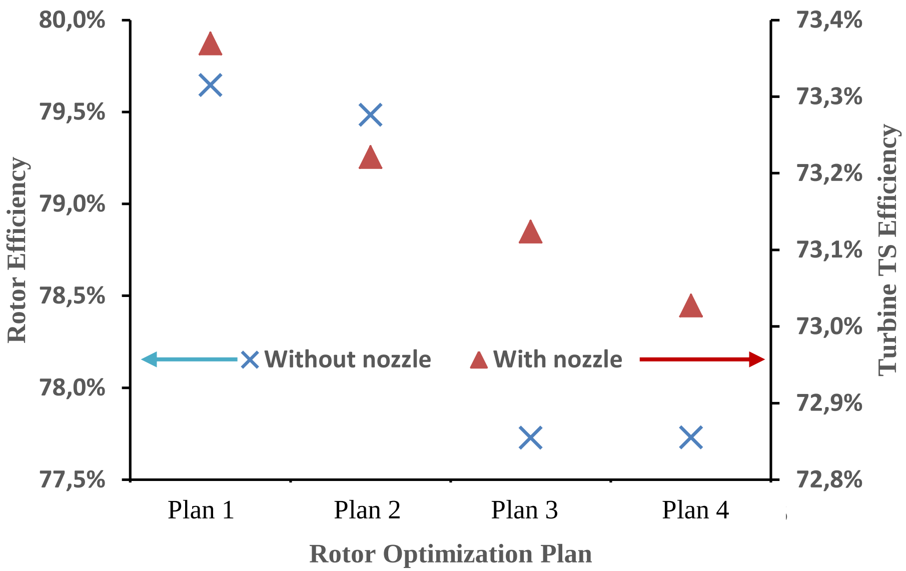


★ Finally Nozzle Optimization Plan

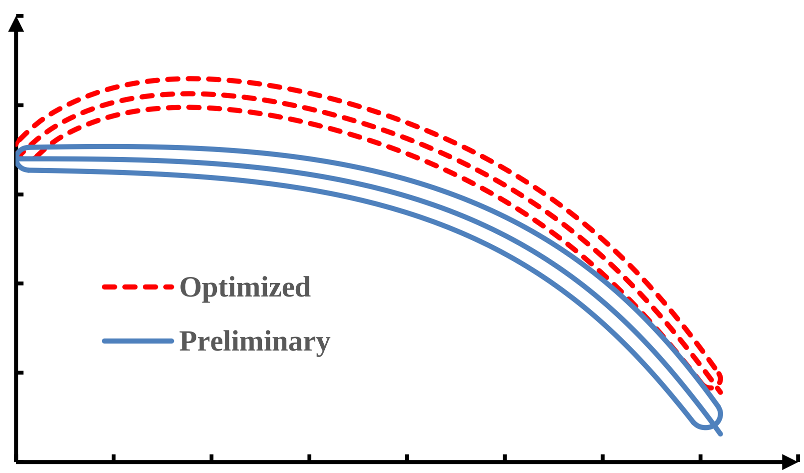


Rotor Optimization

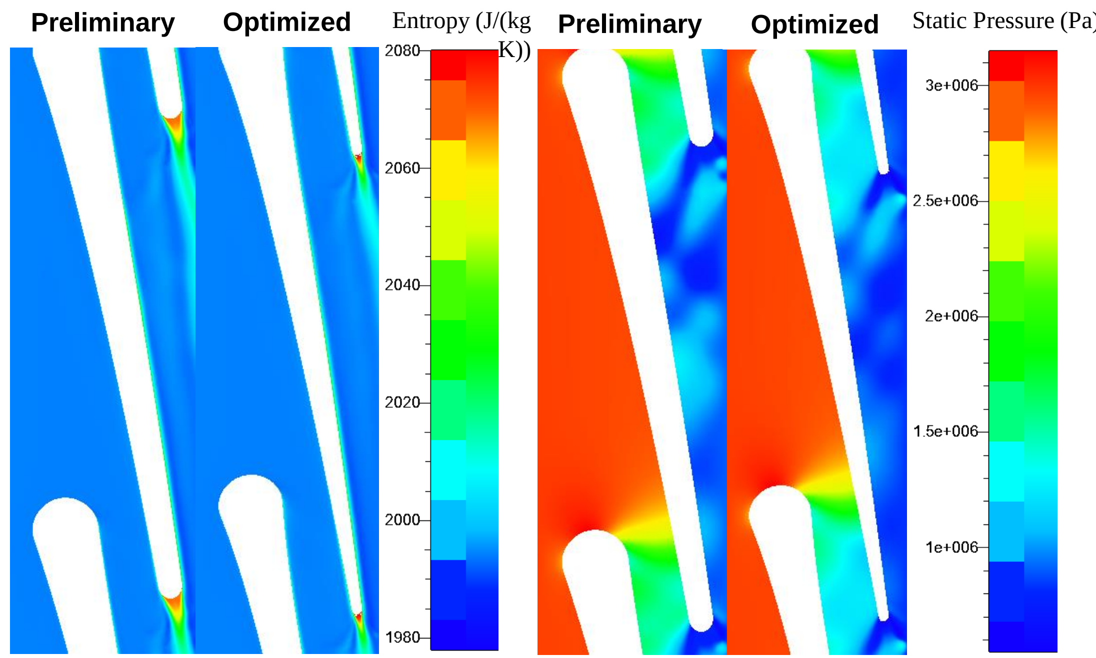
Rotor Optimization	Blade Inlet Angle (°)	Blade Bending Part	Trailing Edge Thickness (mm)
Plan 1	50	30%	1
Plan 2	50	30%	1.75
Plan 3	50	10%	1
Plan 4	50	10%	1.75



★ Finally Rotor Optimization Plan

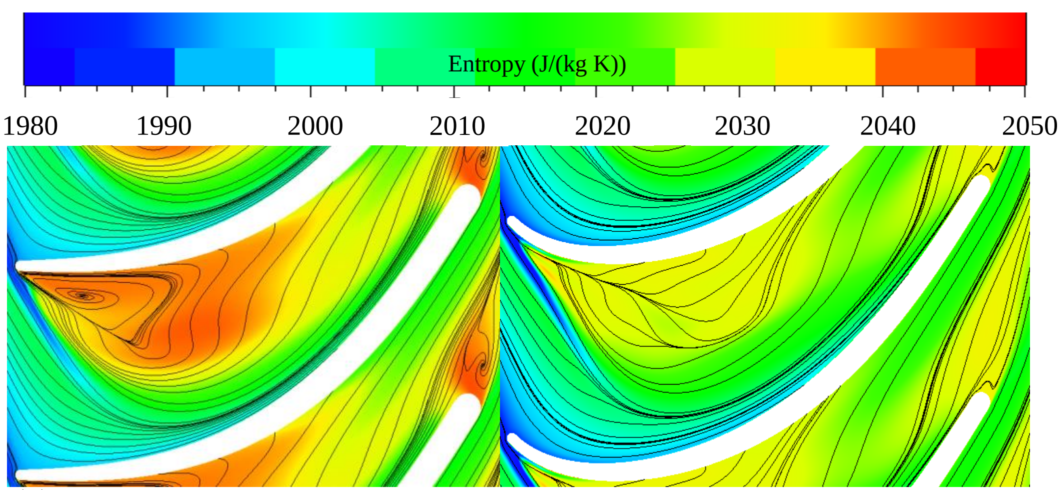


Turbine Optimization



☐ Stator Flow Analysis

- ✓ Trailing edge loss decreases prominently
- ✓ Shock waves are weakened
- ✓ More uniform stream at nozzle outlet



☐ Rotor Flow Analysis

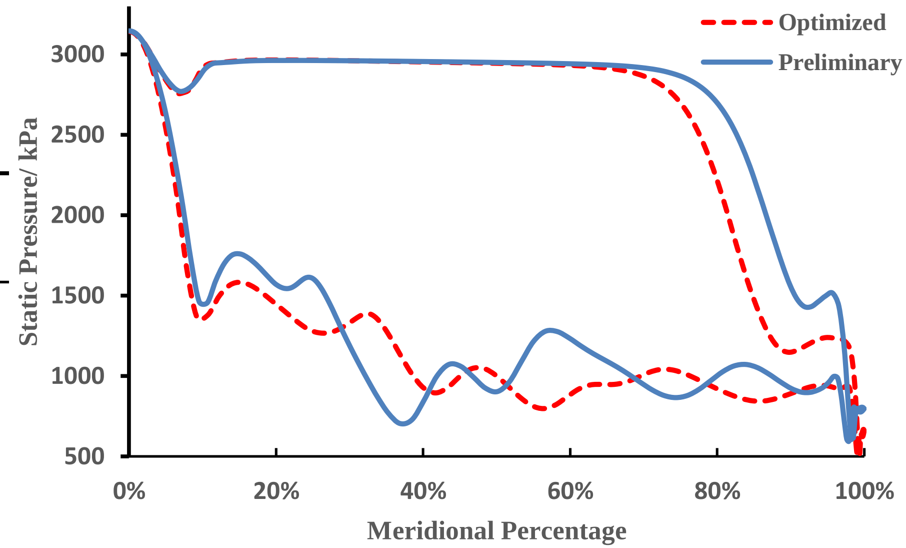
- ✓ Flow separation at leading edge is suppressed
- ✓ Trailing edge loss decreases

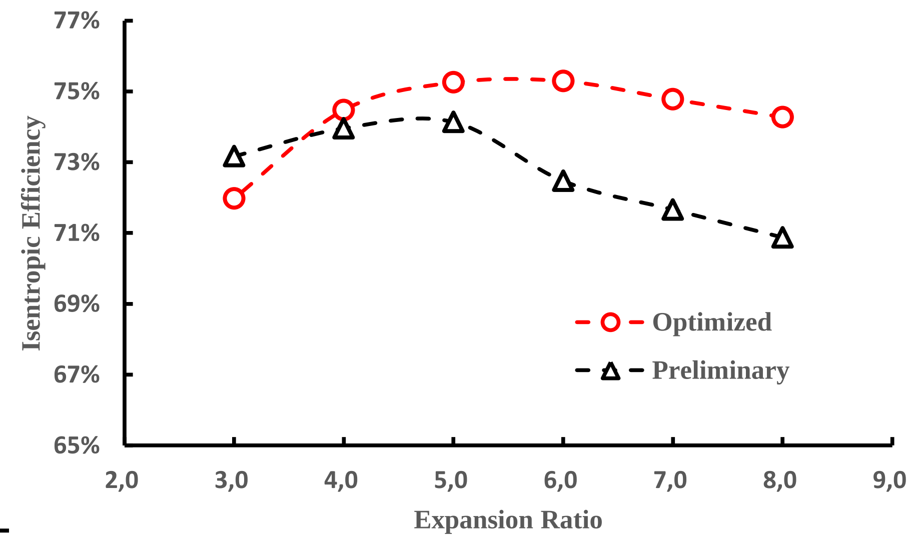
Tsinghua University

Turbine Optimization

- Comparison between optimized and preliminary design

Parameter	Preliminary	Optimized
Inlet Total Pressure	3200（kPa）	3200（kPa）
Mass Flow Rate	0.65（kg/s）	0.67（kg/s）
Output Power	22.4（kW）	24.3（kW）
Stator Outlet Mach Number	1.42	1.48
Stator Total Pressure Loss Coefficient	0.310	0.267
Output Efficiency	69.8（%）	72.7 （%）
Total-Static Efficiency	70.8（%）	74.1（%）





Tsinghua University

Content

- Introduction
- Preliminary turbine design numerical methods
- Results and discussions
- **Conclusions**

Conclusion

1. Effect of blade geometry

- ◆ Increasing blade angle could improve turbine performance
- ◆ Parabola shape with straight rear part has lowest loss coefficient after comparison with four different shapes
- ◆ Rotor bending at leading edge also helps turbine as it promotes the incident angle condition and flow expansion at inlet.

2. Turbine Optimization

- ◆ Reflected waves and trailing losses are suppressed within the nozzle
- ◆ Separation are reduced within the rotor
- ◆ 3.4% efficiency increase

Thank you very much for your attention! Discussions are welcomed

Qiyu YING
PhD Candidate
Department of Automotive Engineering, Tsinghua University, Beijing, China