Scaling of Gas Turbine from Air to Refrigerants using Similarity Concept

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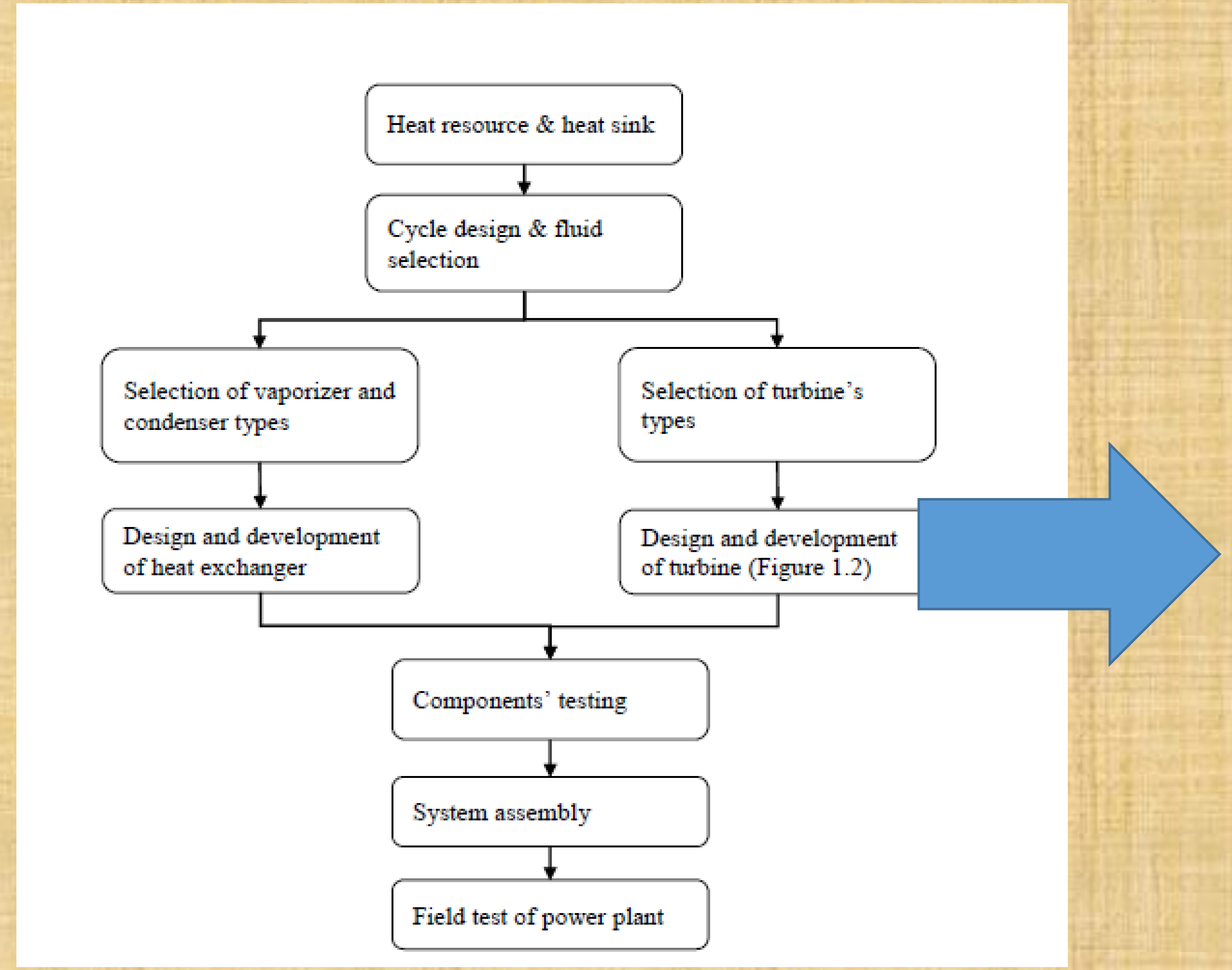
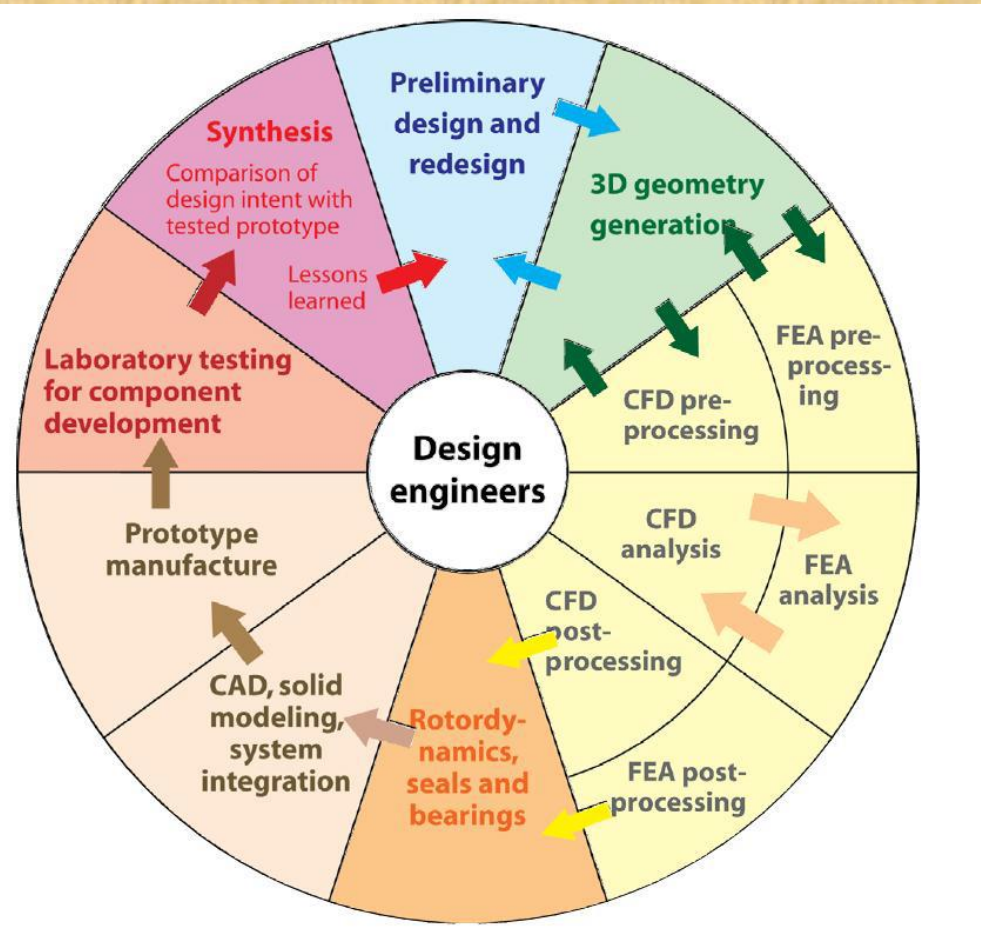
Current turbine design and development process

ORC Design Process



Turbine Design Process



Similarity Analysis

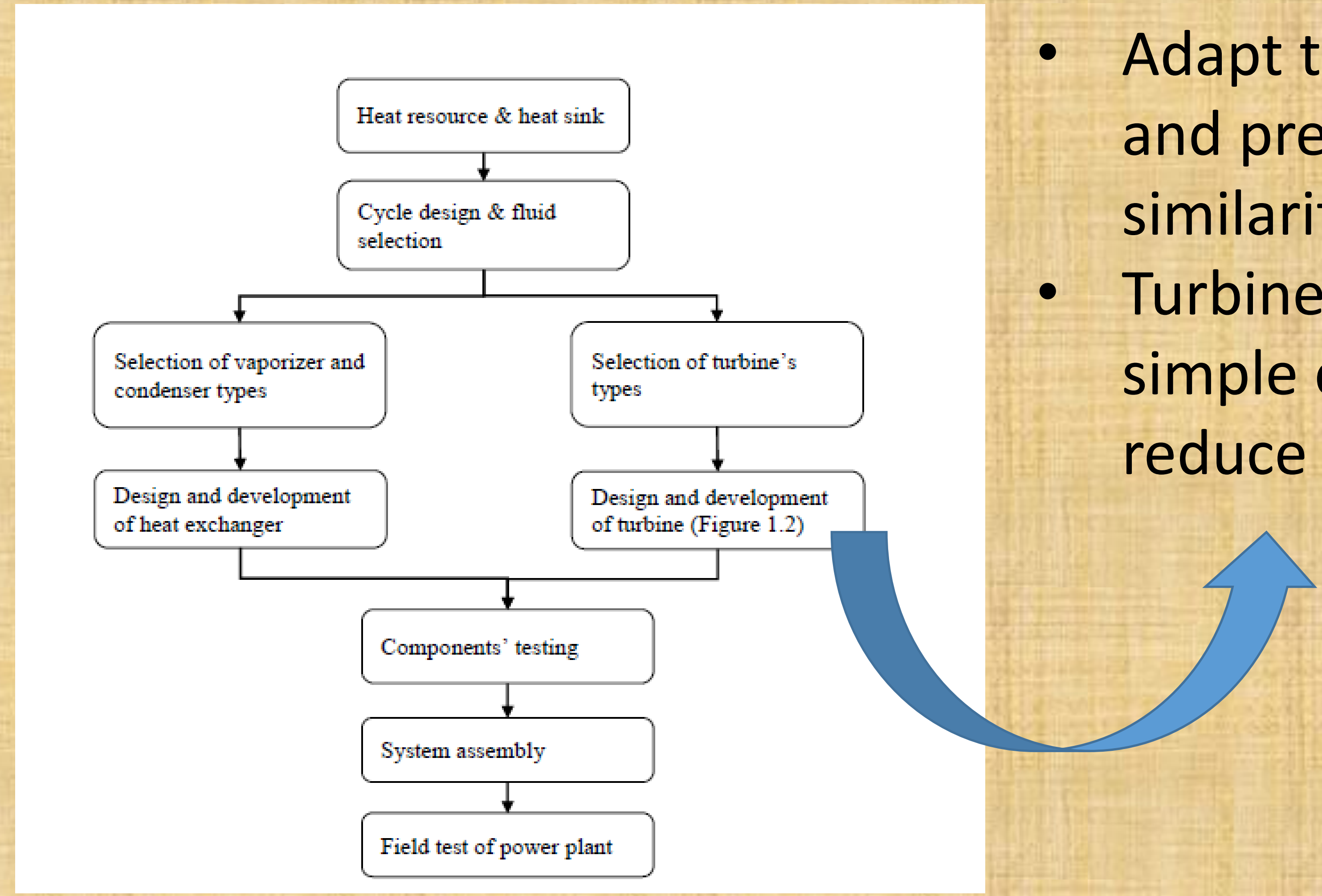
- Scale the turbomachine at different geometry
  - Predict the performance if the turbomachine is geometrically similar – number of blades, blade angle, machine size, blade thickness are scaled proportionally
- Scale the turbomachine for different operating condition
  - Predict the performance at reduced inlet temp/pressure
  - To reduce the operational cost of the testing equipment

Challenge

- A turbomachine cannot be scaled to different fluids due to the variation in compressibility factor and Reynolds number

If we can scale the turbine for different working fluids

ORC Design Process



- Adapt the existing turbines for ORC and predict the performance using similarity analysis
- Turbine performance testing using a simple compressed air test rig to reduce the cost

Objective

- Explore the feasibility of utilizing the similarity concept to predict the turbine performance for refrigerants

Dimensional Analysis

- Reduce the group of variables representing some physical situation to a smaller number of dimensionless group.
- Machine performance can be described in terms of the dimensionless groups.

Incompressible Fluid Machine

- The performance of incompressible fluid machine is a function of 7 parameters.

$$P = f\left(\rho, N, D, Q, (gH), \mu\right)$$

Nomenclature

P	power
ρ	density
N	speed
μ	viscosity
D	machine dimension
Q	volume flow rate
gH	head

- The 7 variables were reduced to 4 dimensionless groups using dimensionless analysis.

$$\frac{P}{\rho N^3 D^5} = f\left(\frac{\rho N D^2}{\mu}, \frac{Q}{N D^3}, \frac{gH}{N^2 D^2}\right)$$

Compressible Fluid Machine

- The performance of compressible fluid machine is a function of the following parameters.

$$\Delta h_{0s}, P, \eta = f\,(N, D, \dot{m}, \rho_{01}, a_{01}, \gamma, \mu)$$

- The variables were reduced to the following:

$$\frac{\Delta h_{0s}}{a_{01}^2}, \eta, \frac{P}{\rho_{01} a_{01}^3 D^5} = f\left\{\frac{\dot{m}}{\rho_{01} N D^3}, \frac{\rho_{01} N D^2}{\mu}, \frac{ND}{a_{01}}, \gamma\right\}$$

Nomenclature

Unit	Description
P	Power
Δh_{0s}	Enthalpy drop
η	Isentropic efficiency
N	Shaft speed
D	Turbine diameter
$\dot{m}$	Mass flow rate
ρ_{01}	Inlet density
a_{01}	Sonic velocity
μ	Dynamic viscosity
γ	Specific heat

Other Turbine Performance Dimensionless Group

- Work coefficient $$\frac{\Delta h_0}{h_{01}} = \frac{h_{01} - h_{02}}{h_{01}}$$
- Mach number $$Ma = \frac{U}{a_{01}}$$
- Velocity ratio $$\nu = \frac{U}{C_{is}} = \frac{U}{\sqrt{2\Delta h_{0s}}}$$
- Stage loading coefficient $$\psi = \frac{\Delta h_0}{U^2}$$
- Flow coefficient $$\phi = \frac{C_m}{U}$$

What is similarity concept?

Complete similarity can be achieved when

- complete geometrical similarity is achieved, in which the turbine is scaled up or scaled down proportionally, *and*
- dynamic similarity is achieved, in which the velocity components and forces are equal.

In this study

- Three different approaches are derived from the dimensionless groups and attempted to scale the performance data from air to refrigerants

Method

Perfect gas approach

Assume refrigerants are perfect gas. Pressure ratio, blade speed coefficient, and mass flow coefficients are hold constant to achieve similarity.

$$\frac{p_{02}}{p_{01}} = \text{constant}$$

$$\frac{ND}{a_{01}} = \text{constant}$$

$$\frac{\dot{m}}{\rho_{01} N D^3} = \text{constant}$$

Variable pressure ratio approach

Ratio of enthalpy drop to the squared of sonic velocity, blade speed coefficient, and mass flow coefficient are hold constant to achieve similarity.

$$\frac{\Delta h_{0s}}{a_{01}^2} = \text{constant}$$

$$\frac{ND}{a_{01}} = \text{constant}$$

$$\frac{\dot{m}}{\rho_{01} N D^3} = \text{constant}$$

Constant specific speed approach

Pressure ratio, velocity ratio, and specific speed are hold constant to achieve similarity.

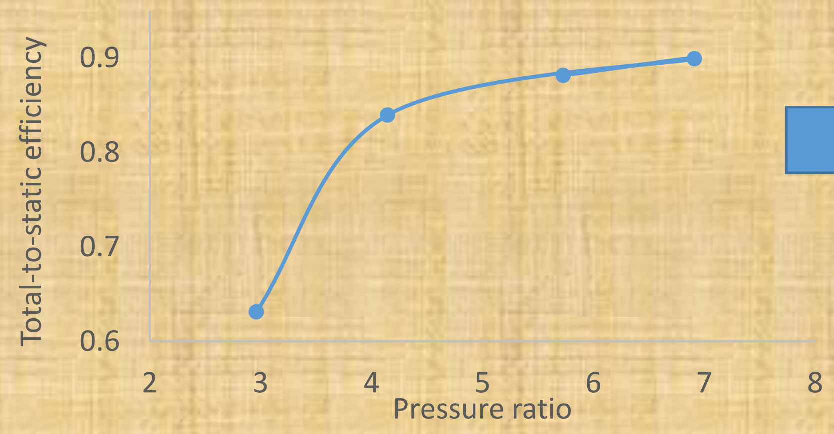
$$\frac{p_{02}}{p_{01}} = \text{constant}$$

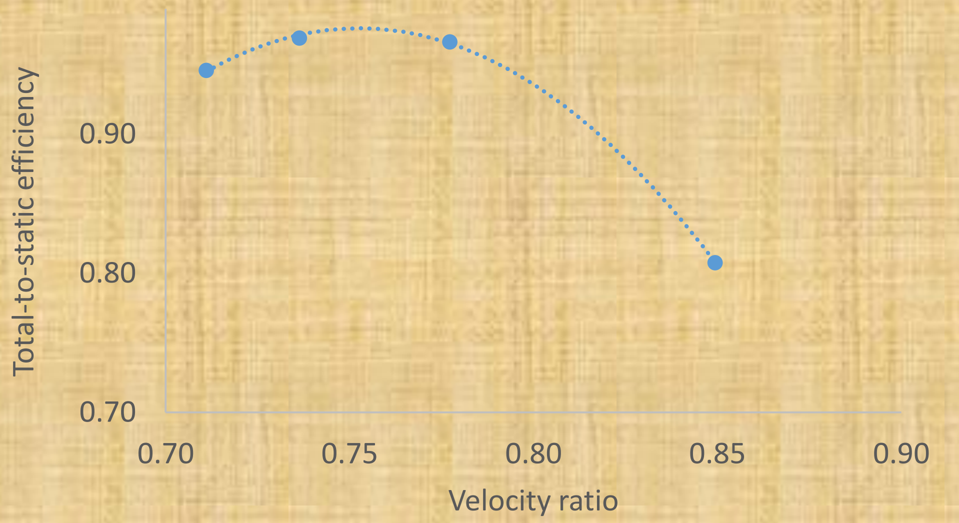
$$\nu = \frac{U}{C_{is}} = \frac{U}{\sqrt{2\Delta h_{0s}}} = \text{constant}$$

$$N_s = \frac{\omega \sqrt{\dot{m}/\rho_{exit}}}{\Delta h_{0s}^{\ 0.75}} = \text{constant}$$

Example of Calculation Procedure (Perfect Gas Approach)

Air performance data





Step 1

<u>Assumption</u>

- The correlation between efficiency and pressure ratio is same for different working fluid.

Step2

$$\frac{ND}{a_{01}} = \text{constant}$$

$$\frac{\dot{m}}{\rho_{01} N D^3} = \text{constant}$$

Calculate the shaft speed for refrigerant

Calculate the mass flow for refrigerant

Step 3

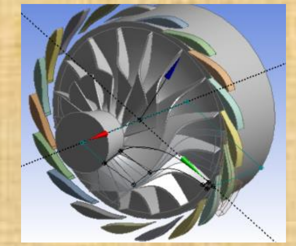
Calculate the velocity ratio and specific speed for refrigerant

Step 4

Plot the efficiency against velocity ratio and specific speed for refrigerant

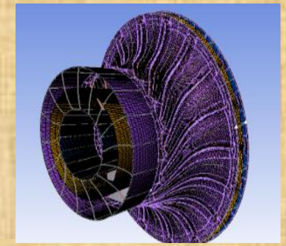
Compare the result from similarity analysis to CFD result to validate the similarity analysis approaches

Performance Evaluation using CFD Analysis for R134a and R245fa



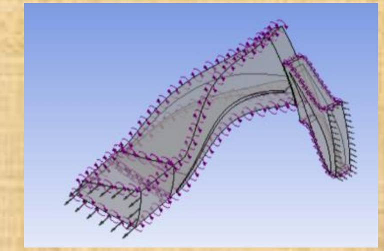
CAD

- Generation of solid model using ANSYS-BladeGen



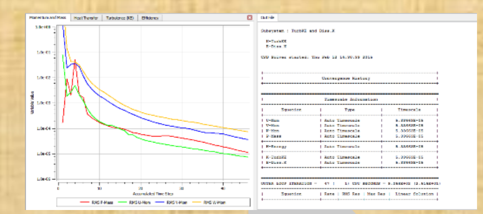
Meshing

- Hexahedral meshes were formed on the fluid zone across the blades.



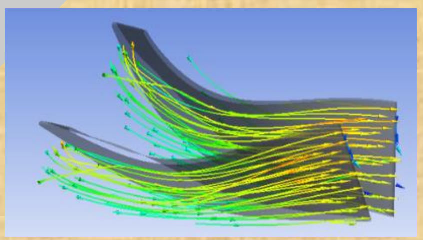
Physics Definition

- Set up boundary conditions
- Select suitable equations of state (EoS) for working medium



Solver

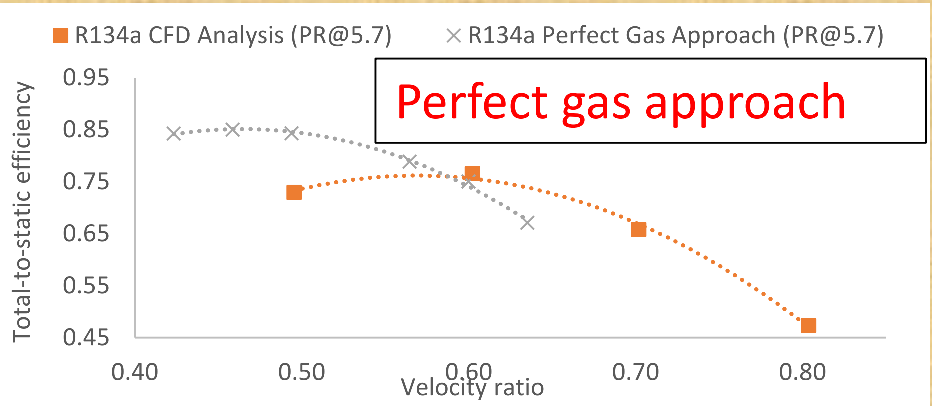
- Solve Navier-Stokes equations in time and 3-D space using k-ε turbulence model.



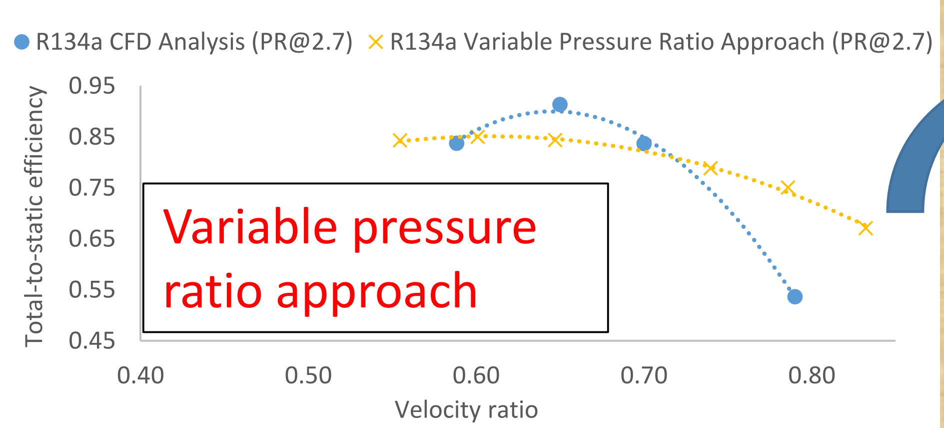
Fluid flow field

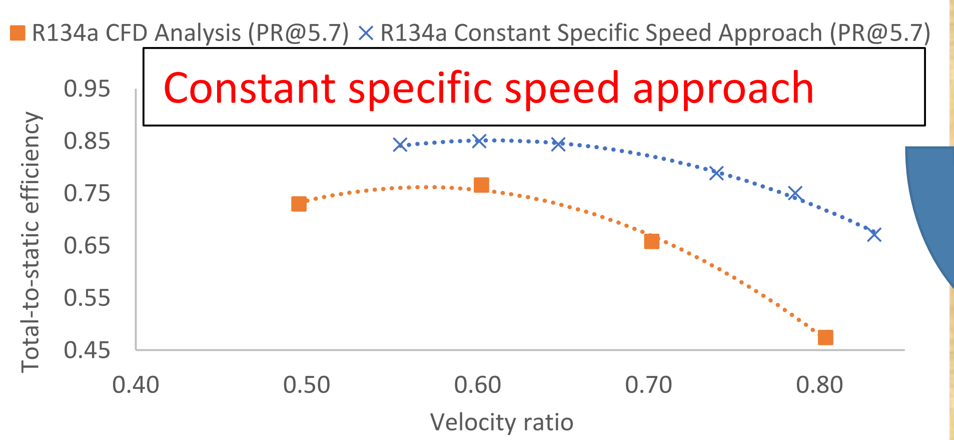
- The result was transformed into velocity vector, temperature and pressure distribution.

Comparison for each approach (using R134a)



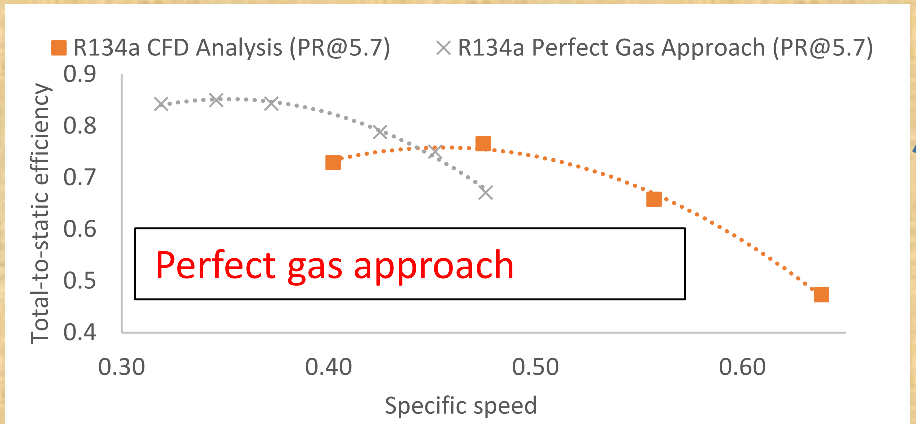
The optimal velocity ratio is underestimated using the perfect gas approach.
Optimal velocity ratio (from *perfect gas approach*): 0.48
Optimal velocity ratio from CFD: 0.6



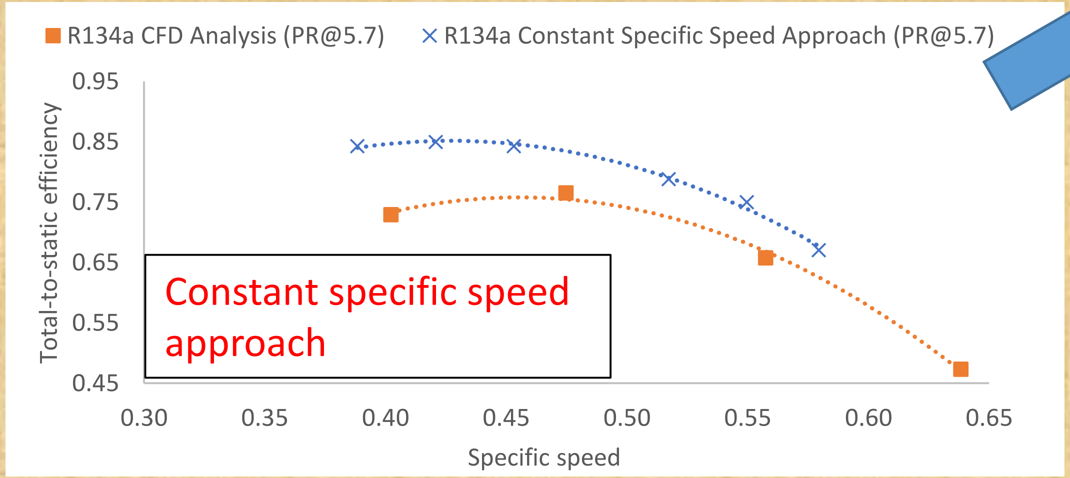


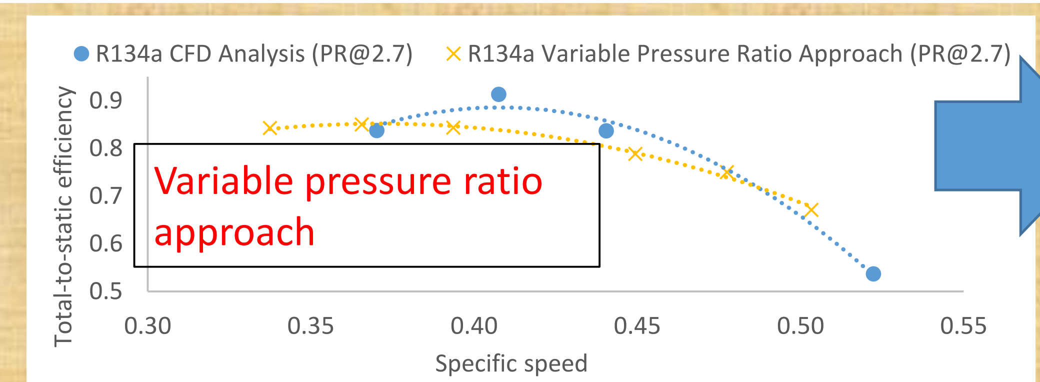
The optimal velocity ratio from the similarity analysis agrees to the value from CFD approach with an error less than 10%.

Comparison for each approach (using R134a) -- Continued



The trend of the performance curve is similar to the result from the CFD simulation.



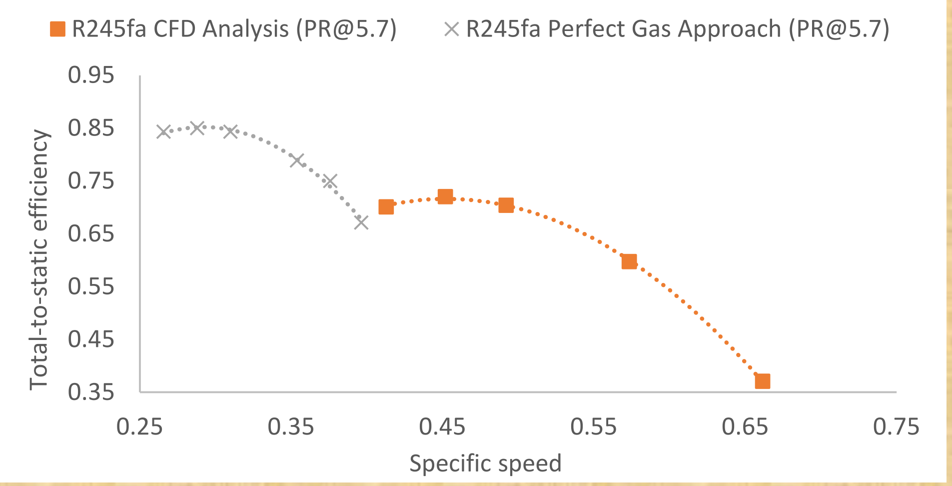


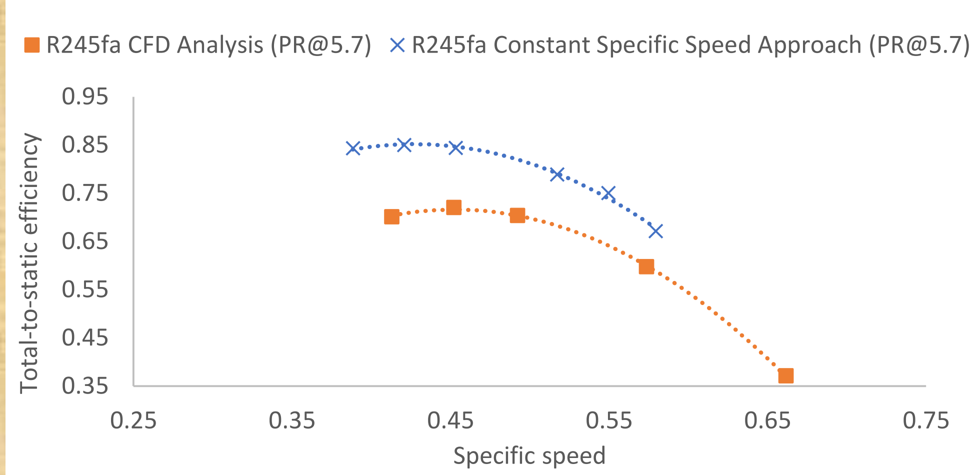
CFD result – shows that the turbine is sensitive to the operating conditions.

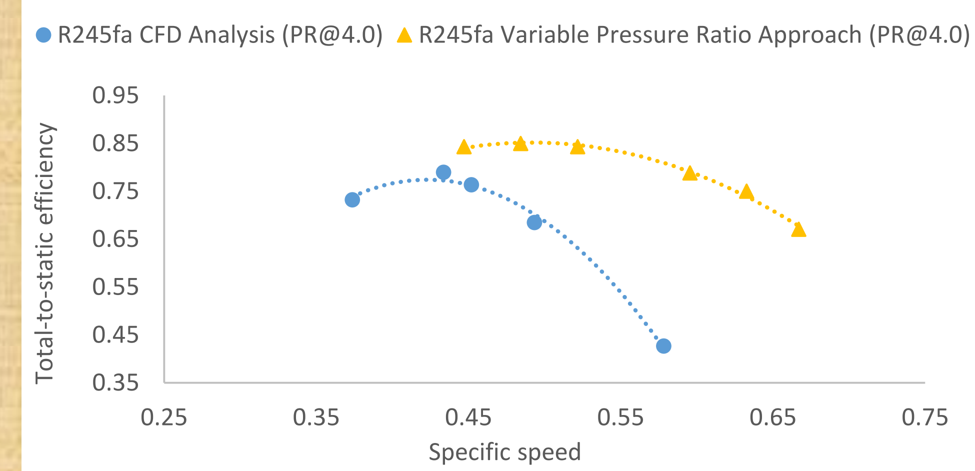
Variable pressure ratio approach

- Shows that the turbine efficiency is fairly flat between specific speed 0.3 to 0.45

Comparison for each approach (using R245fa)







Perform the comparison of each approach to the CFD simulation for R245fa.

Table: Numerical error for different scaling approaches

	Working medium	Pressure ratio	Optimal velocity ratio	Optimal specific speed	Maximum total-to-static efficiency	Mass flow rate (kg/s)	Average Error (%)
Benchmark	Air	5.7	0.6	0.42	0.85	0.29	
Approach 1 (Perfect Gas)	R134a	5.7	0.46	0.35	0.85	3.46	
	Error (%)		23.3	25.5	11.8	4.6	16.3
	R245fa	5.7	0.38	0.29	0.85	3.75	
	Error (%)		31.9	35.9	18.4	9.0	23.8
Approach 2 (Variable Pressure Ratio)	R134a	2.7	0.6	0.37	0.85	3.46	
	Error (%)		7.7	9.8	6.6	4.7	7.2
	R245fa	4.0	0.6	0.48	0.85	3.75	
	Error (%)		2.9	13.5	9.4	9.0	8.7
Approach 3 (Constant Specific Speed)	R134a	5.7	0.6	0.42	0.85	2.99	
	Error (%)		0.0	10.6	11.8	17.6	10.0
	R245fa	5.7	0.6	0.42	0.85	3.15	
	Error (%)		7.5	7.2	18.4	23.5	14.1
CFD	R134a	2.7	0.65	0.41	0.91	3.63	
		5.7	0.60	0.47	0.76	3.63	
	R245fa	4.00	0.58	0.42	0.78	4.12	
		5.7	0.56	0.45	0.72	4.12	

Lessons:

<u>Variable pressure ratio approach</u>

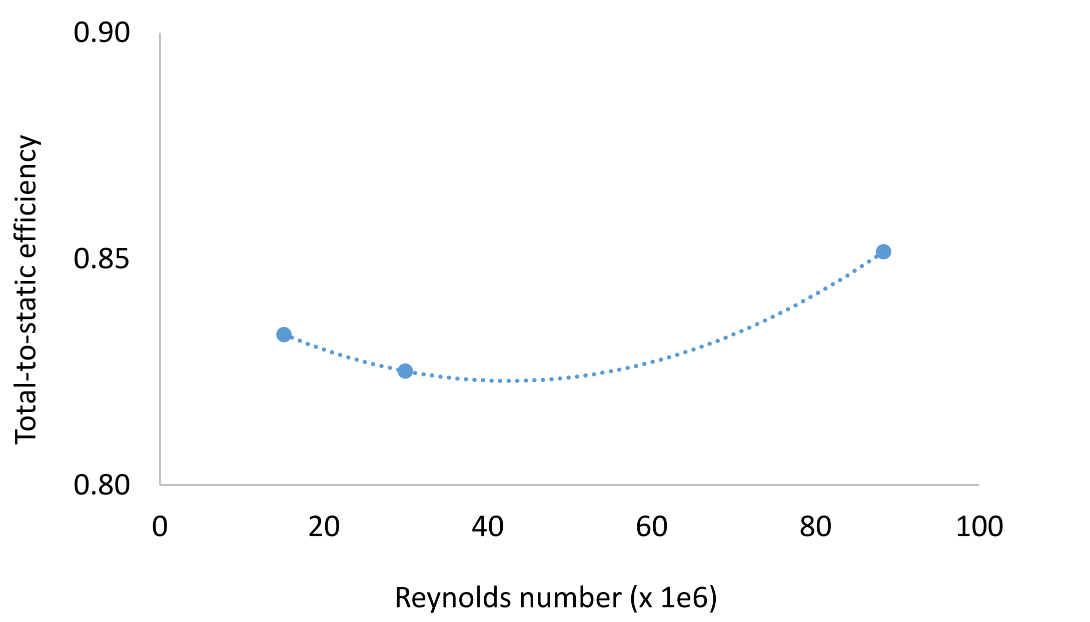
- Provides good prediction of optimal velocity ratio, optimal specific speed, optimal mass flow rate, and maximum efficiency.

<u>Constant specific speed approach</u>

- Provides better estimation of turbine performance away from the best efficiency point.

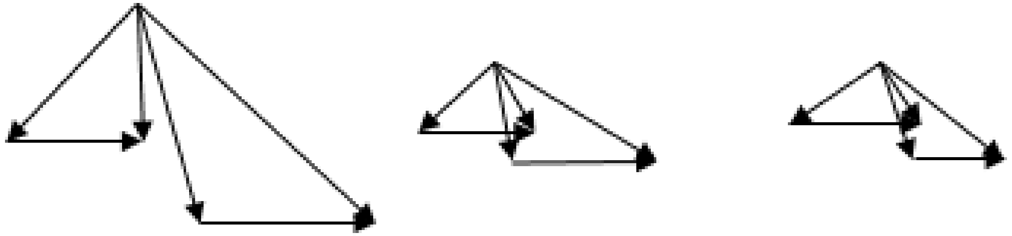
Discrepancy in Efficiency if a turbine is scaled from one fluid to another using Variable Pressure Ratio Approach

Consider the effect of Reynolds number:



- **Does not have significant effect** on the turbine performance as the effect of viscosity and thermal conductivity can be neglected at high Reynolds number (Re)
- Re of air/steam usually in the magnitude of 1×10^6
- Re of refrigerants usually between 1×10^6 and 100×10^6

$\Delta h_{os}/a_{01}^2$ is hold constant to calculate the pressure ratio if the turbine is scaled to different refrigerants. Hence, the volumetric flow ratio is not conserved, and the velocity vector at the turbine exit is not conserved. Complete similarity is not achieved.

Fluids	Air	R134a	R245fa
Velocity triangle			
Pressure ratio	5.7	2.7	4.0
Volumetric flow ratio	5.7	2.7	4.9
Degree of Reaction	0.42	0.47	0.44
Flow coefficient	0.245	0.172	0.249
Stage loading coefficient	1.040	0.974	0.995

Hence, deviation in efficiency since complete similarity is not achieved.

$\Delta h_{os}/a_{01}^2$ is hold constant to calculate the pressure ratio and volumetric flow ratio.

Volumetric ratio	Working fluid
5.7	Air
4.9	R245fa
2.7	R134a

Lowest volumetric flow ratio, hence the lowest entropy change and the lowest irreversibility.

$$\Delta s = c_v \ln\left({T_3}/{T_1} \right) + R \ln\left({v_3}/{v_1} \right)$$

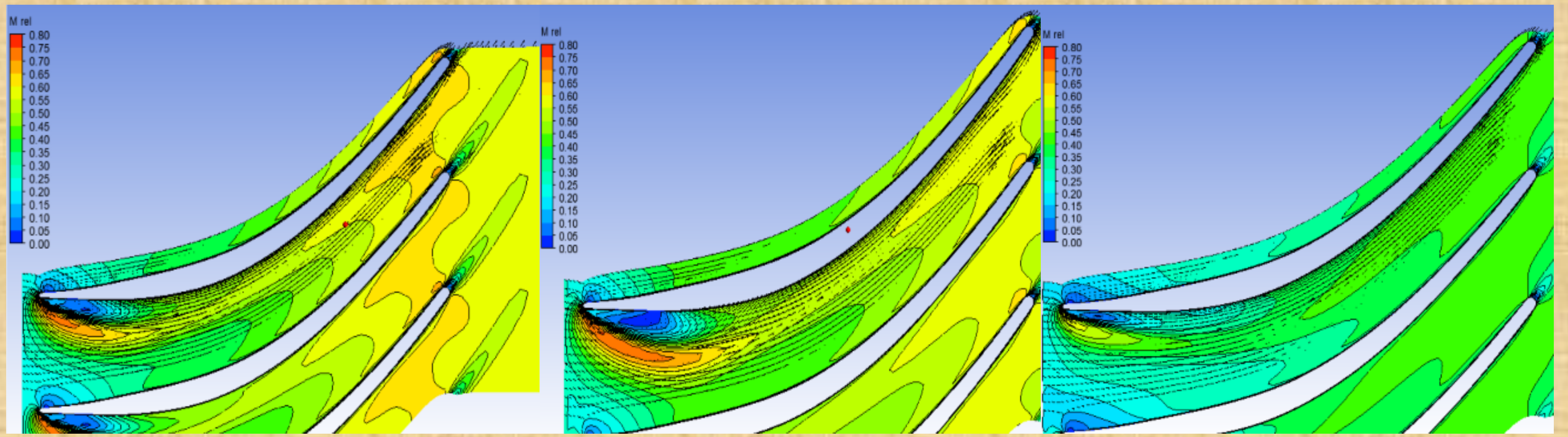
Entropy change of perfect gas in a closed system.

Figure: Distribution of relative Mach number in the meridional plane

Air
Pressure ratio 5.7

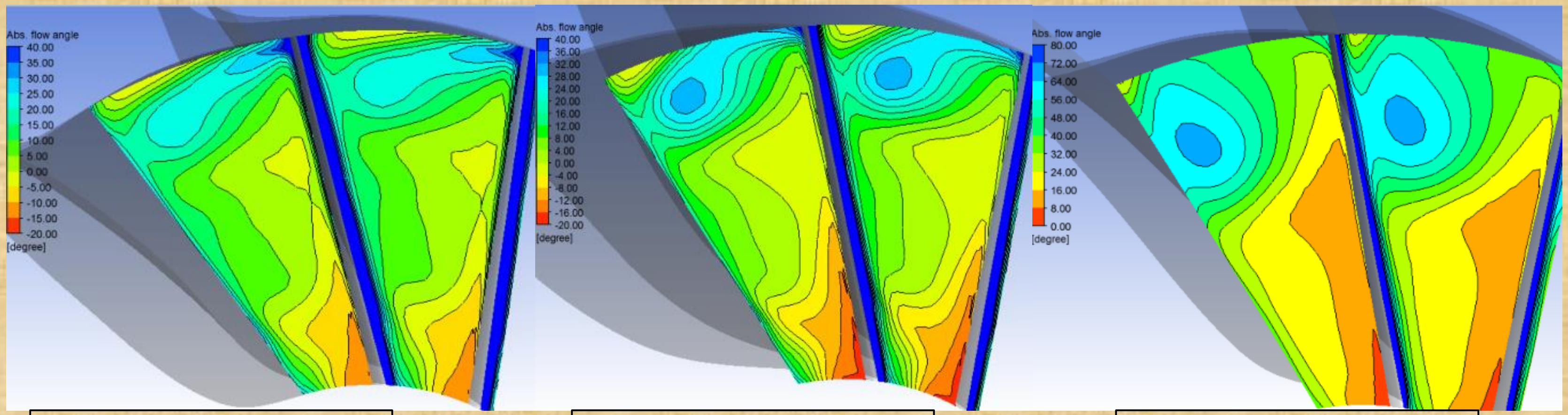
R245fa
Pressure ratio 4.0

R134a
Pressure ratio 2.7



The result implies that the turbine exit swirl angle might increase monotonically with the molecular weight of working fluid.

Figure: Distribution of absolute flow angle at the trailing edge



Air
Pressure ratio 5.7

R245fa
Pressure ratio 4.0

R134a
Pressure ratio 2.7

Averaged swirl angle @outlet	**Working fluid**
1˚	Air
37˚	R245fa
33˚	R134a

Limitation

Refrigerants have heavier molecules than air. Hence, the sonic velocity of the refrigerants is lower. Using $\Delta h_{os}/a_{01}^2$, the calculated pressure ratio of refrigerants is lower than air.

This limitation is not favourable as ORC turbine is characterized with high pressure ratio.

The turbine performance correction chart was attempted for R245fa for higher pressure ratio (or volumetric ratio).

Turbine Performance Correction Chart (for R245fa)

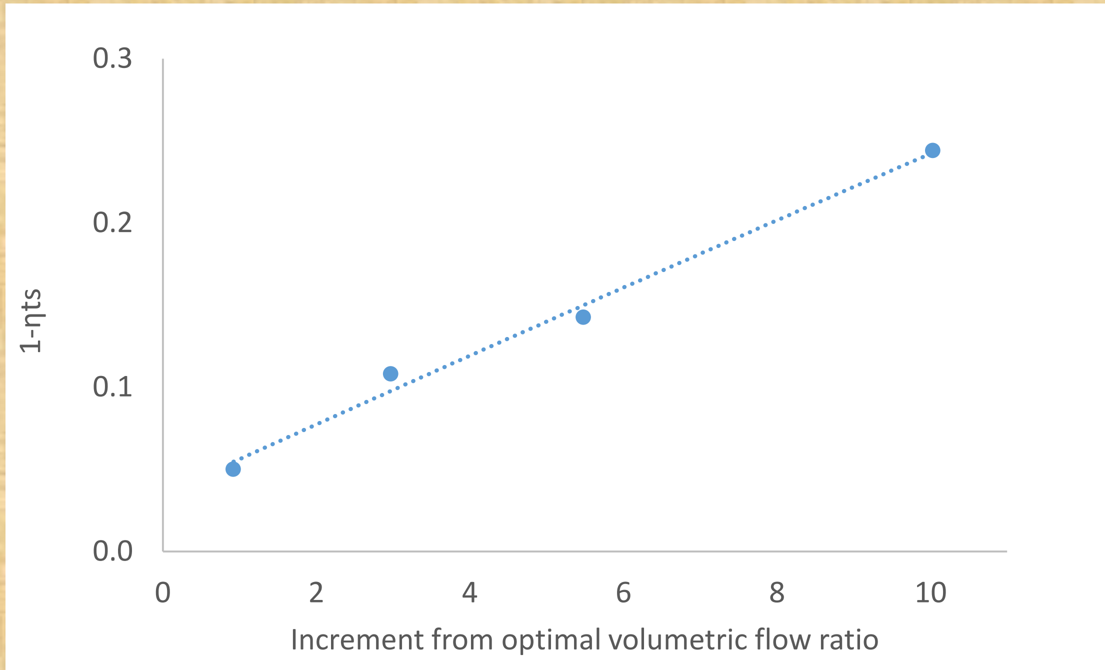


Figure: Deviation of best efficiency point at increasing volumetric flow ratio

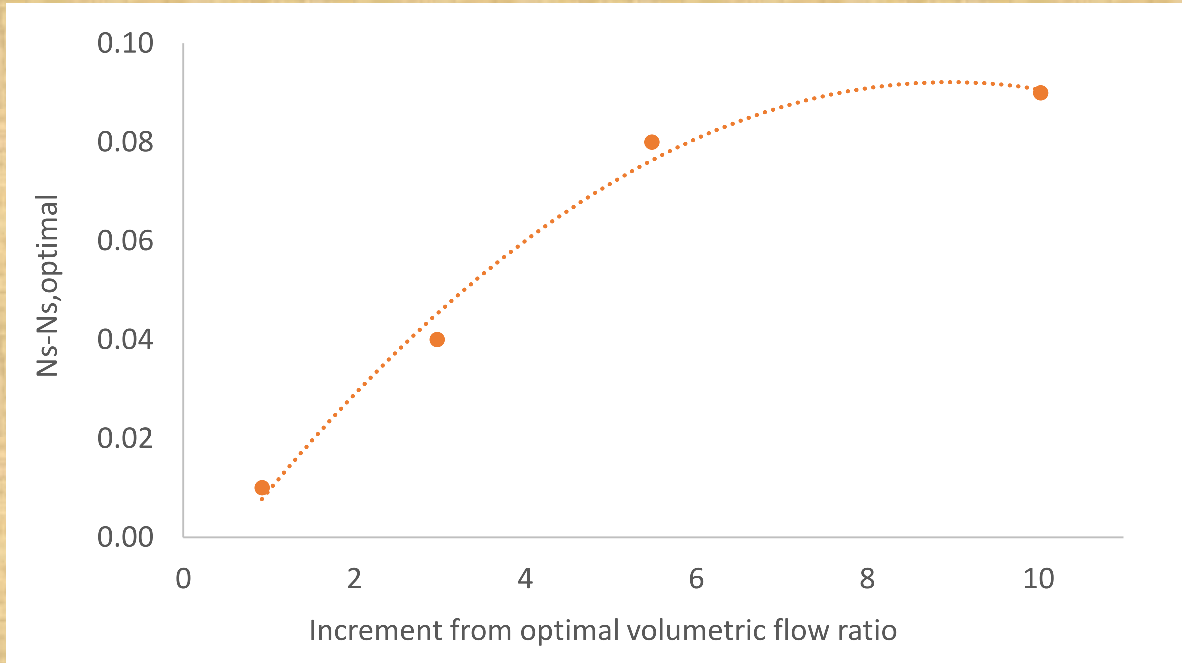


Figure: Deviation of optimal specific speed at increasing volumetric flow ratio

If the pressure ratio is higher than the optimal value, the deficit in efficiency can be determined using the figure for R245fa.

Conclusion

- Variable pressure ratio approach is used to predict the turbine performance at the best efficiency point
- Constant specific speed approach is used to predict the turbine performance away from the best efficiency point
- Variable pressure ratio approach has the following limitations:
  - Complete similarity is not achieved
  - Change in turbine exit swirl angle
  - Not applicable for high pressure ratio application
- Hence, a turbine performance correction chart was presented.

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