1-D Meanline design point calculation and loss calculation of the design and off-design behavior for an axial turbine stage

FH Aachen University of Applied Sciences
Department of Aerospace Engineering

A python code was created to calculate the 1-D Meanline design point calculations for the design and off-design behaviors in an axial turbine stage. The formulae and values used are taken in accordance with the given parameters and allowable boundaries. An excel workbook was created to plot the stage efficiency for a given range of geometric and flow coefficients. The results obtained were then visualized and analyzed. Results show an increase in efficiency and then a decrease giving us a peak/maximum efficiency.

Authors:	Shreyas Ashwin Sunder, Yash Vijaykumar Gandhi
Advisor:	Prof. D.Grates
Team No:	4
Date of Submission:	22.02.2021

Theory:

Meanline method is the calculation of a simplified model of a complex 3-D flow. It uses streamlines or stream tubes to perform calculations and flow quantities are averaged in time and space. In 1-D Meanline design, calculations are done only in the axial direction i.e., flow conditions vary only axially and not radially.

Assumptions [Design calculations]:

1) Repeating stage:

   Flow velocity from the outlet of the rotor = Flow velocity to the inlet of the stator ($c_2 = c_0$ or $c_{m2} = c_{m0}$ and $c_{u2} = c_{u0}$)

2) Φ constant:

   $\Phi_0 = \Phi_1 = \Phi_2$ or c_m = const.

3) Blade velocity constant:

   $u_0 = u_1 = u_2$

4) Mass flow rate in rotor and stator constant:

   dm/dt = const. (for a given ρ_h, Φ and Ψ_h)

Assumptions [Off-design calculations]:

1) Flow follows the blades at the outlet:

   $\alpha_1 = \alpha_{1,\text{ DESIGN}}$ and $\beta_2 = \beta_{2,\text{ DESIGN}}$

2) Enthalpy parameter can be approximated into a linear equation:

   $\Psi_h = 2 + K*\Phi_2$ (K = const.)

Boundary conditions and flow parameter range:

```
# Boundary Conditions(can be changed by user)

n = 7000 #rotational speed(1/min)
R = float(287.0) #gas constant(J/kgK)
Kappa = float(1.31) #ratio of specific heats
Cp = float(1212.81) #heat capacity at constant pressure(J/kgK)
const = float(0.016) #loss constant
Cd = float(0.002) #turbulent flow coefficient
l = float(0.04) #blade length(l1 = l2)
visc = float(6.41*(10**-5)) #dynamic viscosity(kg/ms)
Z = float(46) #blade count
Cpb = float(0.2) #base pressure coefficient
delte = float(0.0004) #Profile thickness at trailing edge(m)
delcl = float(0.0005) #clearance gap height(m)
Cc = 0.6 #contraction coefficient(=deleff/delcl)
Dh = [0.55,0,0] #hub diameter(m)
Ds = [0.65,0,0] #shroud diamter(m)
Ptot = [25,0,0] #total pressure(bar)
Ttot = [800,0,0] #total temperature(K)

# Flow Coefficient Range(should be kept constant)

rhoh = [0, 0.1, 0.2, 0.3, 0.4, 0.5]
psih = [-1.75, -2.0, -2.25, -2.5, -2.75, -3.0, -4.0]
phi = [0.35, 0.4, 0.45, 0.5, 0.55, 0.6, 0.65, 0.7, sqrt(0.5), 0.8]
```

Methodology:

1) Insertion of boundary and initial conditions.
2) Calculation of constant criteria (D_m, u, c_m).
3) Check for maximum rotational speed (for a given rotational speed, T<=0 or T_{TOT}<=0).
4) Calculation of various parameters for every combination of ρ_h, Φ and Ψ_h:
   - Calculation of velocities and angles (α, β, c, w).
   - Calculation of initial conditions (T_0, P_0, ρ_0, A_0, dm/dt).
   - Calculation of conditions at inlet and outlet of rotor (T, P, ρ).
   - Check for choking at any point in the turbine (Mach>=1).
   - Calculation of hub and casing diameters (D_h, D_s).

- Calculation of losses in the turbine (Profile, Wake, Tip leakage, Secondary flow).
- Isentropic efficiency calculation with loss consideration.
- Plotting η_{isen} with Φ and Ψ_h as the axes for every ρ_h.

5) Off-design calculations for the two highest efficiency models from the design point calculations:
    - Calculation of parameters done in step 4 but for a given Φ and using it to calculate a new Ψ_h ($\Psi_{h,OFF}$) and ρ_h ($\rho_{h, OFF}$).
    - Calculation of $\Psi_{y.}$
    - Plotting Ψ_h, Ψ_y and η_{poly} against Φ.
6) Display of results using graphs and contour plots.

Termination Criteria:

1) Rotational speed:

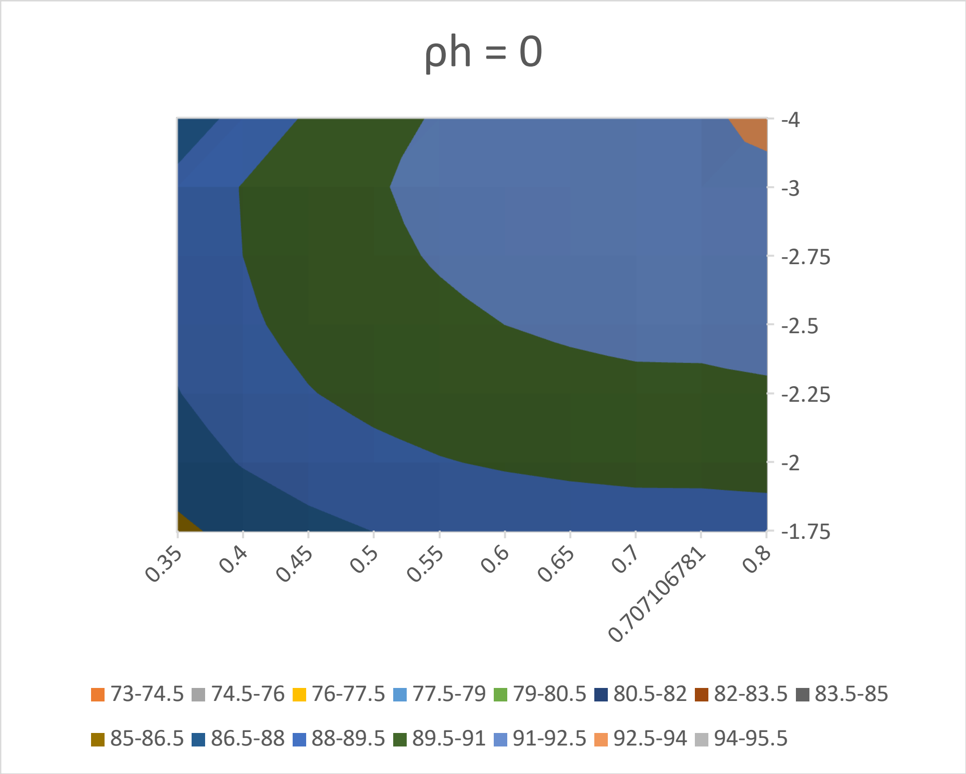
    At a certain speed it was observed that the temperature (static or total) at some point inside the turbine becomes negative which is not realistically possible. Hence the program is designed to be terminated if the given rotational speed is greater than the allowable rotational speed (T and T_{TOT}>0).

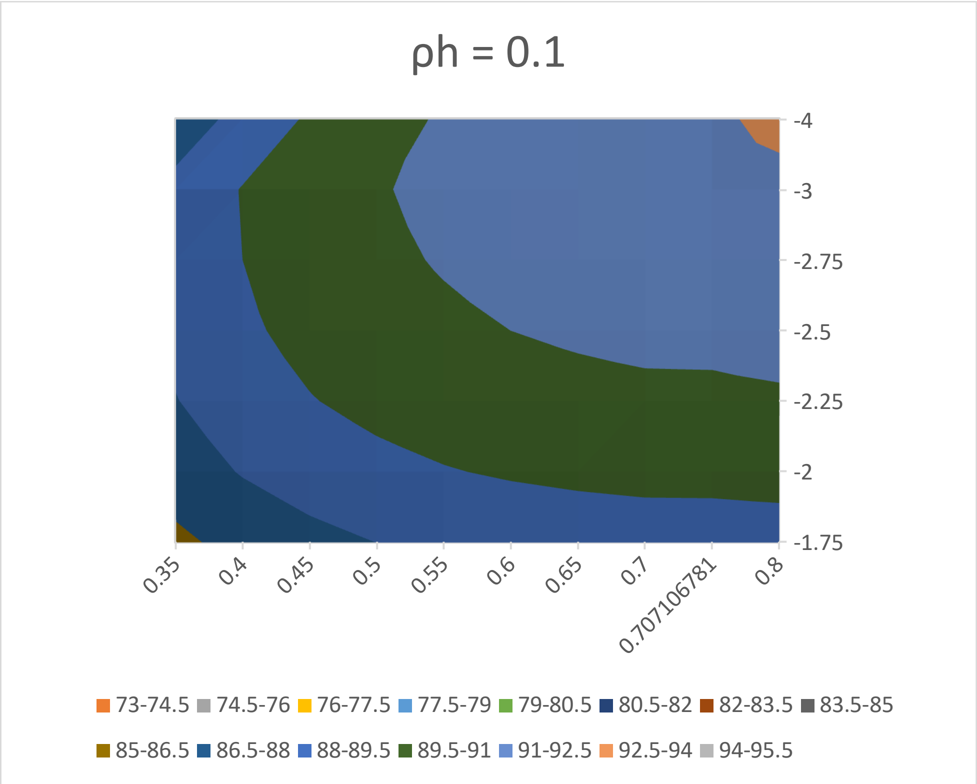
2) Choking:

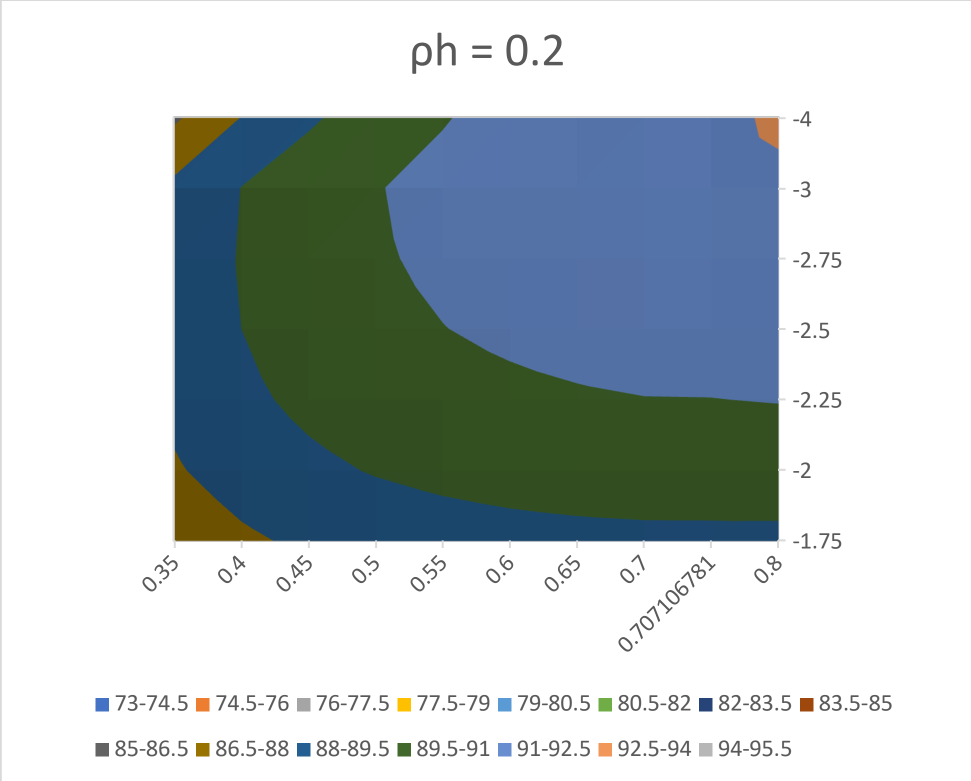
    At any point inside the turbine, if the flow velocity becomes greater than the speed of sound at the local temperature, it leads to a choked flow situation. This is not preferrable as it can lead to formation of shock waves which can cause a sudden increase in pressure, temperature and even cause flow separation. Hence the local Mach number is calculated at all points and the program does not allow the display of efficiency whenever the Mach number exceeds 1.

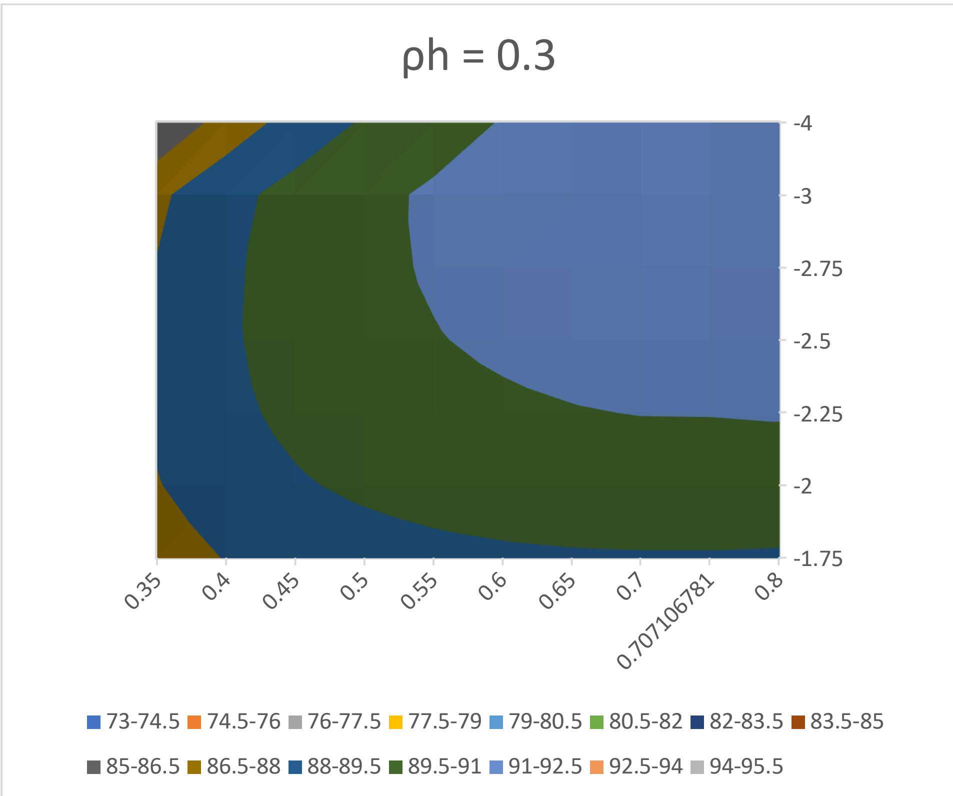
Results:

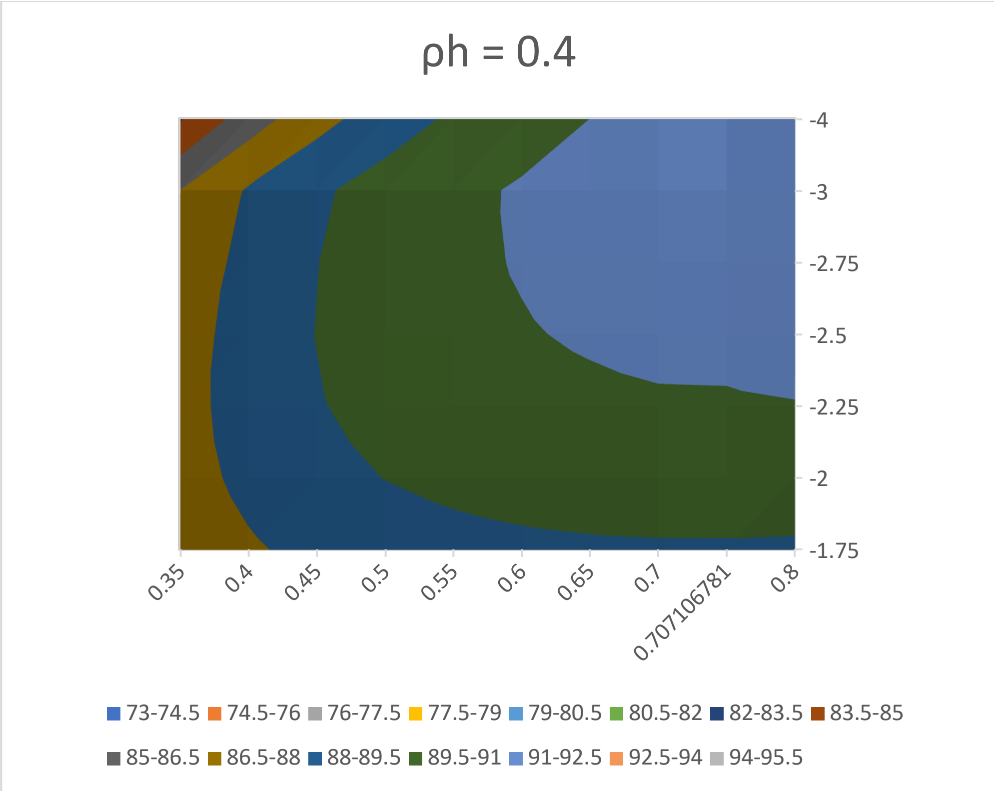
Design Calculations:



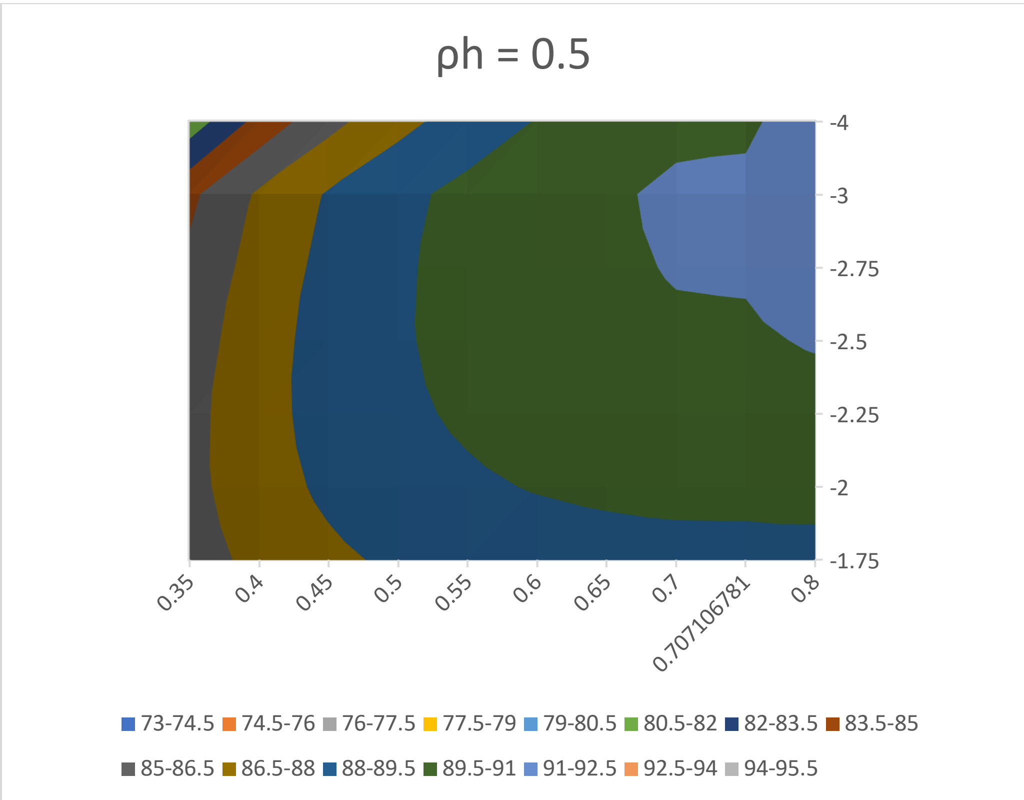



ρh = 0.2
-4
-3
-2.75
-2.5
-2.25
-2
-1.75
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.707106781
0.8
73-74.5 74.5-76 76-77.5 77.5-79 79-80.5 80.5-82 82-83.5 83.5-85
85-86.5 86.5-88 88-89.5 89.5-91 91-92.5 92.5-94 94-95.5


ρh = 0.3
-4
-3
-2.75
-2.5
-2.25
-2
-1.75
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.707106781
0.8
73-74.5 74.5-76 76-77.5 77.5-79 79-80.5 80.5-82 82-83.5 83.5-85
85-86.5 86.5-88 88-89.5 89.5-91 91-92.5 92.5-94 94-95.5



ph = 0.4
-4
-3
-2.75
-2.5
-2.25
-2
-1.75
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.707106781
0.8
73-74.5 74.5-76 76-77.5 77.5-79 79-80.5 80.5-82 82-83.5 83.5-85
85-86.5 86.5-88 88-89.5 89.5-91 91-92.5 92.5-94 94-95.5

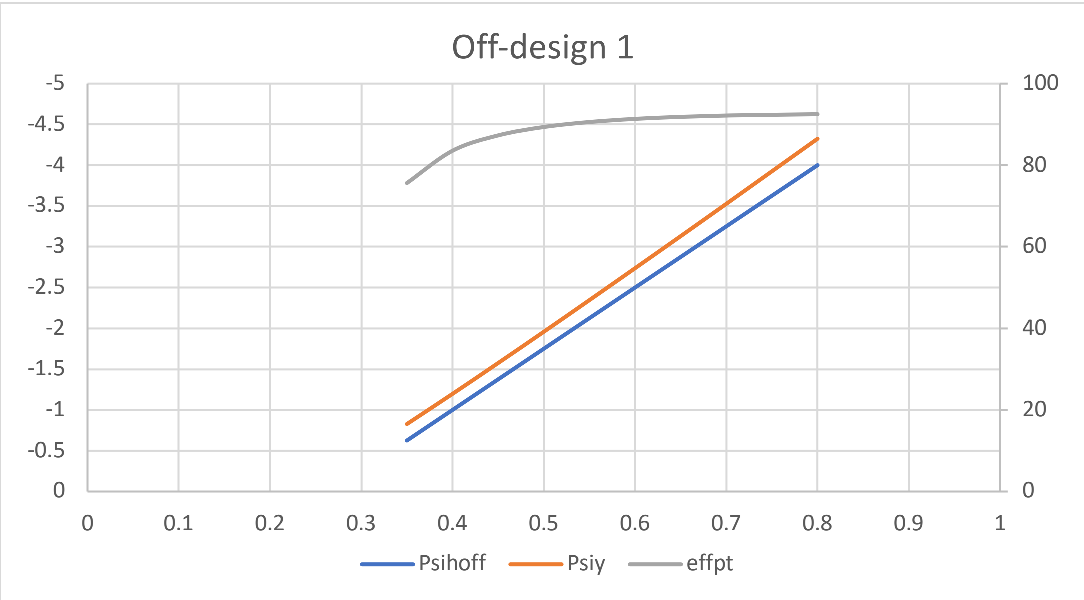


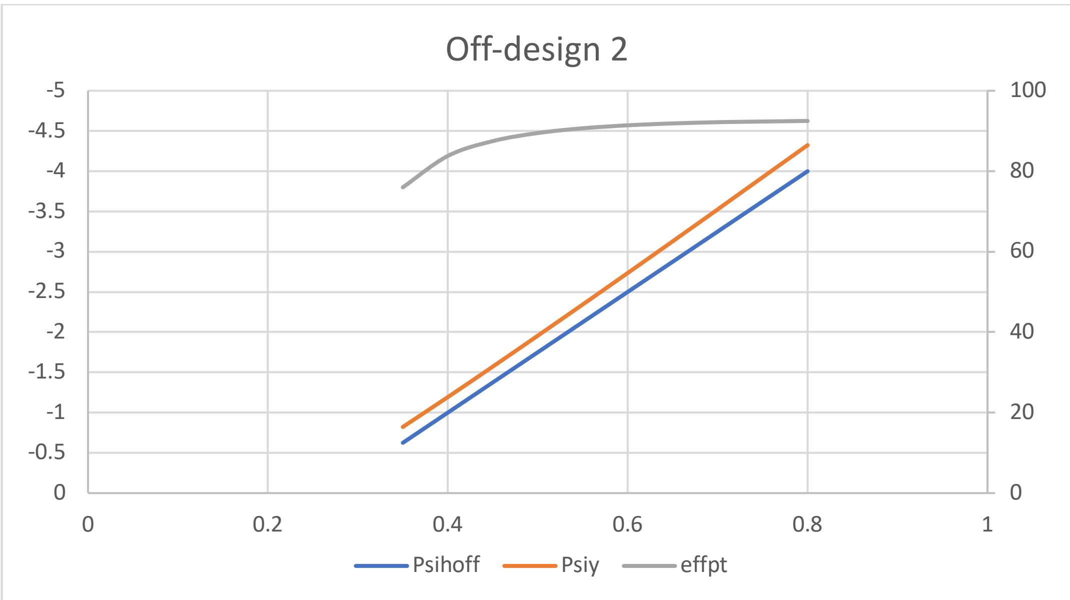
ph = 0.5
-4
-3
-2.75
-2.5
-2.25
-2
-1.75
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.707106781
0.8
73-74.5 74.5-76 76-77.5 77.5-79 79-80.5 80.5-82 82-83.5 83.5-85
85-86.5 86.5-88 88-89.5 89.5-91 91-92.5 92.5-94 94-95.5

From the design point graphs it can be observed that:

- η_{isen} roughly decreases with increase in ρ_h.
- η_{isen} increases with increase in Φ.
- η_{isen} decreases with increase in Ψ_h.

Off-design Conditions:





From the off-design graphs, it can be observed that:

- η_{poly} increases towards the design point flow conditions.
- Ψ_y shows little deviation from Ψ_h.

References:

Loss calculation models: *Denton [1990]and Jeschke [2017]*

Formulae for design calculations: FH Aachen lectures(*D. Grates)*