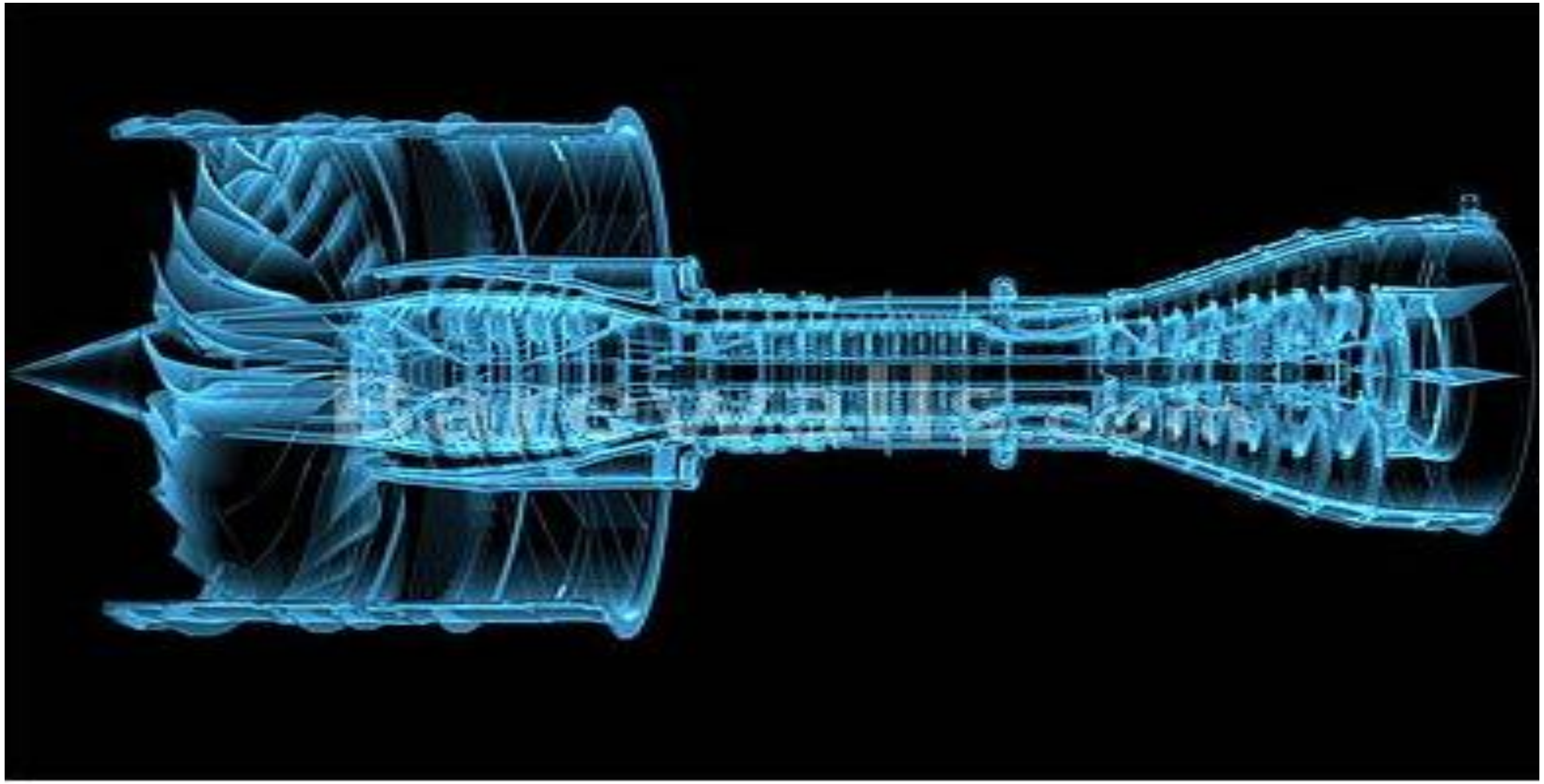

Turbomachinery Design

Project: 1-D Meanline Design of an Axial Turbine

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Task:

Create a python program to calculate for rotor and stator at design and off-design conditions for a turbine using the 1-D Meanline design theory.

Sub-Tasks:

- Calculate inlet and outlet conditions and η_{isen} for design parameters by varying ρ_h, Φ and Ψ_h.
- Plot the efficiencies for various models (combinations of ρ_h, Φ and Ψ_h) and use contour plots in excel to display efficiency graphs.
- Calculate the same parameters for off-design conditions.
- Plot η_{poly} , $\Psi_{h\text{-off-design}}$ and Ψ_y for a given range of Φ in excel.

Assumptions (Design conditions):

- 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 $c_{u2} = c_{u0}$)

- Φ constant:

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

- Blade velocity constant:

  $u_0 = u_1 = u_2$

- Mass flow rate in rotor and stator constant:

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

Assumptions (Off-Design conditions):

- Flow follows the blades at the outlet:

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

- Enthalpy parameter can be approximated into a linear equation:

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

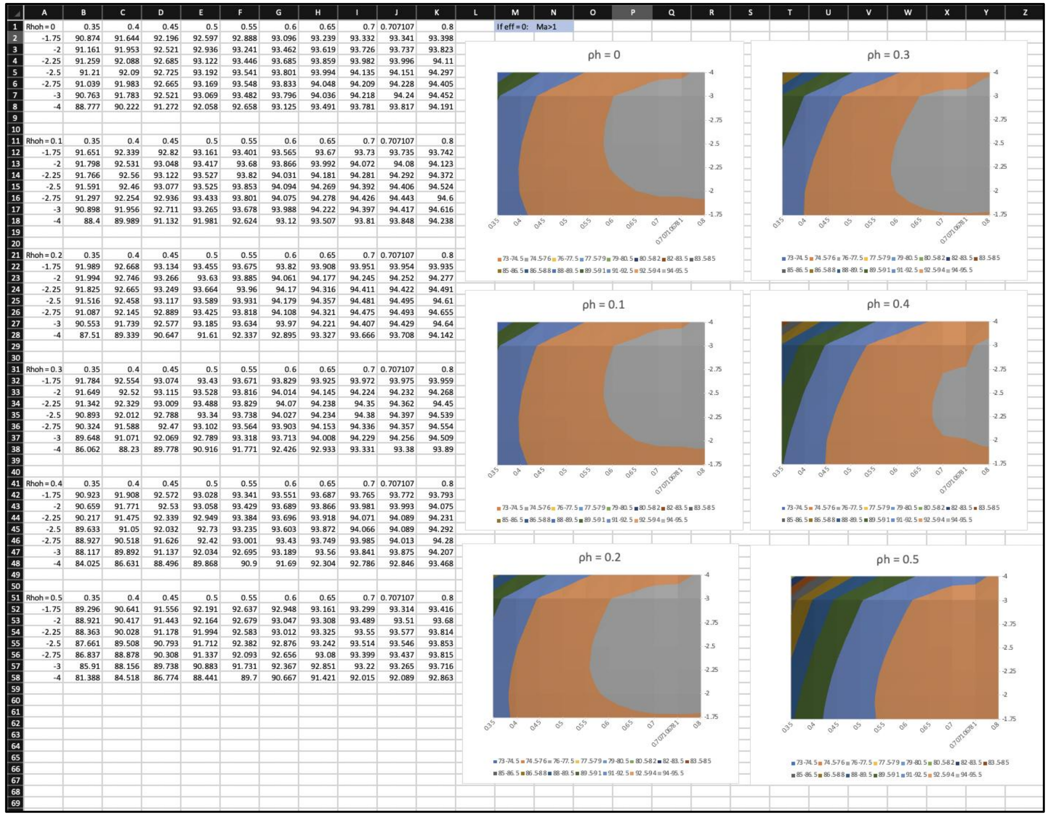
Boundary Conditions and Work Parameter Range:

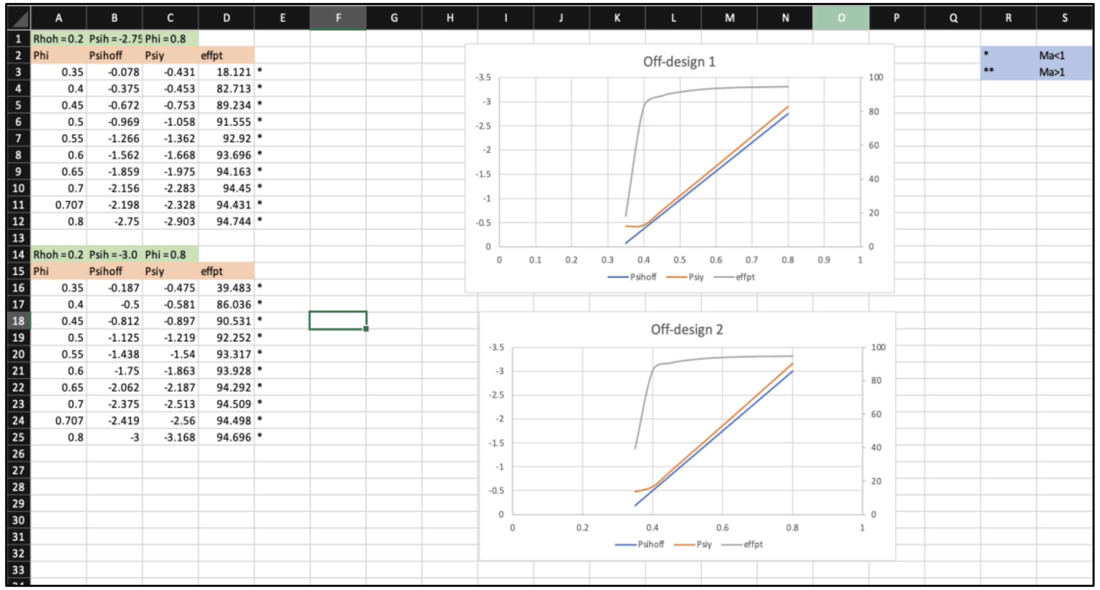
```
# Boundary Conditions(can be changed by user)

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:

- Insertion of boundary and initial conditions.
- Calculation of constant criteria (D_m, u, c_m).
- Check for maximum rotational speed (for a given rotational speed, T<=0 or T_{TOT}<=0).
- Calculation of various parameters for every combination of ρ_h, Φ and Ψ_h:
    1. Calculation of velocities and angles (α, β, c, w).
    2. Calculation of initial conditions (T_0, P_0, ρ_0, A_0, dm/dt).
    3. Calculation of conditions at inlet and outlet of rotor (T, P, ρ).
    4. Check for choking at any point in the turbine (Mach>=1).
    5. Calculation of hub and casing diameters (D_h, D_s).
    6. Calculation of losses in the turbine (Profile, Wake, Tip leakage, Secondary flow).
    7. Isentropic efficiency calculation with loss consideration.
    8. Plotting η_{isen} with Φ and Ψ_h as the axes for every ρ_h.

- Off-design calculations for the two highest efficiency models from the design point calculations:
    1. 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 ($\rho_{h,\ OFF}$).
    2. Calculation of Ψ_y.
    3. Plotting Ψ_h, Ψ_y and η_{poly} against Φ.
- Display of results using graphs and contour plots.





Rhoh = 0.2	Psih = -2.75	Phi = 0.8		
Phi	Psihoff	Psiy	effpt	
0.35	-0.078	-0.431	18.121	*
0.4	-0.375	-0.453	82.713	*
0.45	-0.672	-0.753	89.234	*
0.5	-0.969	-1.058	91.555	*
0.55	-1.266	-1.362	92.92	*
0.6	-1.562	-1.668	93.696	*
0.65	-1.859	-1.975	94.163	*
0.7	-2.156	-2.283	94.45	*
0.707	-2.198	-2.328	94.431	*
0.8	-2.75	-2.903	94.744	*

Rhoh = 0.2	Psih = -3.0	Phi = 0.8		
Phi	Psihoff	Psiy	effpt	
0.35	-0.187	-0.475	39.483	*
0.4	-0.5	-0.581	86.036	*
0.45	-0.812	-0.897	90.531	*
0.5	-1.125	-1.219	92.252	*
0.55	-1.438	-1.54	93.317	*
0.6	-1.75	-1.863	93.928	*
0.65	-2.062	-2.187	94.292	*
0.7	-2.375	-2.513	94.509	*
0.707	-2.419	-2.56	94.498	*
0.8	-3	-3.168	94.696	*

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).

```
#Check for max rotational speed
while ntest < n+100:
    for Rhoh in rhoh:
        for Psih in psih:
            for Phi in phi:
                u = float((pi*Dm*ntest)/60)
                cm = float(Phi*u)
                alpha[1] = acos(((1-Rhoh-(Psih/4)))/sqrt(((1-Rhoh-(Psih/4))**2+Phi**2)))
                beta[1] = acos(((1-Rhoh+(Psih/4)))/sqrt(((1-Rhoh+(Psih/4))**2+Phi**2)))
                alpha[2] = acos(((0-Rhoh-(Psih/4)))/sqrt(((0-Rhoh-(Psih/4))**2+Phi**2)))
                beta[2] = acos(((0-Rhoh+(Psih/4)))/sqrt(((0-Rhoh+(Psih/4))**2+Phi**2)))
                c[1] = float(cm/sin(alpha[1]))
                c[2] = float(cm/sin(alpha[2]))
                T[0] = float(Ttot[0]-(c[2]**2/(2*Cp)))
                Ttot[2] = float(Ttot[0]+(Psih*(u**2))/(2*Cp))
                T[2] = float(Ttot[2]-((c[2]**2)/(2*Cp)))
                Ttot[1] = Ttot[0]
                T[1] = float(Ttot[1]-(c[1]**2/(2*Cp)))
                if T[0] <= 0 or T[1] <= 0 or T[2] <= 0 or Ttot[1] <= 0 or Ttot[2] <= 0:
                    sys.exit("Rotational speed exceeds max allowed speed")
    ntest = ntest+100
```

2. Choking:

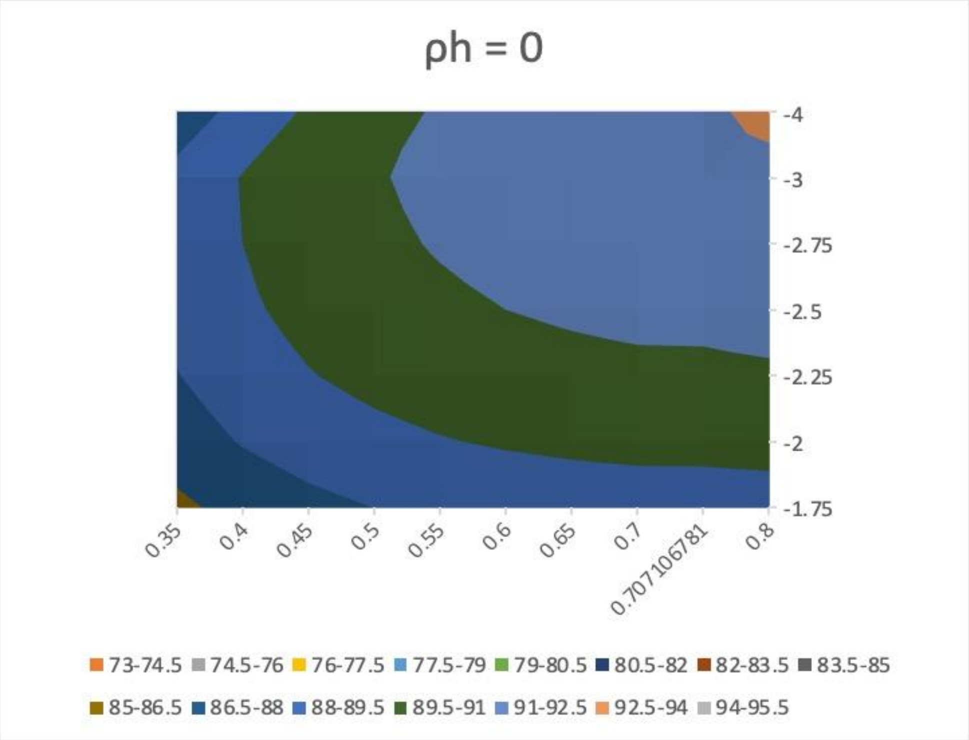
At any point inside the turbine, if the flow velocity becomes greater than the speed of sound at the local temperature, it leads to a choked flow situation. This is not preferrable as it can lead to formation of shock waves which can cause a sudden increase in pressure, temperature and even cause flow 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.

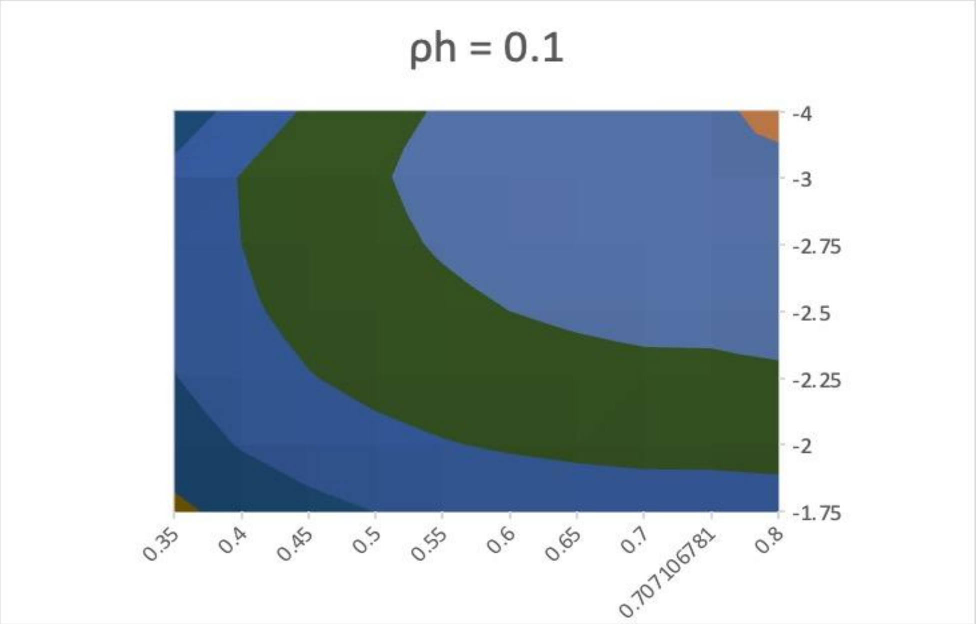
```
#Check for choking at rotor and stator exits
Ma[1] = float(w[1]/sqrt(Kappa*R*T[1]))
Ma[2] = float(c[1]/sqrt(Kappa*R*T[2]))
if Ma[1] >= float(1) or Ma[2] >= float(1):
    count = 1
else:
    count = 0
```

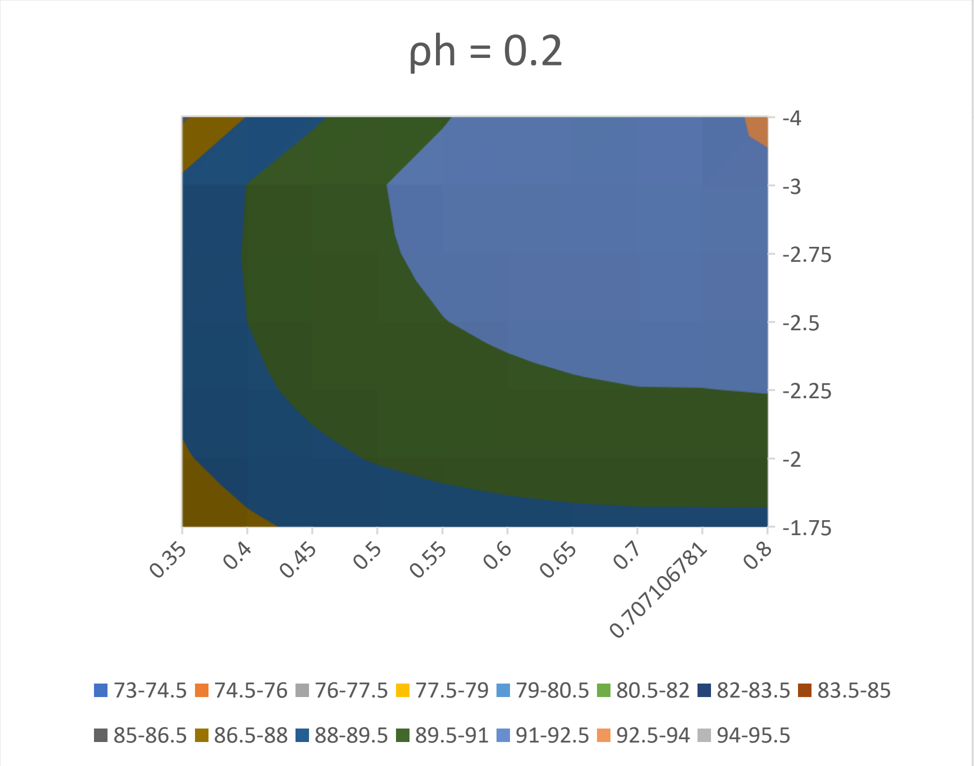
```
    #Writing into the csv file
    if count == 0:
        st1.append(round(effstnew*100, 3))
    else:
        st1.append(0)
df[Phi] = st1
```

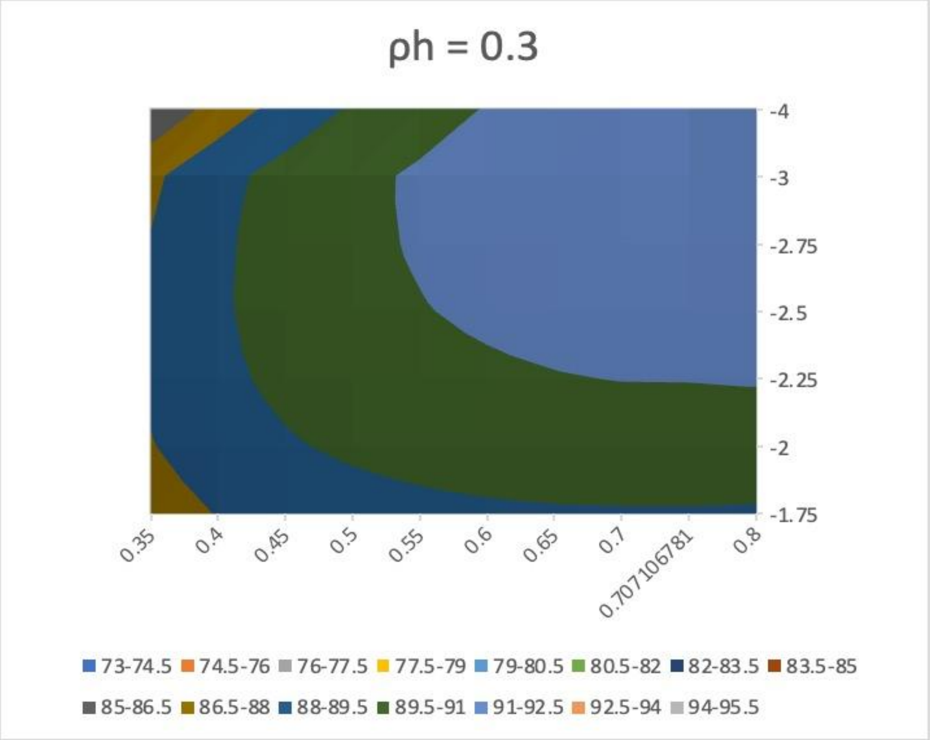
Results:

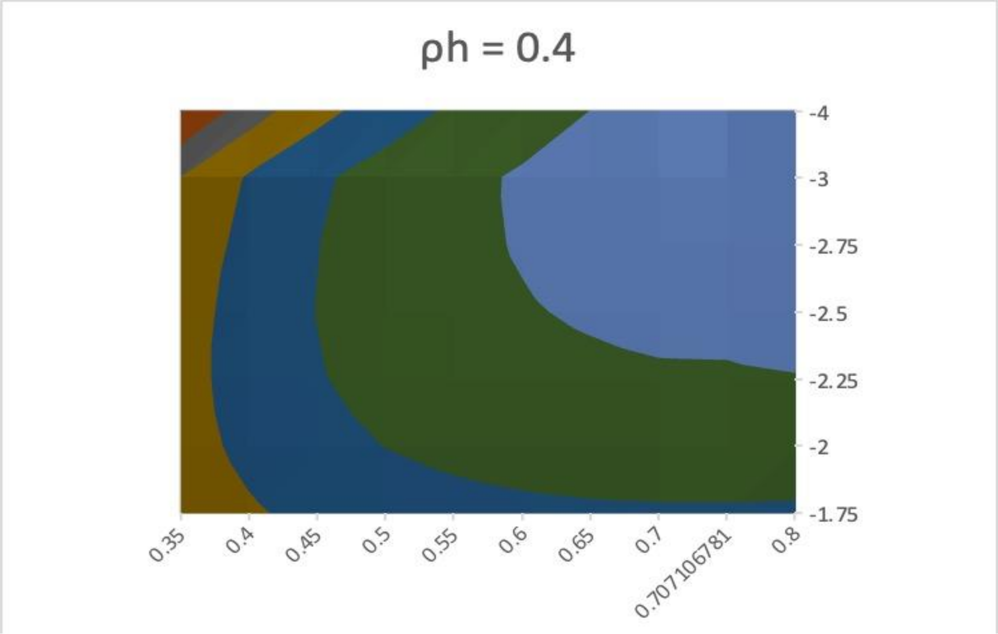
Design Calculations:

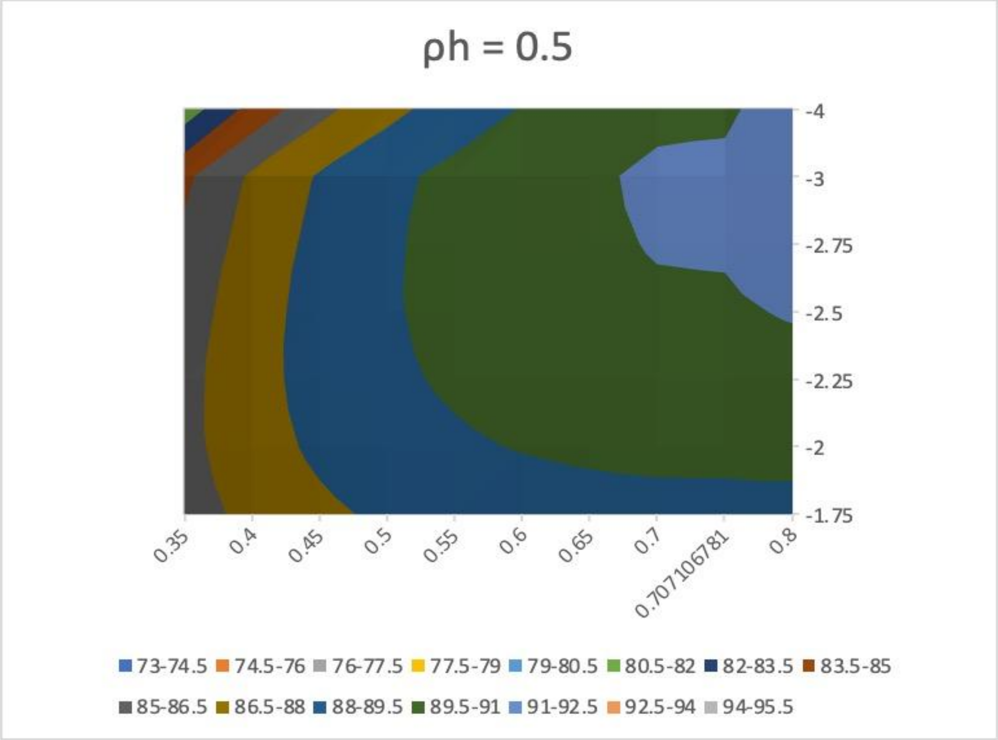












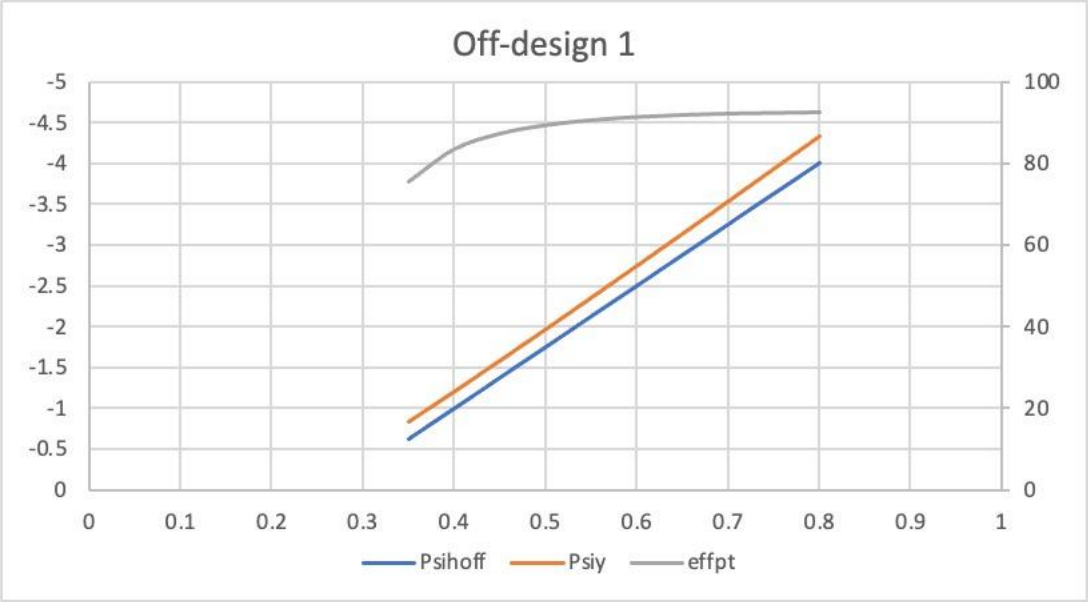
From the design point graphs it can be observed that:

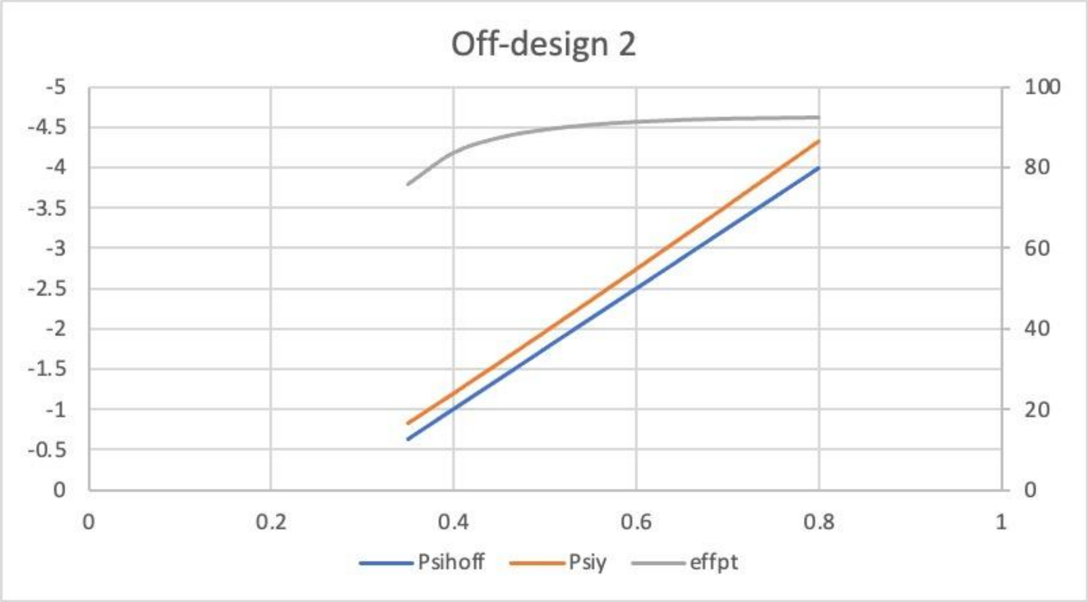
- η_{isen} roughly decreases with increase in ρ_h.
- η_{isen} increases with increase in Φ.
- η_{isen} decreases with increase in Ψ_h.

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.





Scope for Improvement:

- Check for Surge: Location inside the turbine where the pressure gradient is no longer favorable and flow reverses.
- Parameter Limitation: Limit the parameter range to avoid un-feasible results.
- User Interface: Improve user interface for easier usage and better display.

References:

- Loss calculation models: *Denton [1990] and Jeschke [2017]*
- Formulae for design calculations: FH Aachen lectures (*D. Grates)*

Thank You