MEEN 646 – Aerothermodynamics of Turbomachinery

Module IV:
Design of Radial Compressor
Part 1: Aero-Thermo Analysis

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I. Introduction

This module provides a preliminary design for a single stage radial compressor. Using aerodynamic and thermodynamic analysis, the effect of mass flow rate is noted on the inlet and outlet angles, power and on dimensionless coefficients. Matlab code is used to plot the variation of these parameters. These calculations provide design ground for 3D design of compressor components, which will be addressed in part 2 of this module.

II. Aero Thermo Design

1. Given parameters

Table 1: Design Parameters

$\dot{m}_D$ (Design mass flow rate)	3.5 kg/s
T_{in} (Inlet temperature)	300 K
P_{01} (Inlet total pressure)	1 bar
π_{ref} (Reference pressure ratio)	3.0
ω (Angular velocity)	5000
$(\eta_{is})_{Design}$ (Design efficiency)	0.86
D_{m2} (Inlet mean diameter)	160 mm
D_3 (Exit diameter)	240 mm
B_{h2} (Inlet blade height)	100 mm
B_{h3} (Outlet blade height)	40 mm
α_2 (Absolute inlet flow angle)	90^0
β_3 (Relative exit angle)	90^0

The intention of this analysis is to study the effect of flow rate on performance for a given ω for different mass flow rates. Flow rate was varied from 2.5-4.5 kg/s. Efficiency was modelled using the following model.

$$a_0 = -0.3844, a_1 = 3.0222, a_2 = -1.7778$$

$$\eta_{is} = a_0 + a_1\left(\frac{\dot{m}}{\dot{m}_D}\right) + a_2\left(\frac{\dot{m}}{\dot{m}_D}\right)^2, \quad \pi = \eta_{is} * \pi_{ref}$$

2. Schematic of Radial Compressor

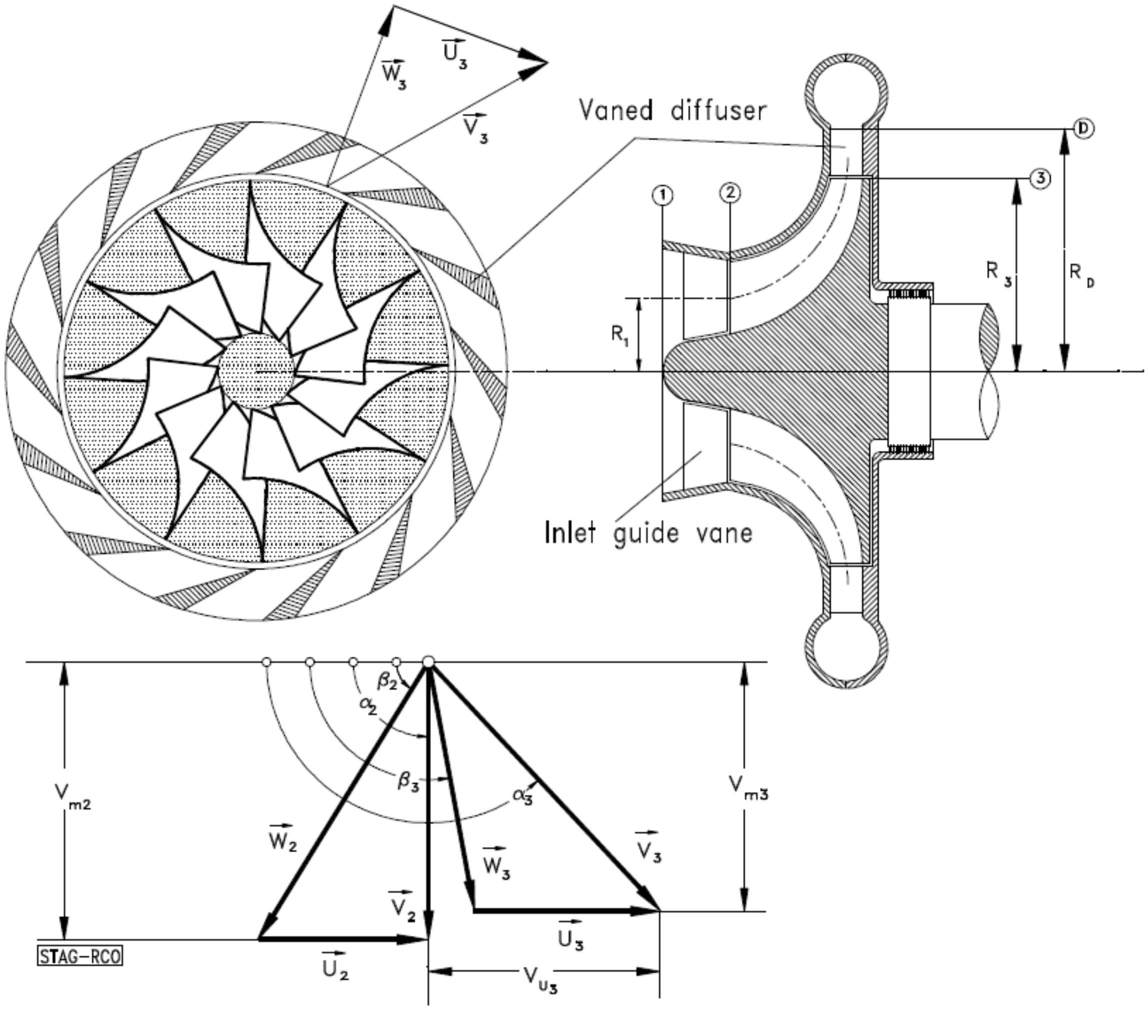


Figure 1: Schematic of Radial Compressor

3. Equations

a. Inlet parameters

$$P_{02} = P_2 + \frac{V_2^2 \rho_2}{2}$$

$$\rho_2 = \frac{P_2}{RT_2}$$

$$V_2 = \frac{\dot{m}}{\rho_2 A_2} = \frac{\dot{m}}{\rho_2 * pi/4 * [(D_{m2} + B_{h2})^2 - (D_{m2} - B_{h2})^2]}$$

$$P_2 = \rho_2 R T_2$$

b. Outlet parameters

$$P_3 = P_2 \pi$$

$$T_{3s} = T_2(\pi)^{\frac{k-1}{k}}$$

$$T_3 = T_2 + \frac{T_{3s} - T_2}{\eta_{is}}$$

$$\rho_3 = \frac{P_3}{RT_3}$$

$$W_3 = \frac{\dot{m}}{\rho_3 A_3}$$

c. Velocity calculations

$$V_3 = \sqrt{W_3^2 + U_3^2}$$

$$W_2 = \sqrt{{V_2}^2 + U_2^2}$$

$$\alpha_3 = 90 + \tan^{-1}\left(\frac{U_3}{W_3}\right)$$

$$\beta_2 = \tan^{-1}\left(\frac{V_2}{U_2}\right)$$

$$\phi = \frac{W_3}{U_3}$$

d. Power calculation

$$Power = \dot{m} * \left(c_p(T_3 - T_2)\right) + \frac{V_3^2 - V_2^2}{2}$$

4. Results

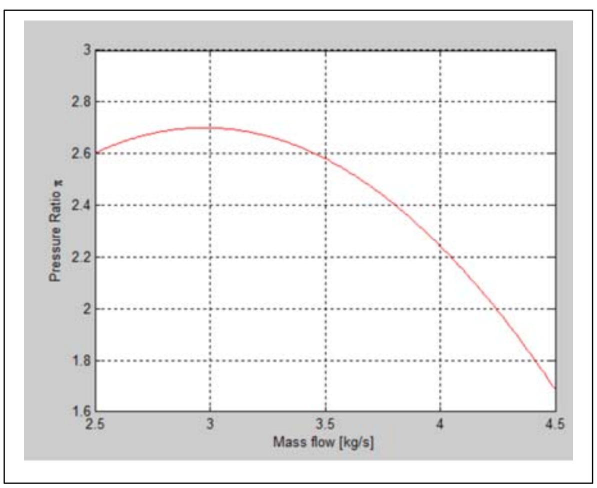


Figure 2: Pressure Ratio vs Mass Flow

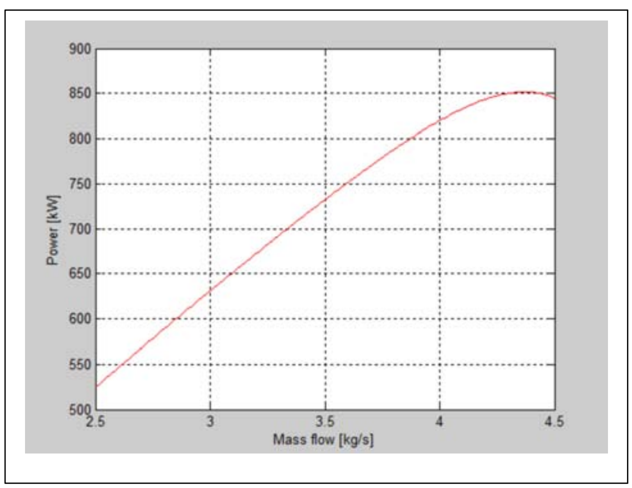


Figure 3: Power vs Mass Flow

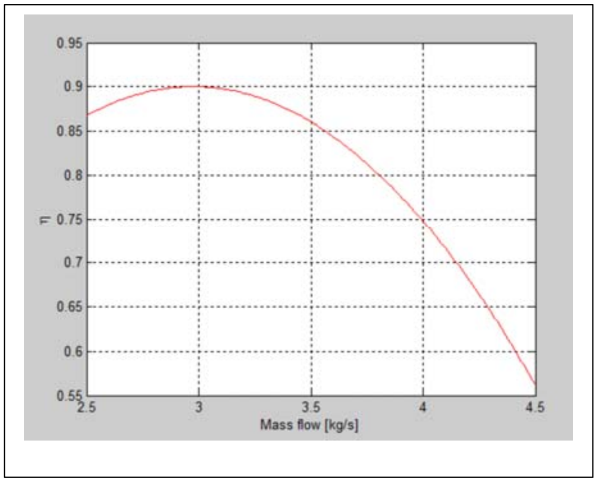


Figure 4: Efficiency vs Mass Flow

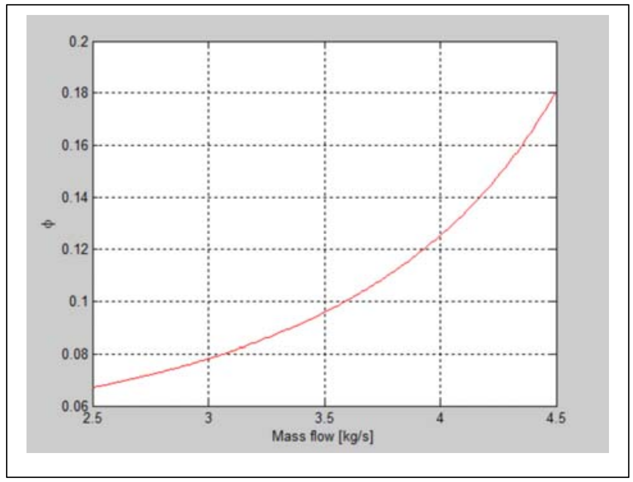


Figure 5: Flow Coefficient vs Mass Flow

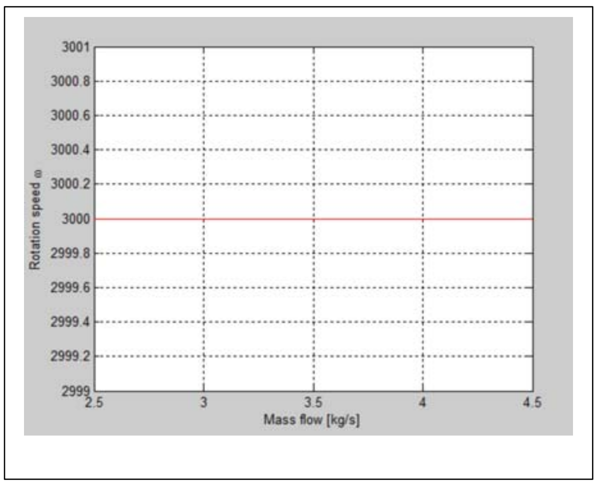


Figure 7: Rotation Speed vs Mass Flow

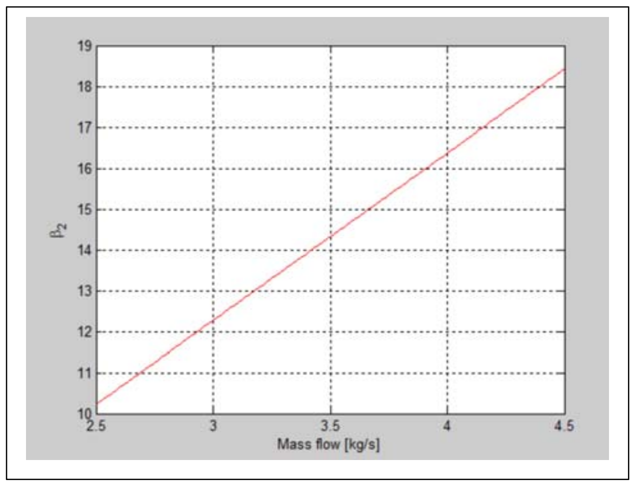


Figure 6: Beta2 vs Mass Flow

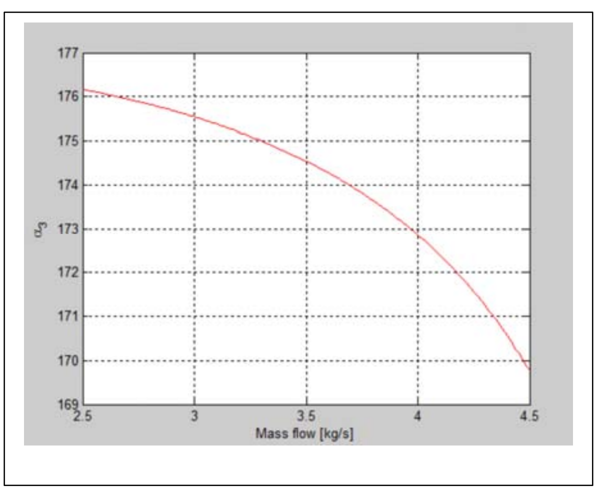


Figure 9: Alpha3 vs Mass Flow

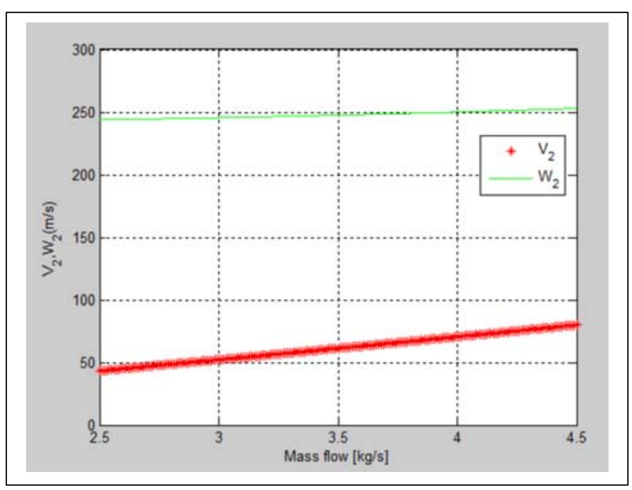


Figure 8: Inlet Velocity vs Mass Flow

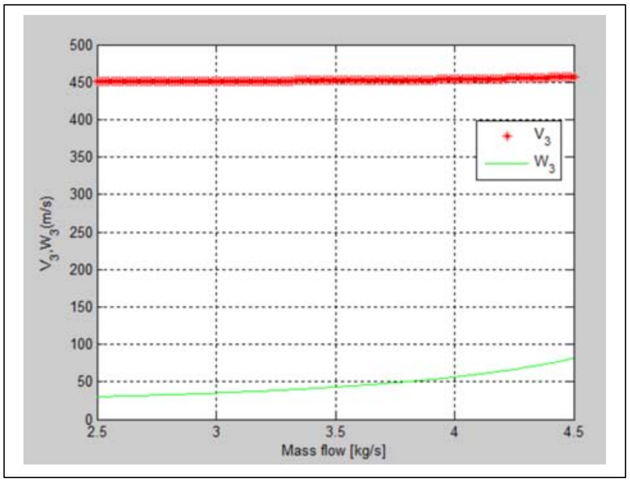


Figure 10: Outlet Velocity vs Mass Flow

5. Table of Design Parameters

Table 2: Complete Design Parameters

Mass flow rate	$\dot{m}_D$	3.5	kg/s
Inlet temperature	T_2	300	K
Inlet pressure	P_2	97,867	Pa
Outlet temperature	T_3	408	K
Outlet pressure	P_3	252,500	Pa
Pressure ratio	π	2.58	
Angular velocity	ω	3,000	Rad/s
Design efficiency	$(\eta_{is})_{Design}$	0.86	
Inlet mean diameter	D_{m2}	160	mm
Exit diameter	D_3	300	mm
Inlet blade height	B_{h2}	100	mm
Outlet blade height	B_{h3}	40	mm
Absolute inlet flow angle	α_2	90	deg
Relative inlet flow angle	β_2	14.3	deg
Absolute exit angle	α_3	174.5	deg
Relative exit angle	β_3	90	deg
Flow coefficient	ϕ	0.0957	
Absolute inlet velocity	V_2	61.26	m/s
Relative inlet velocity	W_2	247.7	m/s
Absolute outlet velocity	V_3	452.1	m/s
Relative outlet velocity	W_3	43.05	m/s
Power	P	732	kW

III. Solidworks design

1. Compressor

a. Compressor casing

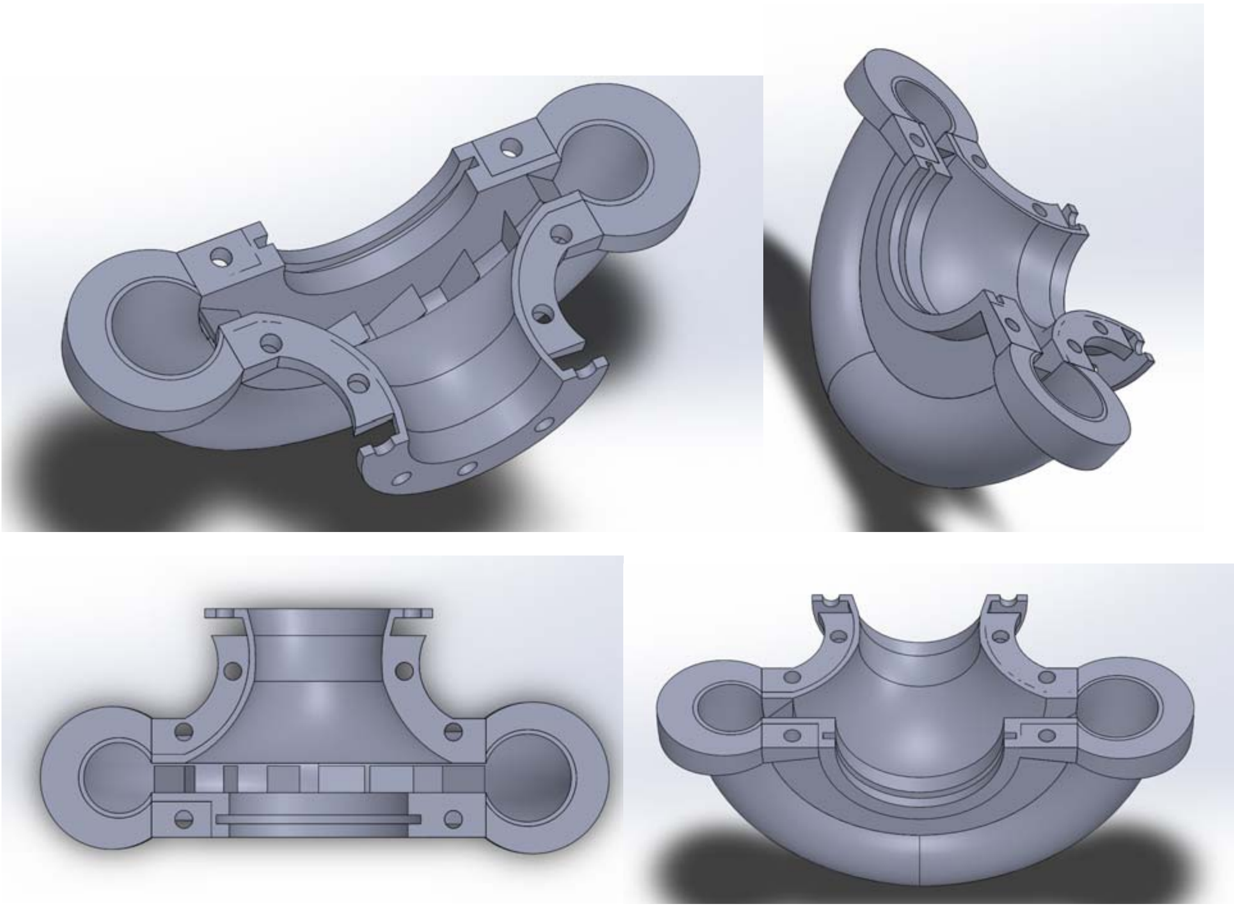


Figure 11: Bottom casing

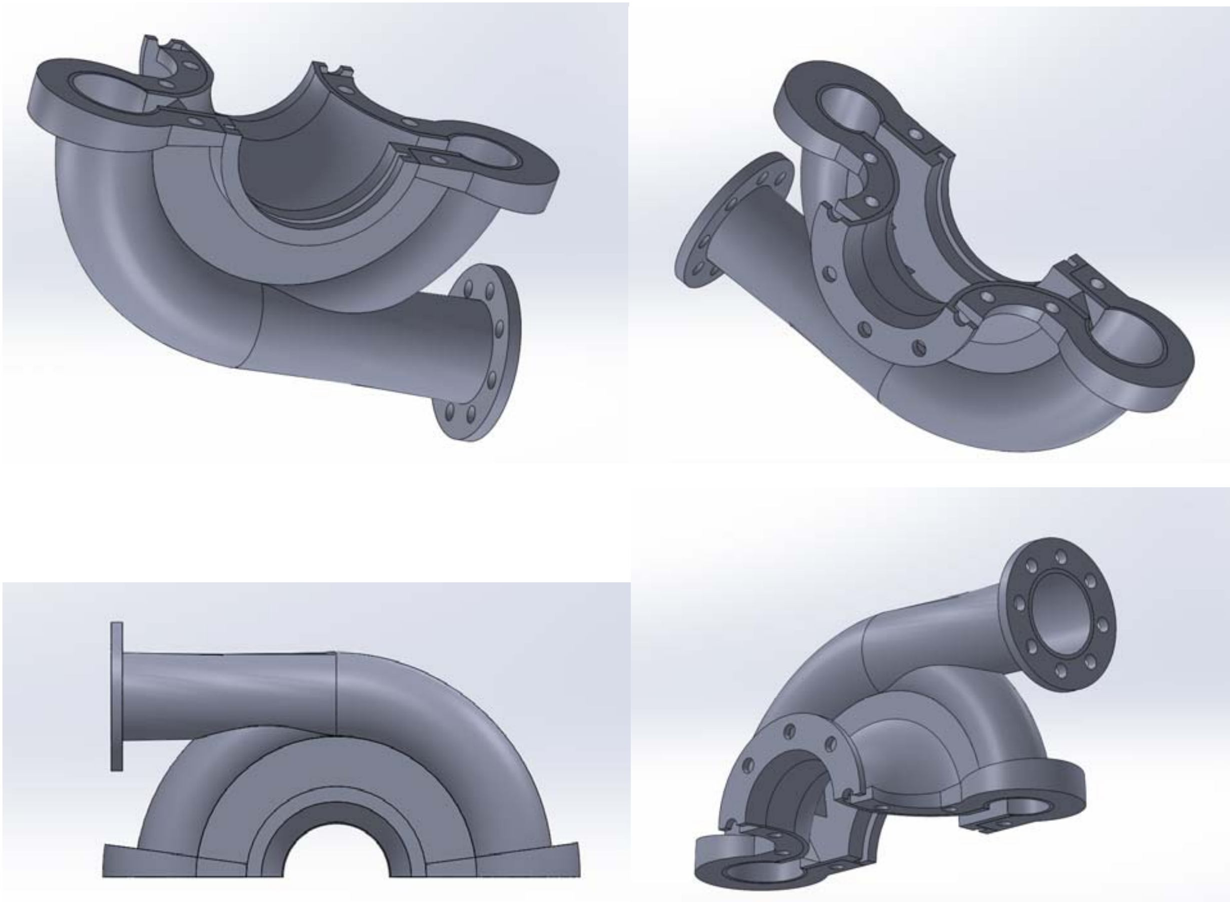


Figure 12: Top casing

b. Impeller design

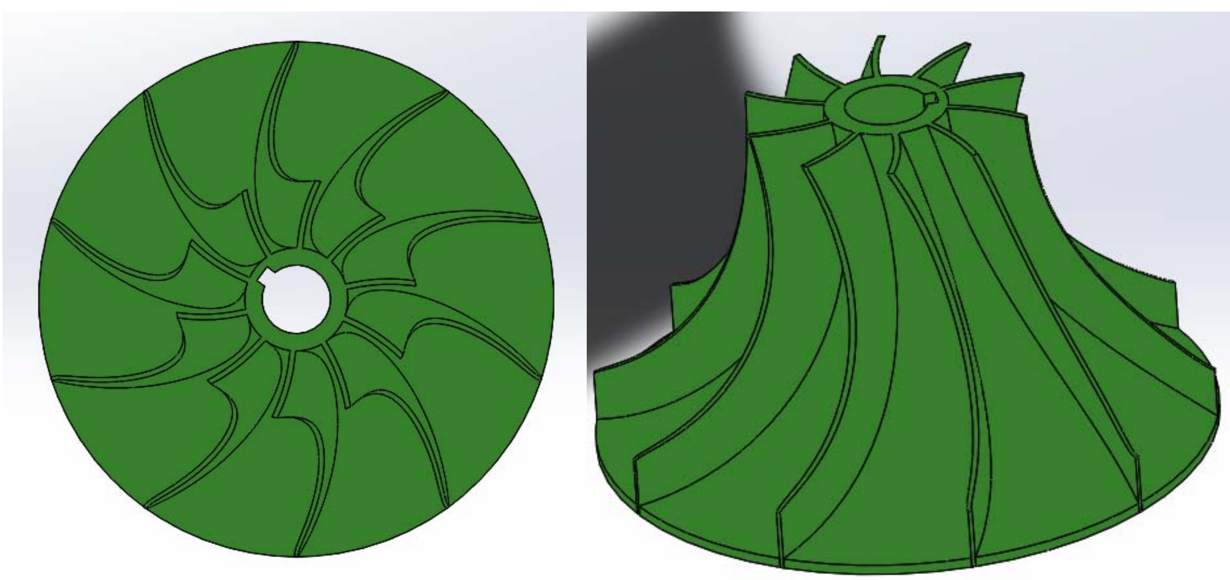


Figure 13: Impeller

c. Bearing housing arrangement

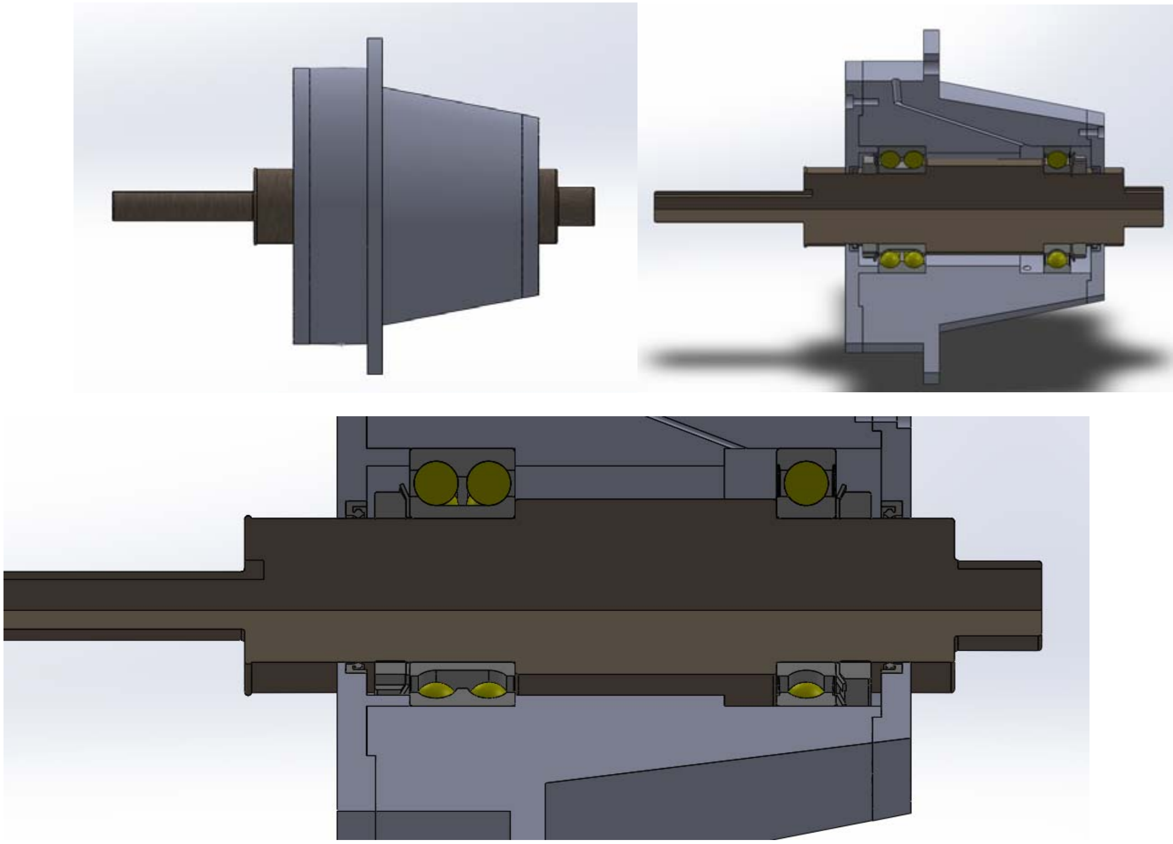
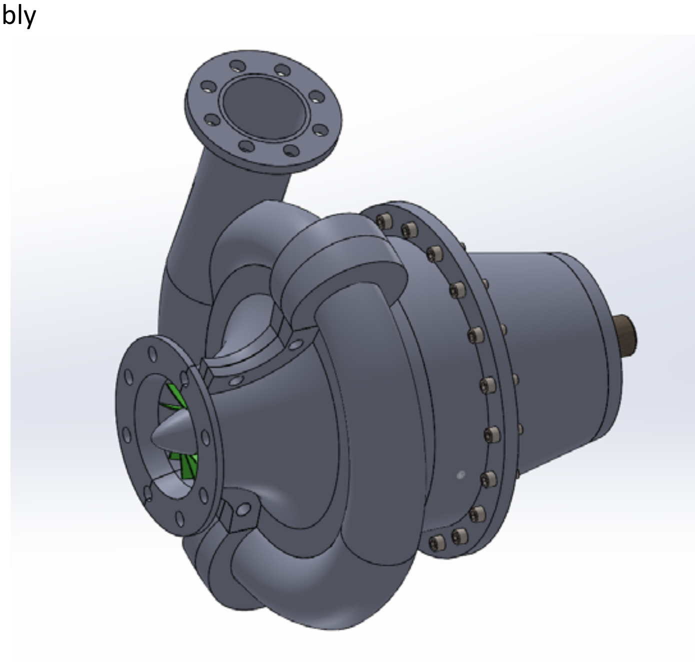


Figure 14: Bearing housing arrangement

d. Full assembly



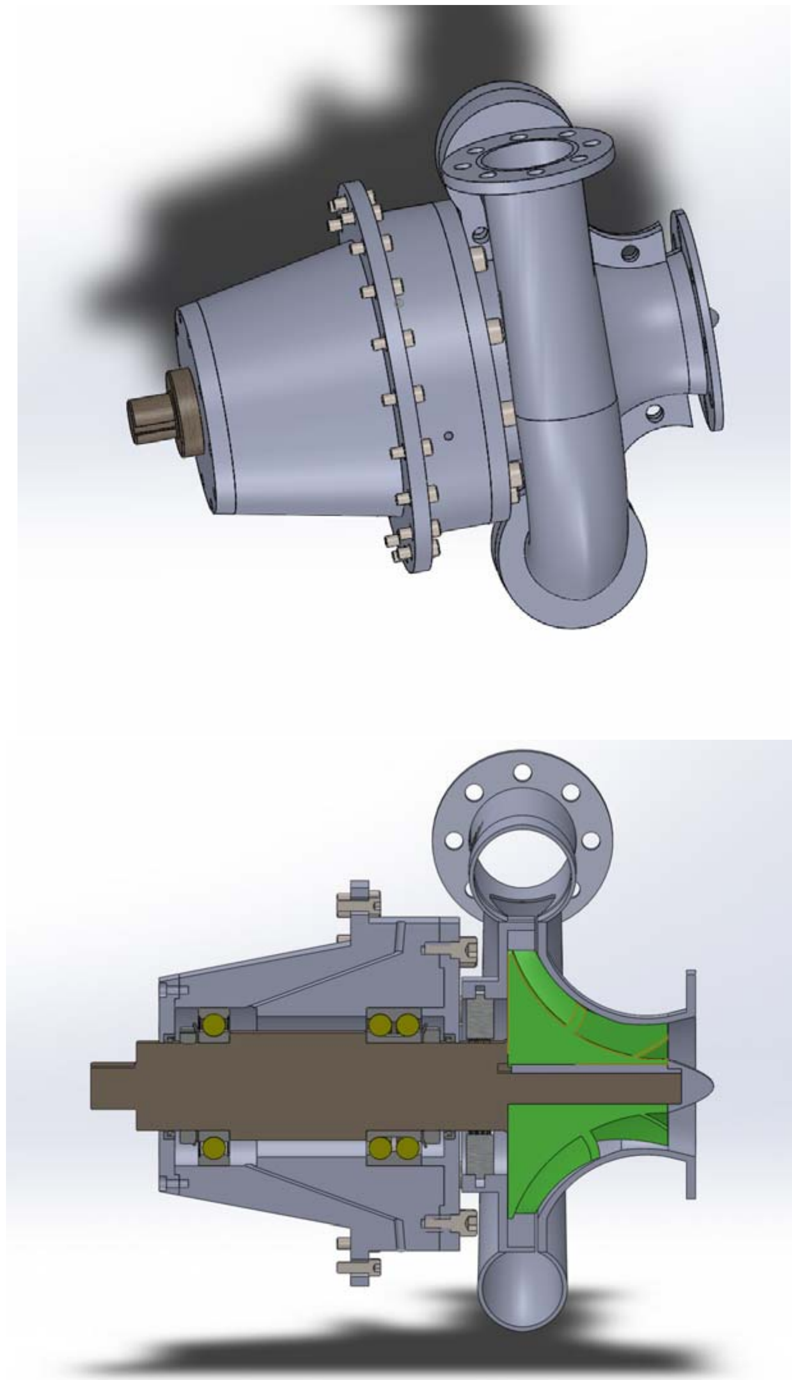


Figure 15: Compressor full assembly

e. Explored view

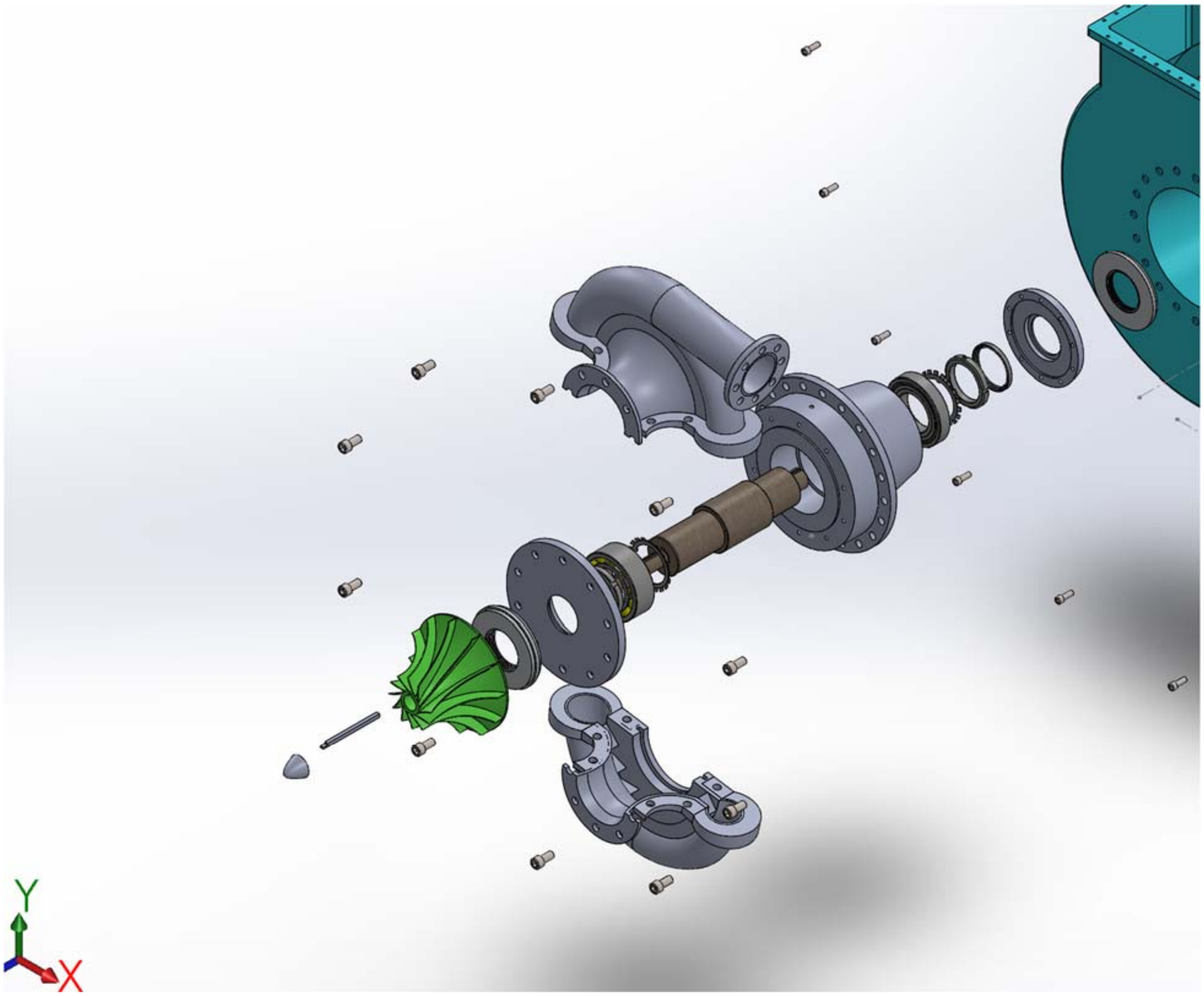
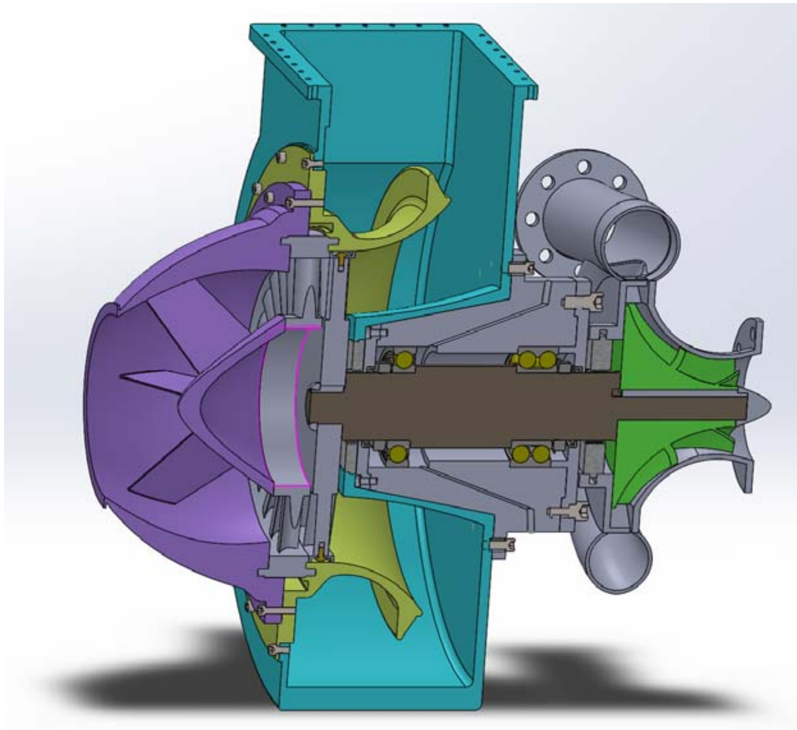
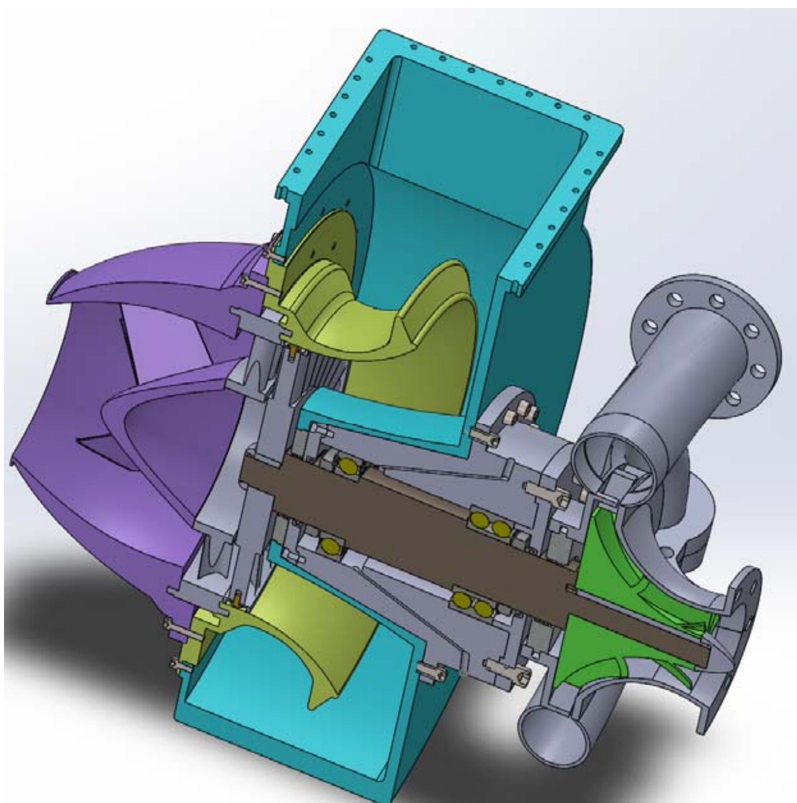
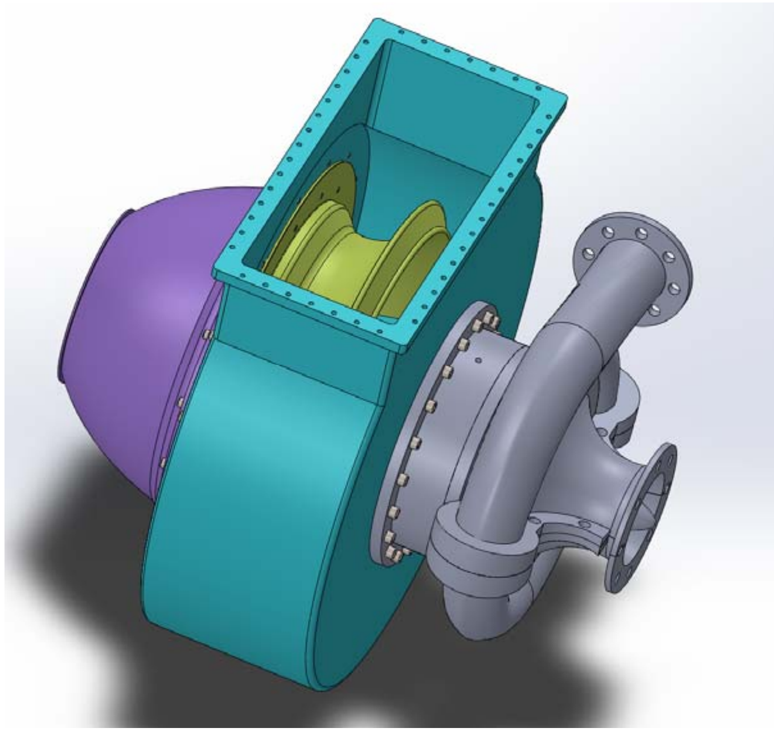


Figure 16: Compressor exploded view

2. Complete Turbocharger







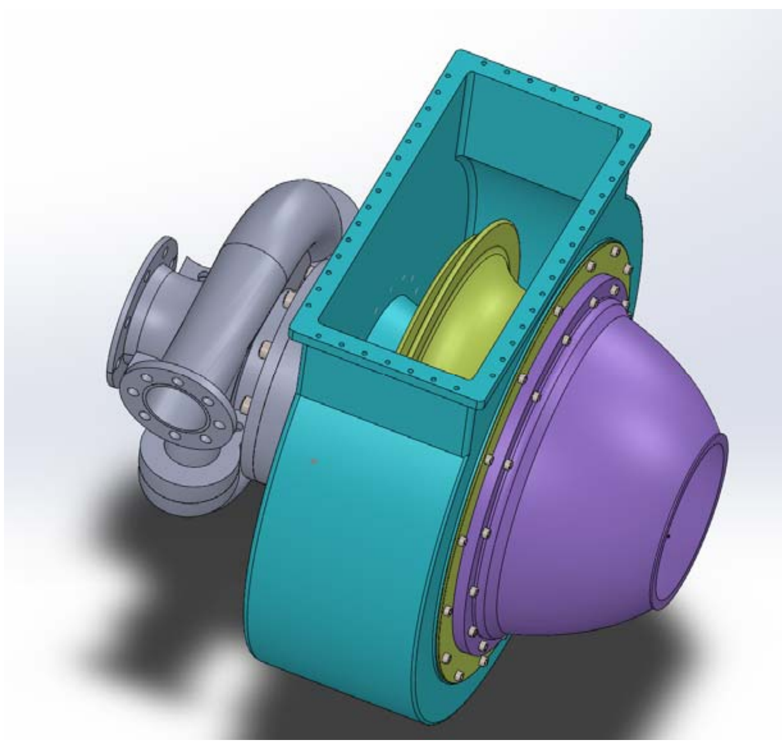


Figure 17: Complete Turbocharger full assembly

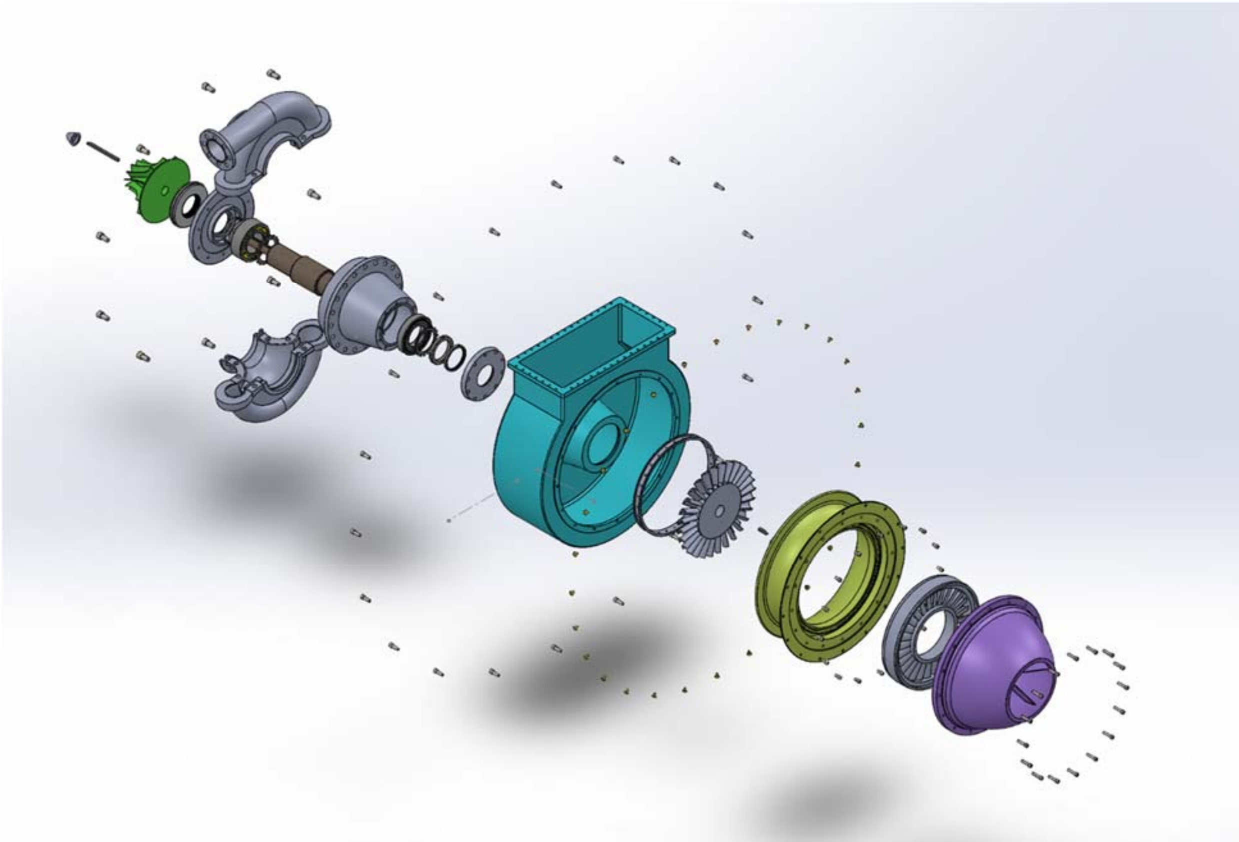


Figure 18: Turbocharger exploded view

References

[1] Schobeiri, Meinhard T., *Turbomachinery Flow Physics and Dynamic Performance – Chapter 5*, 2nd Ed. Springer 2012. Print & Online

```
%%% MEEN 646 Module 4 %%%

clear all
clc
mdot_d=3.5;
T2=300;
p02=10^5;
pi_ref=3.0;
om=3000; %rad/s
eta_d=0.86;
Dm2=0.16;
Rm2=0.08;
D3=0.3;
R3=0.15;
hb2=0.1;
hb3=0.04;
alp2=pi/2;
bet3=pi/2;
mdot=[2.5:0.01:4.5];
R=287;
k=1.3975; %subjected to change
cp=1009; %subjected to change

a0=-0.3844; a1=3.0222; a2=-1.7778;

U2=om*(Dm2/2); U3=om*(D3/2);
IR2=Dm2/2-hb2/2; OR2=Dm2/2+hb2/2;
A2=pi*(OR2^2-IR2^2);
A3=pi*D3*hb3;

for i=1:length(mdot)
    %Efficiency parameters (given)
    eta(i)=a0+a1*(mdot(i)/mdot_d)+a2*(mdot(i)/mdot_d)^2;
    p_ratio(i)=eta(i)*pi_ref;
    %Inlet parameters
    syms a %a=V2
    a=solve(p02==mdot(i)*R*T2/(A2*a)+mdot(i)*a/(2*A2),a);
    b(i,1:2)=double(vpa(a));
    V2(i)=double(vpa(min(a)));
    rho2(i)=mdot(i)/(A2*V2(i));
    P2(i)=rho2(i)*R*T2;
    %Outlet parameters
    P3(i)=P2(i)*p_ratio(i);
    T3s=T2*(p_ratio(i)^((k-1)/k));
    T3(i)=T2+(T3s-T2)/eta(i);
    rho3(i)=P3(i)/(R*T3(i));
    W3(i)=mdot(i)/(rho3(i)*A3);
    %Velocity calculations
    bet2(i)=atan(V2(i)/U2);
    bet2_deg(i)=bet2(i)*180/pi; %in degree
    W2(i)=sqrt(V2(i)^2+U2^2);
    %check(i)=acos(U3/V3(i));
    V3(i)=sqrt(W3(i)^2+U3^2);
    alp3(i)=pi/2+atan(U3/W3(i));
    alp3_deg(i)=alp3(i)*180/pi; %in degree
    %Additional calculations
    phi(i)=W3(i)/U3;
    ome(i)=om;
    %Power(i)=(abs(mdot(i)*cp*(T3(i)-T2)))/10^3;
    Power(i)=mdot(i)*(cp*(T3(i)-T2)+0.5*(V3(i)^2-V2(i)^2)); %unit in W
```

```
    Power1(i)=Power(i)/10^3; %unit in kW
    i=i+1;
end

figure (1)
plot(mdot',p_ratio','r')
xlabel('Mass flow [kg/s]')
ylabel('Pressure Ratio \pi')
%xlim([2 4.5])
grid on

figure (2)
plot(mdot',Power1','r')
xlabel('Mass flow [kg/s]')
ylabel('Power [kW]')
%xlim([3 4])
grid on

figure (3)
plot(mdot',eta','r')
xlabel('Mass flow [kg/s]')
ylabel('\eta')
%xlim([2 4.5])
grid on

figure (4)
plot(mdot',phi','r')
xlabel('Mass flow [kg/s]')
ylabel('\phi')
%xlim([3 4])
grid on

figure (5)
plot(mdot',ome','r')
xlabel('Mass flow [kg/s]')
ylabel('Rotation speed \omega')
%xlim([3 4])
grid on

figure (6)
plot(mdot',bet2_deg','r')
xlabel('Mass flow [kg/s]')
ylabel('\beta_2')
%xlim([3 4])
grid on

figure (7)
plot(mdot',alp3_deg','r')
xlabel('Mass flow [kg/s]')
ylabel('\alpha_3')
%xlim([3 4])
grid on

figure (8)
plot(mdot',V2','r*'); hold on
plot(mdot',W2','g'); hold off
xlabel('Mass flow [kg/s]')
ylabel('V_2,W_2(m/s)')
legend('V_2','W_2')
%xlim([3 4])
```

```
grid on

figure (9)
plot(mdot',V3','r*'); hold on
plot(mdot',W3','g'); hold off
xlabel('Mass flow [kg/s]')
ylabel('V_3,W_3(m/s)')
legend('V_3','W_3')
%xlim([3 4])
grid on
```