4.1 Engine Specifications:-

- Number of cylinders : 4
- Compression ratio (R_C) : 16.5:1
- Crankshaft rotation speed (N) : 4000 rpm
- Power output (N_o): 103 kW
- Lower heating value of the fuel and the mole fraction for each component (H_u) : 42.44 MJ/kg (O = 0.004, H = 0.126, C = 0.87)

4.2 Engine design without turbocharger:-

The engine was designed without taking the turbocharger in to account.

4.2.1 Thermodynamic calculations:-

Calculations of pressure and temperature at the end of each stroke.

4.2.1.1 Engine parameters:-

a. The sufficient amount of air for burning 1 kg of fuel:-

$$L_o = \frac{1}{0.208}\left(\frac{C}{12} + \frac{H}{4} - \frac{O}{32}\right)$$

$$= \frac{1}{0.208}\left(\frac{0.87}{12} + \frac{0.126}{4} - \frac{0.004}{32}\right) = 0.5 \ \text{kmol}_{\text{air}} / \text{kg}_{\text{fuel}}$$

$$l_o = \frac{1}{0.23}\left(\frac{8 \times C}{3} + 8 \times H - O\right)$$

$$l_o = \frac{1}{0.23}\left(8 \times \frac{0.87}{3} + (8 \times 0.126) - 0.004\right) = 14.452 \ \ \text{kg}_{\text{air}} / \text{kg}_{\text{fuel}}$$

b. Amount of air charge:-

$M_1 = \alpha \times L_o$, Take ($\alpha = 1.4$)

$M_1 = 1.4 \times 0.5 = 0.7 \ \text{kmol}_{\text{air}} / \text{kg}_{\text{fuel}}$

$= 1.4 \times 14.452 = 20.2328 \ \text{kg}_{\text{air}} / \text{kg}_{\text{fuel}}$

c. Content of exhaust gas:-

$$M_{H_2O} = \frac{H}{2}$$

$$= \frac{0.126}{2} = 0.063 \ \text{kmol}_{\text{H}_2\text{O}}/\text{kg}_{\text{fuel}}$$

$$M_{CO_2} = \frac{C}{12}$$

$$= \frac{0.87}{12} = 0.0725 \ \ \text{kmol}_{\text{CO}_2}/\text{kg}_{\text{fuel}}$$

$$M_{O_2} \ = 0.208 \times Lo \times (\alpha - 1)$$

$$= 0.208 \times 0.5 \times (1.4 - 1) = 0.041 \ \text{kmol}_{\text{O}_2}/\text{kg}_{\text{fuel}}$$

$$M_{N_2} \ = 0.792 \times M1$$

$$= 0.792 \times 0.7 \times 0.5544 \ \text{kmol}_{\text{N}_2}/\text{kg}_{\text{fuel}}$$

d. Amount of exhaust gas:-

$$M_2 = M_{CO_2} + M_{H_2O} + M_{O_2} + M_{N_2}$$

$$= 0.0725 + 0.063 + 0.0416 + 0.5544 = 0.7315 \ \text{kmol}_{\text{exhaust}}/\text{kg}_{\text{fuel}}$$

e. Ambient conditions:-

Ambient Temperature (T_o) = 300 K.

Atmospheric pressure (P_o) = 0.1 MPa.

Exhaust Pressure (P_{ex}) = 0.105 MPa.

$(\Delta T) = 20$°C.

4.2.1.2 Intake stroke

a. Air density at the cylinder inlet

$$\rho_o = P_o \times \frac{10^6}{R \times T_o}$$

$$= \frac{0.1 \times 10^6}{287 \times 300} = 1.16 \ \text{kg/m}^3$$

b. Air Pressure at the end of intake stroke

During intake stroke, a drop in pressure occurs through the manifold and valves holes. It could be found using the following relation.

$$\Delta P_a = \left(\beta^2 + \xi_{in}{}^2\right) \times w_{in}{}^2 \times \frac{\rho_o}{2}$$

We will take $\left(\beta^2 + \xi_{in}{}^2\right) = 2.7$, and $w_{in} = 110\,\mathrm{m/s}$

$\Delta P_a = 2.7 \times 110^2 \times \frac{1.16}{2} = 18948.6\, pa \cong 0.019$ MPa

$\therefore P_a = P_o - \Delta P_a = 0.1 - 0.019 = 0.081$ MPa

c. Volumetric efficiency

$$\eta_v = \frac{\mathrm{T_o} * (\mathrm{R_c} \times \mathrm{P_a} - \mathrm{P_r})}{\mathrm{P_a}(\mathrm{T} + \Delta\mathrm{T})(\mathrm{R_c} - 1)} \quad P_r = 0.105 \text{ MPa}$$

$$= \frac{300 * (16.5 \times 0.081 - 0.105)}{0.081(300 + 20)(16.5 - 1)} = 0.92$$

d. Coefficient of residual burned gas

$$\gamma_r = \frac{(\mathrm{T_{o+}}\Delta\mathrm{T})}{\mathrm{T_r}} \times \frac{\mathrm{P_r}}{\mathrm{R_c} \times \mathrm{P_a} - \mathrm{P_r}}, \quad T_r = 715.4 \text{ K}$$

$$= \frac{(300 + 20)}{715.4} \times \frac{0.105}{16.5 \times 0.081 - 0.105} = 0.038$$

e. Temperature at the end of intake stroke

$$T_a = \frac{T_o + \Delta T + \gamma_r \times T_r}{1 + \gamma_r}$$

$$= \frac{293 + 20 + 0.038 \times 715.4}{1 + 0.038} = 327.73 \text{ K}$$

4.2.1.3 Compression stroke

a. Pressure at the end of compression

$P_c = P_a(R_c)^n$

Take polytropic coefficient (n) 1.35

$P_c = 0.081(16.5)^{1.35} = 3.565$ MPa

b. Temperature at the end of compression

$T_c = T_a(R_c)^{n-1}$

$= 327.73 \times (16.5)^{1.35-1} = 874.25$ K

c. Mean molar heat capacity

$$(m\,C_v) = \frac{1}{M_2}\Big(\big(M_{CO_2} \times (m\,C_v)_{CO_2}\big) + (M_{H_2O} \times (m\,C_v)_{H_2O}) + \big(M_{O_2} \times (m\,C_v)_{O_2}\big) + \big(M_{N_2} \times (m\,C_v)_{N_2}\big)\Big)$$

$$20.01 + 5.7432 * 10^{-3} * T + 6.285 * 10^{-6} * T^2 - 1.674 * 10^{-9} * T^3 = \frac{1}{0.7315}\Big(0.0725(13.947 + 5.981 * 10^{-2} * T + 1.055 * 10^{-5} * T^2 - 3.595 * 10^{-9} * T^3) + 0.063(23.9257 + 0.1923 * 10^{-2} * T + 1.055 * 10^{-5} * T^2 - 3.595 * 10^{-9} * T^3) + 0.0416(17.18 + 1.520 * 10^{-2} * T - 0.71155 * 10^{-5} * T^2 + 1.312 * 10^{-9} * T^3) + 0.5544(20.5856 - 0.1571 * T + 0.8081 * 10^{-5} * T^2 - 2.873 * 10^{-9} * T^3)\Big)$$

4.2.1.4 Combustion Stroke

$\mu_o = \frac{M_2}{M_1}$

$= \frac{0.731}{0.7} = 1.045$

$\mu = \frac{\mu_o \times \gamma_r}{1 + \gamma_r}$

$= \frac{1.045+0.03}{1+0.03} = 1.043$

$H_{mix} = \frac{H_u}{M_1(1+\gamma_r)}$

$= \frac{42440}{0.7(1+0.03)} = 58748.6$ kJ/kmol

$H_{mix} = (m\ C_v) \times T_z - (m\ C_v) \times T_c$ (Take $T_c = 601$ ℃)

$58748.6 = \left(20.01 + 5.7432 * 10^{-3} * T_z + 6.285 * 10^{-6} * {T_z}^2 - 1.674 * 10^{-9} * {T_z}^3\right) \times T_z - \left(220.01 + 5.7432 * 10^{-3} * T_c + 6.285 * 10^{-6} * {T_c}^2 - 1.674 * 10^{-9} * {T_c}^3\right) \times T_c$

$20.01 + 5.7432 * 10^{-3} * T_z + 6.285 * 10^{-6} * {T_z}^2 - 1.674 * 10^{-9} * {T_z}^3 - 63970.94 = 0$

$T_z = 1804$ ℃ $= 2077.4$ K

$P_z = P_c \times \lambda$

$\lambda = \frac{T_z}{T_c} = \frac{2077.4}{874} = 2.3764$

$P_z = 3.565 \times \frac{2077.4}{874} = 8.5$ MPa

4.2.1.5 Expansion Stroke

a. Expansion coefficient

$\delta = \frac{R_c}{\mu}$

$= \frac{16.5}{1.043} = 15.8$

b. Pressure at the end of expansion

$P_b = \frac{P_z}{\delta^n}$

$= \frac{8.4736}{15.8^{1.27}} = 0.255$ MPa

c. Temperature at the end of expansion

$T_b = \frac{T_z}{\delta^{n-1}}$

$= \frac{2077.4}{15.8^{1.27-1}} = 985.8$ K

$$T_r = \frac{T_b}{\sqrt[3]{\frac{P_b}{P_r}}}$$

$$= \frac{985.8}{\sqrt[3]{\frac{0.255}{0.105}}} = 733.4 \text{ K}$$

$$Error = \frac{733.4 - 715.4}{7.15.4} = 0.025 = 2.5\% < 5\% \qquad \text{(acceptable)}$$

4.2.2 Indicated parameters

4.2.2.1 Theoretical mean Indicted pressure

$$P_i{}' = \frac{P_c}{R_c - 1}\left(\lambda(\rho - 1) + \frac{\lambda \times \rho}{n - 1}\left(1 - \frac{1}{\delta^{n-1}}\right) - \left(\frac{1}{\gamma - 1}\right)\left(1 - \frac{1}{Rc^{n1-1}}\right)\right)$$

$$= \frac{3.565}{16.5-1}\left(2.3764(1.043 - 1) + \frac{2.3764 \times 1.043}{1.27-1}\left(1 - \frac{1}{15.8^{1.27-1}}\right) - \left(\frac{1}{1.35-1}\right)\left(1 - \frac{1}{16.5^{1.35-1}}\right)\right) = 0.722 \text{ MPa}$$

4.2.2.2 Mean indicated pressure considering the losses:-

Take the losses coefficient $(\varphi) = 0.95$

$$P_i = P_i{}' \times \varphi$$

$$= 0.722 \times 0.95 = 0.6859 \text{ MPa}$$

4.2.2.3 Indicated efficiency:-

$$\eta_i = \frac{P_i \times l_o \times \alpha}{H_u \times \rho \times \eta_v}$$

$$= \frac{0.6859 \times 14.452 \times 1.4}{42.44 \times 1.16 \times 0.92} = 0.3064 = 30.64\%$$

4.2.2.4 Indicated fuel consumption:-

$$g_i = \frac{3600}{H_u \times \eta_i}$$

$$= \frac{3600}{42.44 \times 0.3064} = 276.8 \text{ g/kW h}$$

4.2.3 Effective parameters

4.2.3.1 Mechanical losses

$$P_m = P_i - 0.85 \times P_i$$

$$= 0.6859 - 0.85 \times 0.6859 = 0.1034 \text{ MPa}$$

4.2.3.2 Effective mean pressure

$$P_e = P_i - P_m$$

$$= 0.6859 - 0.1034 = 0.5825 \text{ MPa}$$

4.2.3.3 Mechanical efficiency

$$\eta_m = \frac{P_e}{P_i}$$

$$= \frac{0.583}{0.6859} = 0.85 = 85\%$$

4.2.3.4 Effective efficiency

$$\eta_e = \eta_i \times \eta_m$$

$$= 0.3064 * 0.85 = 0.26044 = 26.044\%$$

4.2.3.5 Effective fuel consumption

$$g_e = \frac{3600}{H_u \times \eta_e}$$

$$= \frac{3600}{42.44 \times 0.26044} = 325.7 \text{ g/kW h}$$

4.2.4 Main parameters

4.2.4.1 Displacement

$$V_{liter} = \frac{60 \times \tau \times N_o}{P_e \times N}$$

$$= \frac{60 * 2 \times 103}{0.583 \times 4000} = 5.3 \text{ liter}$$

4.2.4.2 Displacement per cylinder

$$V_h = \frac{\mathrm{V_{liter}}}{4}$$

$$= \frac{5.3}{4} = 1.325 \text{ Liter}$$

4.2.4.3 Cylinder measurements

Cylinder bore and stork

$$D = S = 100 * \sqrt[3]{\frac{4 * \mathrm{V_h}}{\pi * 1}} = 119 \text{ mm}$$

4.2.4.4 Mean piston velocity

$$V_{pm} = \frac{\mathrm{S \times N}}{30 \times 10^3}$$

$$= \frac{119 \times 4000}{30 \times 10^3} = 15.8 \,\mathrm{m/s}$$

4.2.4.5 Piston cross section area

$$A_p = \frac{\pi D^2}{4}$$

$$= \frac{3.14 \times 119^2}{4} = 0.011122 \text{ m}^2$$

4.2.4.6 Effective torque

$$M_e = 3 \times 10^4 \times \frac{\mathrm{N_e}}{\pi \mathrm{N}}$$

$$= \frac{3 \times 10^4 \times 103}{\pi \times 4000} = 246 \text{ N.m}$$

4.2.4.7 Total fuel consumption

$$G_f = N_e \times g_e$$

$$= 103 \times 325.7 = 33.547 \,\mathrm{kg/hr}$$

4.2.4.8 Volumetric power

$$N_{liter} = \frac{N_e}{V_{liter}}$$

$$= \frac{103}{5.3} = 19.43 \text{ kW/cm}^3$$

4.2.4.9 Volume of combustion chamber

$V_c = 8.5388 * 10^{-4}$ m^3

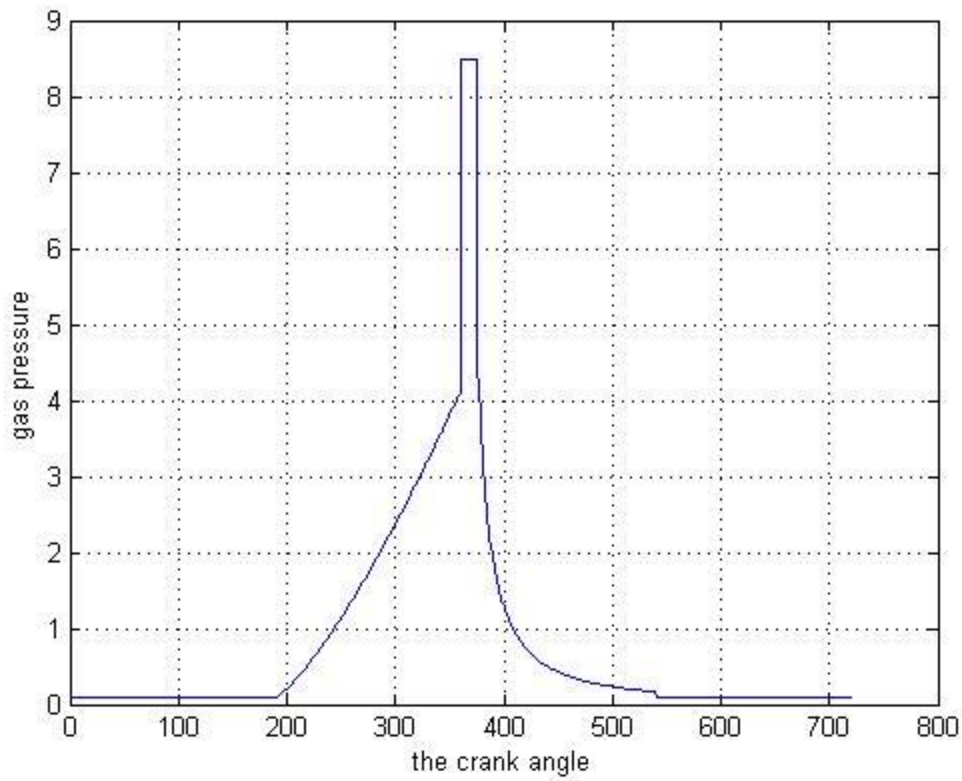

Figure (4.1): Gas pressure (MPa) vs the crank angle:

4.2.5 Kinematics calculation without turbocharger

4.2.5.1 The displacement of the piston

Given parameters S = 0.1215 ($\zeta = 0.3$)

$$S_x = \frac{S}{2} * ((1 - cos\theta) + \frac{\zeta}{4} * (1 - cos2\theta))$$

Where:-

S = the diameter of the crankshaft

ζ = Ratio between the crankshaft rad and the length connecting rod

θ = Crank angle

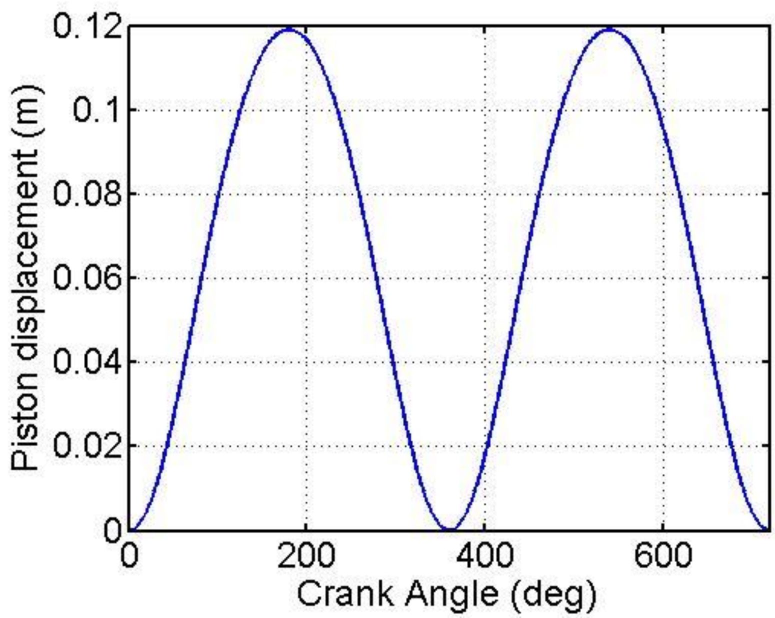

Figure (4.2): piston displacement vs crank angle

4.2.5.2 Piston velocity

$$\omega = \frac{2 * \pi * N}{60}$$

$$V_x = \frac{S}{2} * \omega * ((1 - sin\theta) + \frac{\zeta}{4} * (1 - sin2\theta))$$

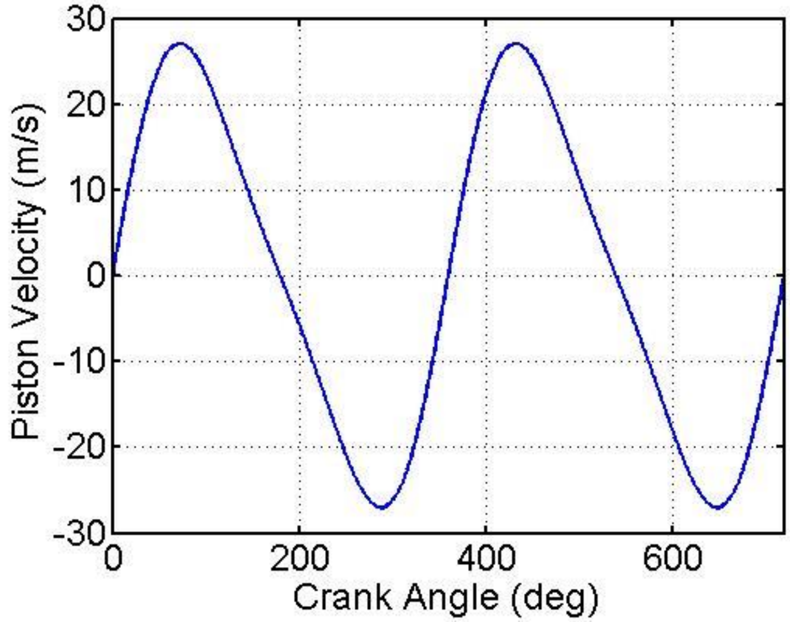

Figure (4.3): piston velocity vs crank angle

4.2.5.3 Piston acceleration

$a_x = \frac{S}{2} * \omega^2 * ((1 - sin\theta) + \frac{\zeta}{4} * (1 - sin2\theta))$

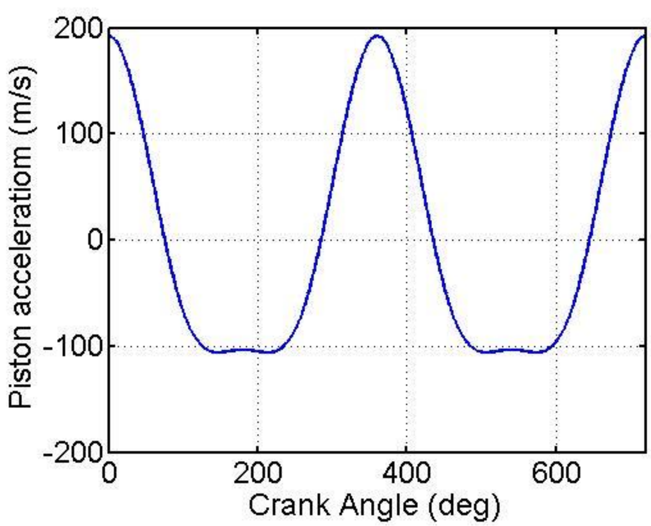

Figure (4.4): piston acceleration vs crank angle

4.2.6 Dynamic calculations

4.2.6.1 Inertia force

$F_1 = m * a_x$

Where:

$m = m_p + m_c$

$m_p = piston\ mass$

$m_c = conecting\ rod\ mass$

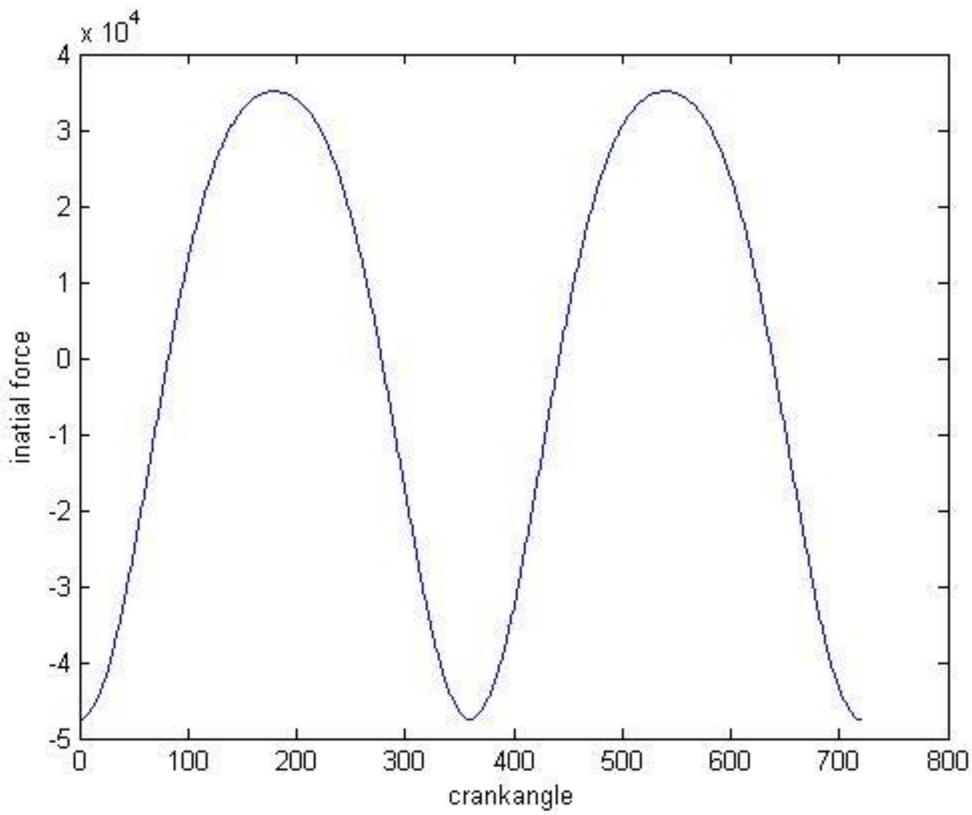

Figure (4.5): Piston inertia force (N) vs crank angle

4.2.6.2 Torque

$M = F_T * r$

Where:

M = torque

F_T = total force acting in crankshaft

r = the crank shaft radios

$F_T = F_g + F_1$

F_g = Gas force N

F_1 =Indicator force

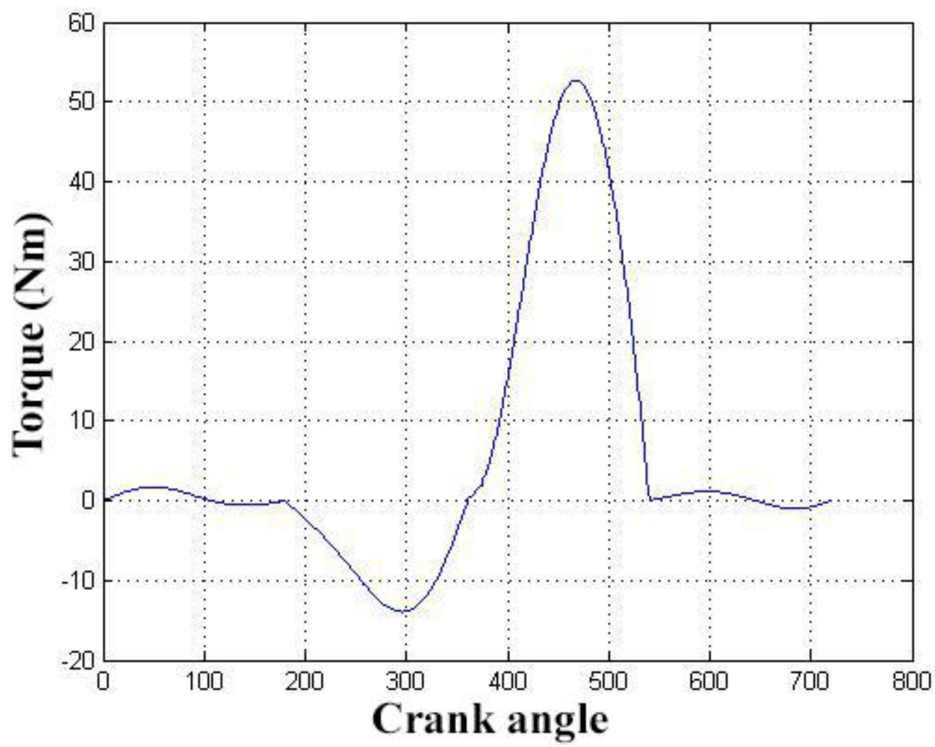

Figure (4.6) the torque for one cylinder

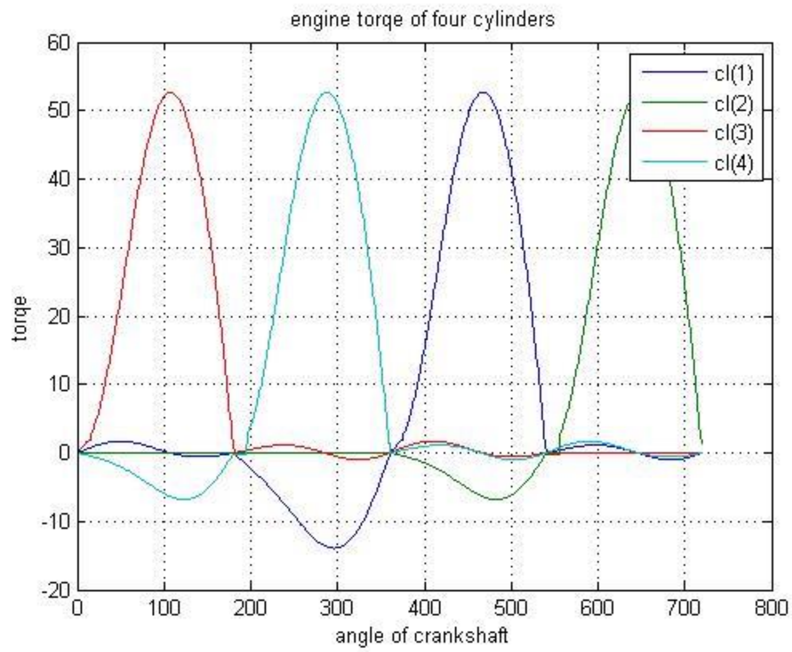

Figure (4.7) Torque (Nm) for 4 cylinders

4.3 Engine design with turbocharger

After designing the engine without the turbocharger, the turbocharger was added in order to increase the engine efficacy and volumetric power, and decrease the displacement of the engine

4.3.1 Thermodynamic calculations

Calculations of pressure and temperature at the end of each stroke.

4.3.1.1 Engine Parameters

a. Amount of air charge

$M_1 = \alpha \times L_o$, Take ($\alpha = 1.8$)

$M_1 = 1.8 \times 0.5 = 0.9$ $\text{kmol}_{\text{air}} / \text{kg}_{\text{fuel}}$

$= 1.8 \times 14.452 = 26.0136$ $\text{kg}_{\text{air}} / \text{kg}_{\text{fuel}}$

b. Content of exhaust gas:-

$$M_{H_2O} = \frac{H}{2}$$

$$= \frac{0.126}{2} = 0.063 \ \ \text{kmol}_{\text{H}_2\text{O}}/\text{kg}_{\text{fuel}}$$

$$M_{CO_2} = \frac{C}{12}$$

$$= \frac{0.87}{12} = 0.0725 \ \ \text{kmol}_{\text{CO}_2}/\text{kg}_{\text{fuel}}$$

$$M_{O_2} = 0.208 \times \text{Lo} \times (\alpha - 1) = 0.208 \times 0.5 \times (1.6 - 1)$$

$$= 0.0832 \ \text{kmol}_{\text{O}_2}/\text{kg}_{\text{fuel}}$$

$$M_{N_2} = 0.792 \times M1$$

$$= 0.792 \times 0.9 = 0.7128 \ \text{kmol}_{\text{N}_2}/\text{kg}_{\text{fuel}}$$

c. Amount of exhaust gas

$$M_2 = M_{CO_2} + M_{H_2O} + M_{O_2} + M_{N_2}$$

$$= 0.0725 + 0.063 + 0.0832 + 0.7128 = 0.9315 \ \text{kmol}_{\text{exhaust}}/\text{kg}_{\text{fuel}}$$

d. Ambient conditions:-

Ambient Temperature (T_o) = 300 K.

Atmospheric pressure (P_o) = 0.1 MPa.

With turbocharger compression ratio: 1.6

$\Delta T = 20$°C.

e. Pressure and temperature after the turbocharger:

$$T_{o2} = 300 \times 1.6^{1.35-1} = 353.64 \ \text{K}$$

$$P_{o2} = 0.1 * 1.6^{1.35} = 0.1886 \ \text{MPa}$$

4.3.1.2 Intake stroke

a. Air density at the cylinder inlet

$$\rho_o = P_{o2} \times \frac{10^6}{R \times T_{o2}}$$

$$= \frac{0.1 \times 10^6}{287 \times 353.64} = 1.858 \ \ \text{kg/m}^3$$

b. Air Pressure at the end of intake stroke

During intake stroke, a drop in pressure occurs through the manifold and valves holes. It could be found using the following relation.

$$\Delta P_a = (\beta^2 + {\xi_{in}}^2) \times {w_{in}}^2 \times \frac{\rho_o}{2}$$

We will take $(\beta^2 + {\xi_{in}}^2) = 2.7$, and $w_{in} = 110 \text{ m/s}$

$$\Delta P_a = 2.7 \times 110^2 \times \frac{1.16}{2} = 18948.6\ pa \cong 0.019 \text{ MPa}$$

$$\therefore P_a = P_{o2} - \Delta P_a = 0.1886 - 0.019 = 0.1696 \text{ MPa}$$

$$P_r = \frac{1.05}{1.25} \times P_o = \frac{1.05}{1.25} \times 0.1886 = 0.158 \text{ MPa}$$

c. Volumetric efficiency

$$\eta_v = \frac{T_o * (R_c \times P_a - P_r)}{P_a (T + \Delta T)(R_c - 1)},$$

$$= \frac{353.64 \times (16.5 \times 0.1696 - 0.158)}{0.1696 \times (353.64 + 20)(16.5 - 1)} = 0.95$$

d. Coefficient of residual burned gas

$$\gamma_r = \frac{(T_o + \Delta T)}{T_r} \times \frac{P_r}{R_c \times P_a - P_r}\ , (T_r = 745.3 \text{ K})$$

$$= \frac{(353.64 + 20)}{745.3} \times \frac{0.158}{16.5 \times 0.1696 - 0.158} = 0.03$$

e. Temperature at the end of intake stroke

$$T_a = \frac{T_o + \Delta T + \gamma_r \times T_r}{1 + \gamma_r}$$

$$= \frac{353.64 + 20 + 0.03 \times 745.3}{1 + 0.03} = 384 \text{ K}$$

4.3.1.3 Compression stroke

a. Pressure at the end of compression

$P_c = P_a (R_c)^n$ Take polytropic coefficient (n = 1.35)

$$P_c = 0.1696 \times (16.5)^{1.35} = 7.465 \text{ MPa}$$

b. Temperature at the end of compression

$T_c = T_a (R_c)^{n-1}$

$= 384 \times (16.5)^{1.35-1} = 1024 \text{ K}$

c. Mean molar heat capacity

$(m\,C_v) = \frac{1}{M_2}\Big(\big(M_{CO_2} \times (m\,C_v)_{CO_2}\big) + (M_{H_2O} \times (m\,C_v)_{H_2O} + \big(M_{O_2} \times (m\,C_v)_{O_2}\big) + \big(M_{N_2} \times (m\,C_v)_{N_2}\big)\Big)$

$19.607 + 6.023 \times 10^{-3} \times T + 6 \times 10^{-6} \times T^2 - 1.7123 \times 10^{-9} \times T^3 = \frac{1}{0.9315}\Big(0.0725(13.947 + 5.981 \times 10^{-2} \times T - 3.501 \times 10^{-5} \times T^2 + 7.469 \times 10^{-9} \times T^3) + 0.063(23.9257 + 0.1923 * 10^{-2} \times T + 1.055 \times 10^{-5} \times T^2 - 3.595 \times 10^{-9} \times T^3) + 0.0832(17.18 + 1.520 \times 10^{-2} \times T - 0.71155 \times 10^{-5} \times T^2 + 1.312 \times 10^{-9} \times T^3) + 0.7128(20.5856 - 0.1571 \times 10^{-3} \times T + 0.8081 \times 10^{-5} \times T^2 - 2.873 \times 10^{-9} \times T^3)\Big)$

4.3.1.4 Combustion Stroke

$\mu_o = \frac{M_2}{M_1}$

$= \frac{0.9315}{0.9} = 1.015$

$\mu = \frac{\mu_o \times \gamma_r}{1+\gamma_r}$

$= \frac{1.015+0.03}{1+0.03} = 1.0145$

$H_{mix} = \frac{H_u}{M_1(1+\gamma_r)}$

$= \frac{42440}{0.9(1+0.03)} = 45782.1 \text{ kJ/kmol}$

$H_{mix} = (m\ C_v) \times T_z - (m\ C_v) \times T_c$ (Take $T_c = 751$ ℃)

$45782.1 = \left(19.607 + 6.023 \times 10^{-3} \times T_z + 6 \times 10^{-6} \times {T_z}^2 - 1.7123 \times 10^{-9} \times {T_z}^3\right) \times T_z - \left(19.607 + 6.023 \times 10^{-3} \times T_c + 6 \times 10^{-6} * {T_c}^2 - 1.7123 \times 10^{-9} \times {T_c}^3\right) \times T_c$

$19.607 * T_z + 6.023 * 10^{-4} \times {T_z}^2 + 6 \times 10^{-6} \times {T_z}^3 - 1.7123 \times 10^{-9} \times {T_z}^4 - 65900.6 = 0$

$T_z = 2094.9$ ℃ $= 2367.9$ K

$P_z = P_c \times \lambda$

$\lambda = \frac{T_z}{T_c} = \frac{2367.9}{1024} = 2.3125$

$P_z = 7.465 \times 2.3125 = 17.263$ MPa

4.3.1.5 Expansion Stroke

$\rho = \frac{\mu \times T_z}{\lambda \times T_c} = \frac{1.0145 \times 2367.9}{2.3125 \times 1024} = 1.0145$

a. Expansion coefficient

$\delta = \frac{R_c}{\mu}$

$= \frac{16.5}{1.0145} = 16.26$

b. Pressure at the end of expansion

$P_b = \frac{P_z}{\delta^n}$

$= \frac{17.263}{16.26^{1.27}} = 0.5$ MPa

c. Temperature at the end of expansion

$T_b = \frac{T_z}{\delta^{n-1}}$

$$= \frac{2367.9}{16.26^{1.27-1}} = 1115.22 \text{ K}$$

$$T_r = \frac{T_b}{\sqrt[3]{\frac{P_b}{P_r}}}$$

$$T_r = \frac{1115.22}{\sqrt[3]{\frac{0.5}{0.158}}} = 759.6 \text{ K}$$

$$Error = \frac{759.6 - 745.3}{759.6} = 0.0188 = 1.88\% < 5\% \qquad acceptabole$$

4.3.2 Indicated parameters

a. Theoretical mean Indicted pressure

$$P_i{}' = \frac{P_c}{R_c - 1}\left(\lambda(\rho - 1) + \frac{\lambda \times \rho}{n-1}\left(1 - \frac{1}{\delta^{n-1}}\right) - \left(\frac{1}{\gamma - 1}\right)\left(1 - \frac{1}{Rc^{n1-1}}\right)\right)$$

$$P_i{}' = \frac{7.465}{16.5-1}\left(2.3125(1.0145 - 1) + \frac{2.3125 \times 1.0145}{1.27-1}\left(1 - \frac{1}{16.26^{1.27-1}}\right) - \left(\frac{1}{1.35-1}\right)\left(1 - \frac{1}{16.5^{1.35-1}}\right)\right) = 1.37 \text{ Mpa}$$

b. Mean indicated pressure considering the losses

Take the losses coefficient $(\varphi) = 0.95$

$$P_i = P_i{}' \times \varphi$$

$$= 1.37 \times 0.95 = 1.3015 \text{ MPa}$$

c. Indicated efficiency

$$\eta_i = \frac{P_i \times l_o \times \alpha}{H_u \times \rho \times \eta_v}$$

$$= \frac{1.3015 \times 14.452 \times 1.8}{42.44 \times 1.858 \times 0.95} = 0.4797 = 48\%$$

d. Indicated fuel consumption

$$g_i = \frac{3600}{H_u \times \eta_i}$$

$$= \frac{3600}{42.44 \times 0.48} = 176.72 \text{ g/kW h}$$

4.3.3 Effective parameters

a. Mechanical losses

$P_m = 0.1952$ MPa

b. Effective mean pressure

$P_e = P_i - P_m$

$= 1.3015 - 0.1952 = 1.1063$ MPa

c. Mechanical efficiency

$$\eta_m = \frac{P_e}{P_i}$$

$$= \frac{1.1063}{1.3015} = 0.85 = 85\%$$

d. Effective efficiency

$\eta_e = \eta_i \times \eta_m$

$= 0.48 * 0.85 = 0.408 = 40.8\%$

e. Effective fuel consumption

$$g_e = \frac{3600}{H_u \times \eta_e}$$

$$= \frac{3600}{42.44 \times 0.6153} = 207.906 \text{ g/kW h}$$

4.3.4 Main parameters

4.3.4.1 Displacement

$$V_{liter} = \frac{60 \times \tau \times N_o}{P_e \times N}$$

$$= \frac{60 * 2 \times 103}{1.1063 \times 4000} = 2.8 \text{ liter}$$

4.3.4.2 Displacement per cylinder

$$V_h = \frac{V_{liter}}{4}$$

$$= \frac{2.8}{4} = 0.7\ Liter$$

4.3.4.3 Cylinder measurements

$$D = S = 100 \times \sqrt[3]{\frac{4*V_h}{\pi*1}} = 96.5 \text{ mm}$$

4.3.4.4 Mean piston velocity

$$V_{pm} = \frac{S\times N}{30\times10^3}$$

$$= \frac{96.5\times4000}{30\times10^3} = 12.86 \text{ m/s}$$

4.3.4.5 Piston cross-section area

$$A_p = \frac{\pi D^2}{4}$$

$$= \frac{3.14\times96.5^2}{4} = 0.00731 \text{ m}^2$$

4.3.4.6 Effective torque

$$M_e = 3\times10^4\times\frac{N_o}{\pi N}$$

$$= \frac{3\times10^4\times103}{\pi\times4000} = 246 \text{ N m}$$

4.3.4.7 Total fuel consumption

$$G_f = N_o \times g_e$$

$$= 103 \times 207.906 = 21.41 \text{ kg/h}$$

4.3.4.8 Volumetric power

$$N_{liter} = \frac{N_e}{V_{liter}}$$

$$= \frac{103}{2.8} = 36.9 \text{ kW/cm}^3$$

4.3.4.9 Volume of combustion chamber

$Vc = 0.00004551 = 4.551 * 10^{-5}$ m³

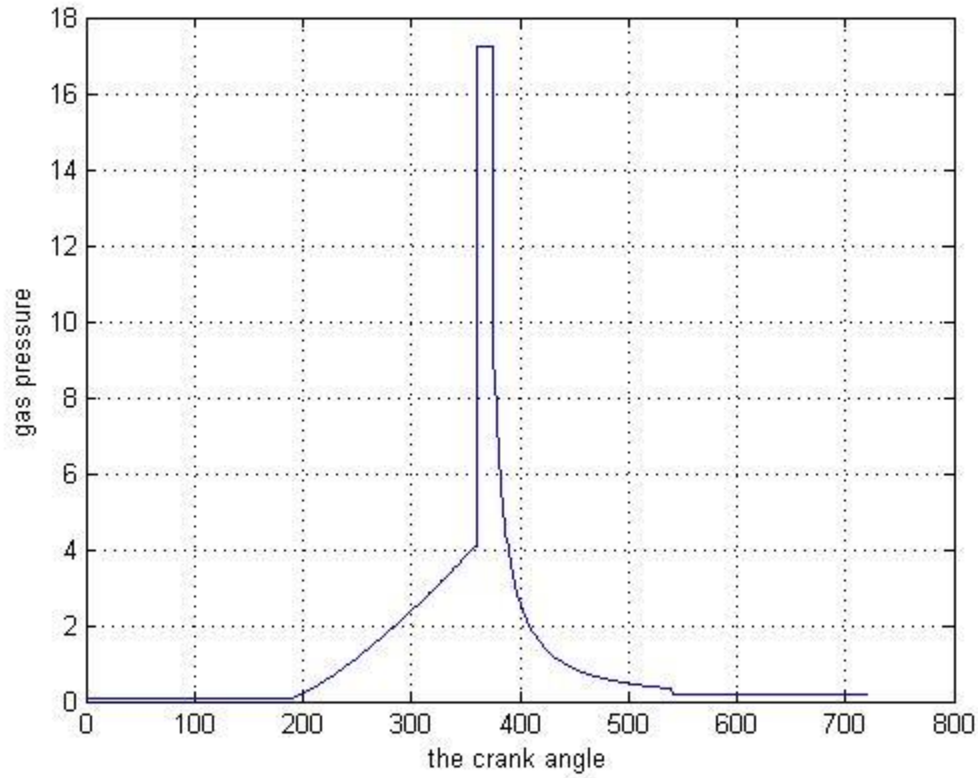

Figure (4.8): Gas pressure (MPa) vs crank angle

4.3.5 Kinematic calculation with turbocharger

4.3.5.1 The displacement of the piston

Given parameters S=0.1215, $\zeta = 0.3$

$$S_x = \frac{S}{2} * ((1 - cos\theta) + \frac{\zeta}{4} * (1 - cos2\theta))$$

S= the diameter of the crankshaft

ζ = Ratio between the crankshaft rad and the length connecting rod

θ = Crank angle

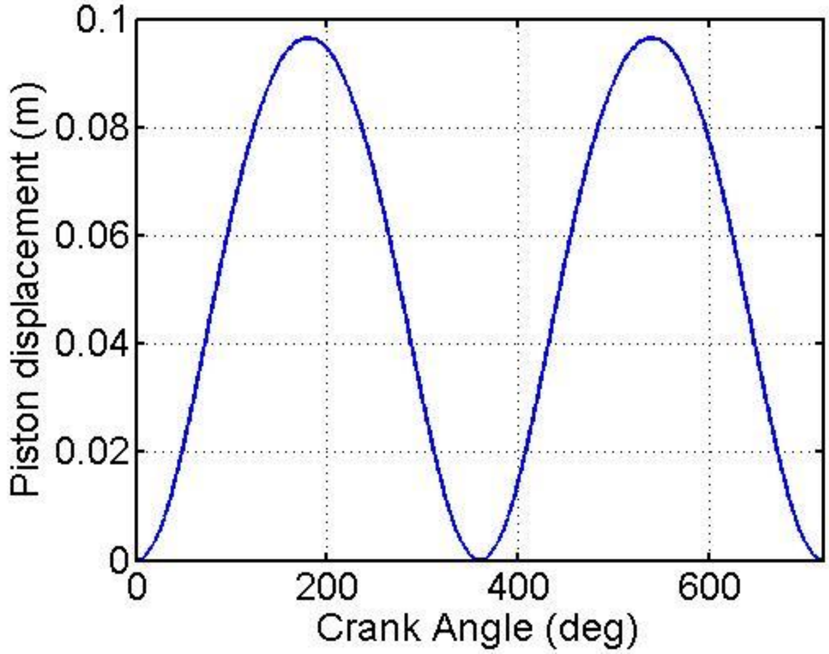

Figure (4.9): Piston displacement vs. crank angle

4.3.5.2 The velocity of the piston

$$\omega = \frac{2 * \pi * N}{60}$$

$$V_x = \frac{S}{2} * \omega * ((1 - sin\theta) + \frac{\zeta}{4} * (1 - sin2\theta))$$

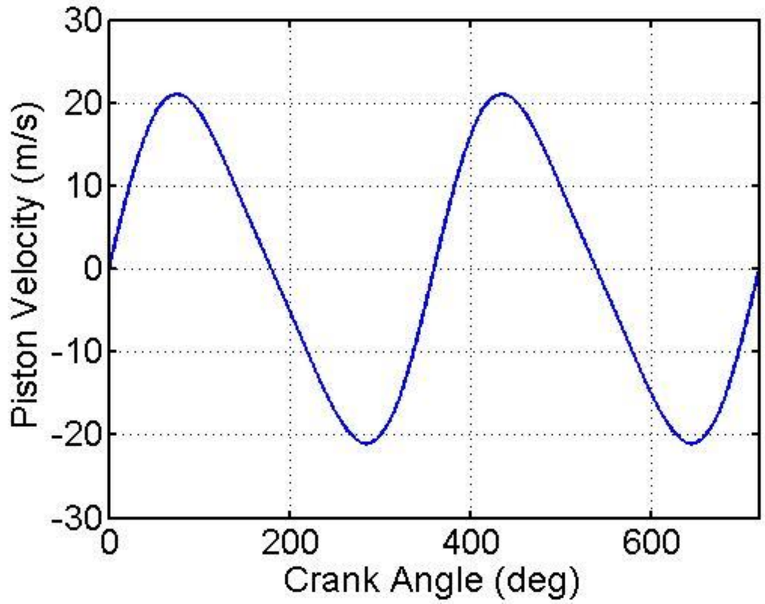

Figure (4.10): Piston velocity vs. crank angle

4.3.5.3 Piston acceleration

$$a_x = \frac{S}{2} * \omega^2 * ((1 - sin\theta) + \frac{\zeta}{4} * (1 - sin2\theta))$$

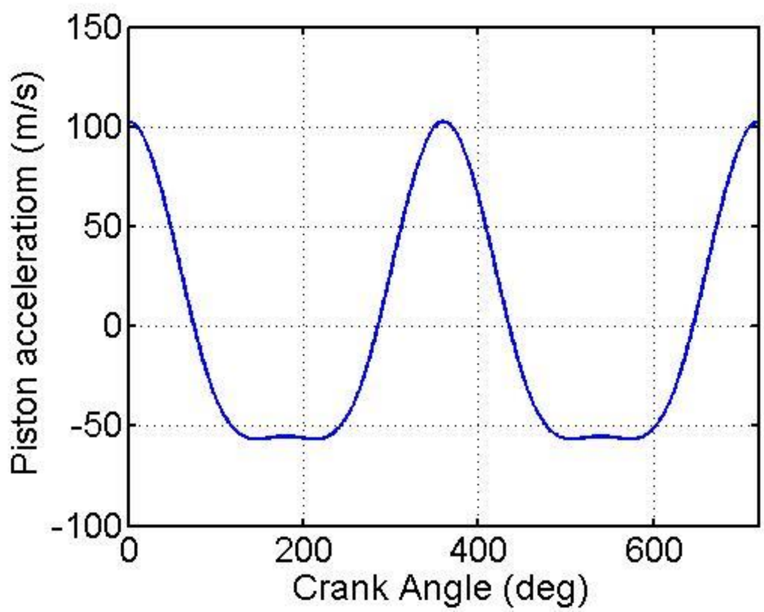

Figure (4.11): Piston acceleration vs. crank angle

4.3.6 Dynamic calculation

Analyses of the effect of pressure and the mass of the engine components on the engine

4.3.6.1 Inertia force

$F_1 = m * a_x$

Where:

$m = m_p + m_c$

$m_p = piston\ mass$

$m_c = connecting\ rod\ mass$

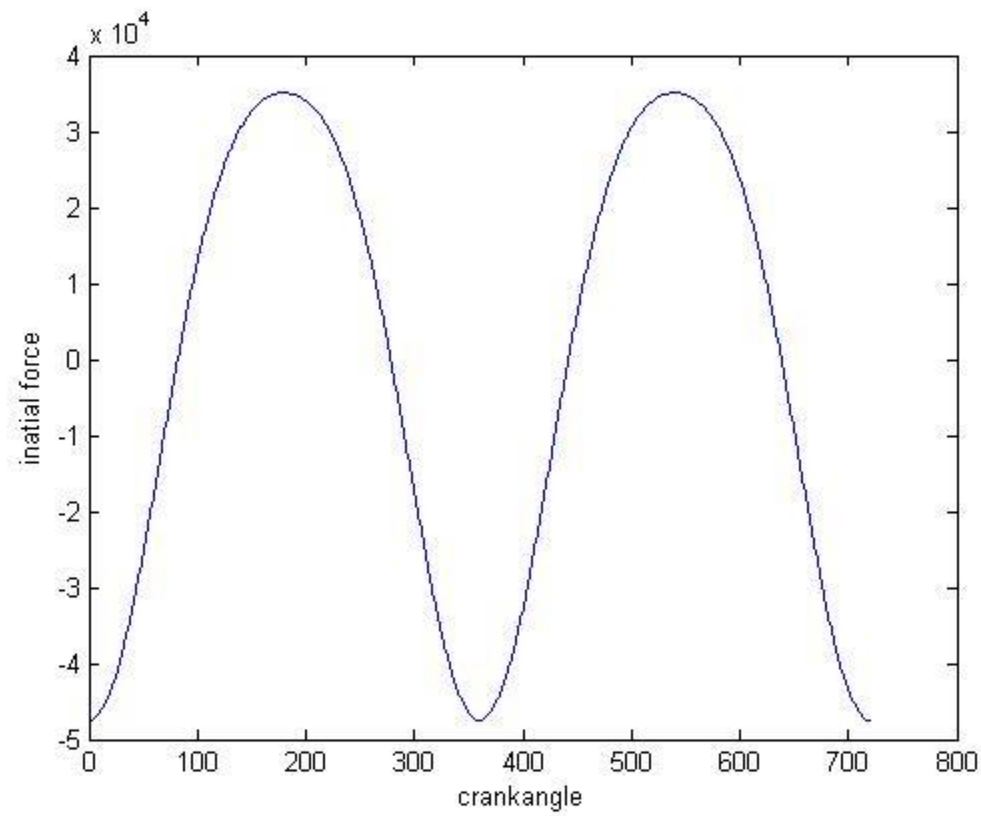

Figure (4.12): Piston inertia force (N) vs crank angle

4.3.6.2 Torque:-

$M = F_T * r$

Where:-

M=torque

F_T = total force acting in crankshaft

r = the crank shaft radios

$F_T = F_g + F_1$

F_g = Gas force N

F_1 = Indicated force

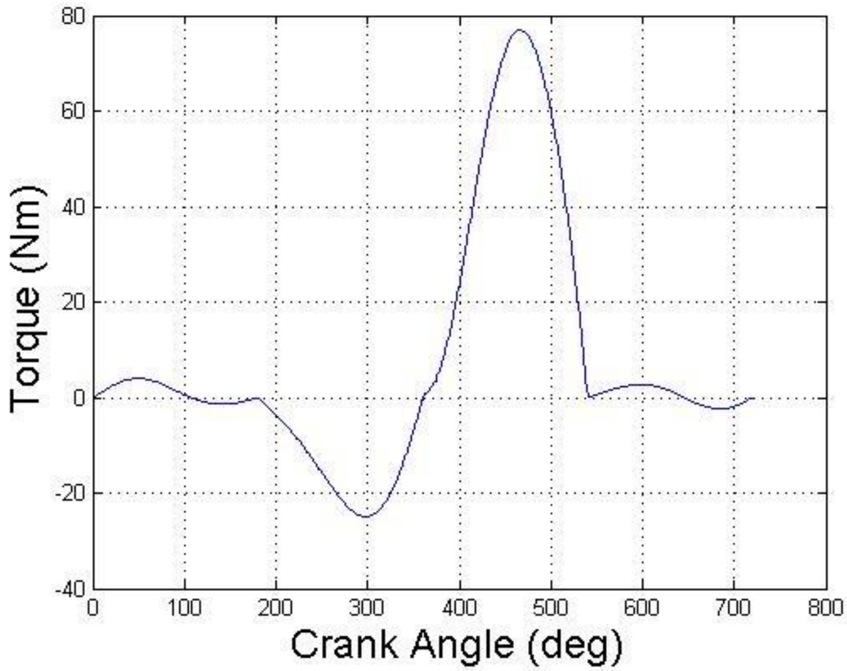

Figure (4.13): torque for one cylinder

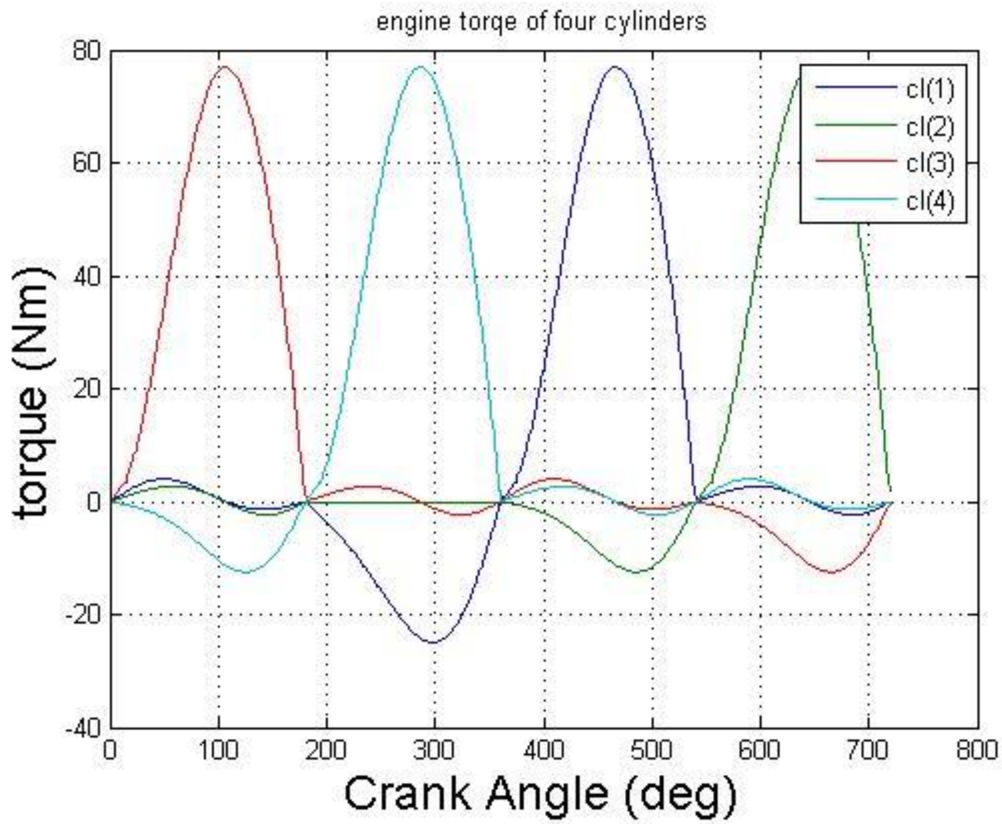

Figure (4.14): Torque for 4 cylinders

4.4 The dimensional design for the engine with turbo:-

4.4.1 Calculation of piston:-

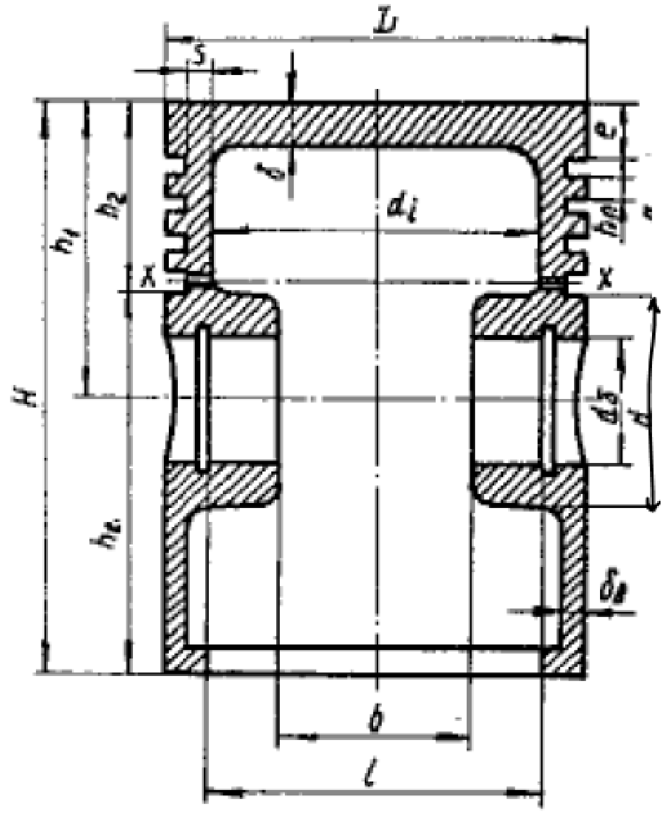

Figure (4.15): The main structural dimension of piston

The martial of piston is Aluminum 2024-T361 and the physical and mechanical properties are:-

Table (4.1) Mechanical properties of Aluminum 2024-T361 [11].

PROPERTIES	VALUES
Elastic Modulus	72.4 GPa
Poisson's ratio	0.33
Shear Modulus	28 GPa
Density	2780 kg/m^3
Tensile Strength σ_t	495 MPa
Yield Strength	395 MPa
Thermal conductivity	120W/m.K

Take factor of safety for the design equals to 2.25

a. Thickness of piston crown

$$T_c = \sqrt{\frac{3\times Pz\times D^2}{16\times\sigma_t}} = \sqrt{\frac{3\times 17.263\times 96.5^2}{16\times 220}} = 11.7 \cong 12 \text{ mm}$$

b. Height of the piston

$H = (0.8\sim1.3)\times D$

$= 1.3 \times 96.5 = 125$ mm

c. Distance from the front to the axis of piston pin

$h_1 = (0.45\sim0.47) \times D$

$= 0.47 \times 96.5 = 45$ mm

e. Size

$b = (0.3\sim0.5) \times D$

$= 0.41 \times 96.5 = 39.565 \approx 40$ mm

f. The wall thickness of leading part

$T_L = (1.5\sim4.5)$

$T_L = 4$ mm

g. Thickness of the sealing part

$s = (0.03\sim0.08) \times D$

$= 0.04 \times 96.5 = 3.86 \cong 4$ mm

h. The distance from the front to the first ring channel

$e = (0.06\sim0.12) \times D$

$= 0.12 \times 96.5 = 11.58 \cong 12$ mm

i. Wall thickness between channels

$h_n = (0.03 \sim 0.05) \times D$

$= 0.04 \times 96.5 = 3.86 \cong 4$ mm

j. Hole diameter of piston pin

$d_\delta = (0.22 \sim 0.28) \times D$

$= 0.28 \times 96.5 = 27$ mm

k. Height of the leading part

$h_\delta = (0.6 \sim 0.8) \times D$

$= 0.8 \times 96.5 = 77$ mm

l. Inner diameter of the blot

$d_i = (0.65 \sim 0.75) \times d_\delta$

$= 0.75 \times 27 = 20$ mm

m. Length of the bolt

$l = (0.88 \sim 0.93) \times D$

$= 0.93 \times 96.5 = 89$ mm

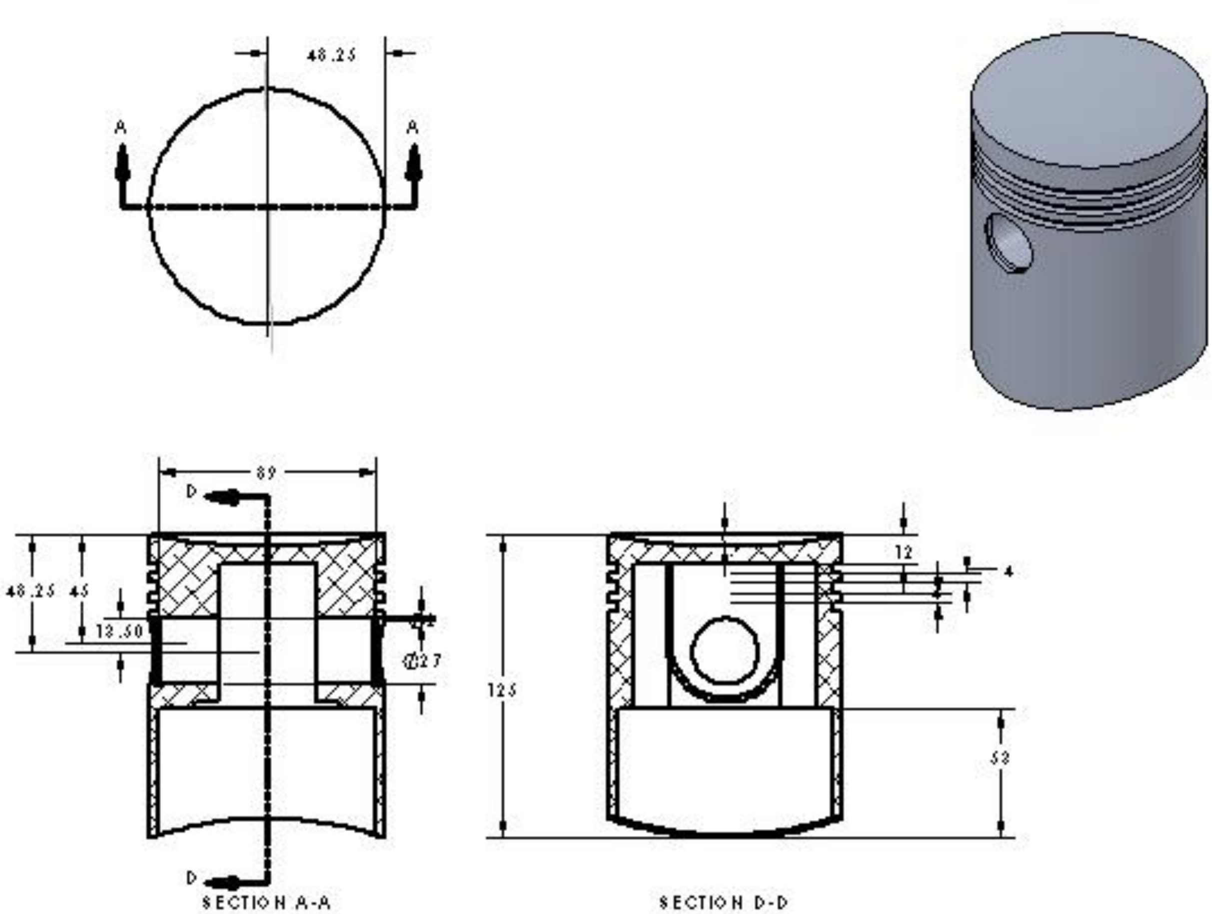

Figure (4.16): SOLIDWORKS drawing of the piston

4.4.2 Calculation of the connecting rod:

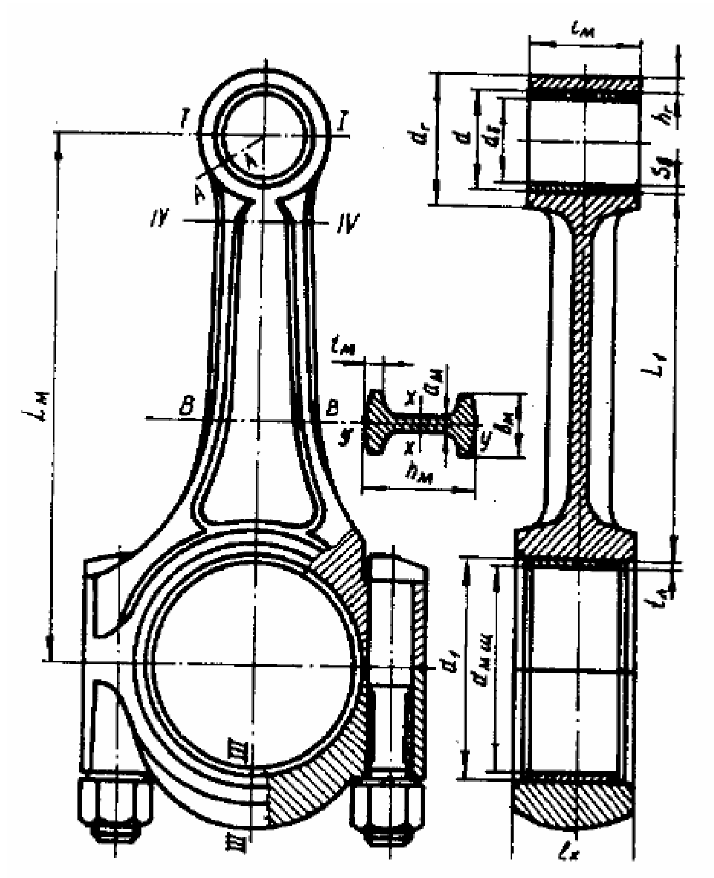

Figure (4.17): connecting rod

a. Length of the upper head of the rod

$l_m = (0.28 \sim 0.38) \times D$

$= 0.38 \times 96.5 = 36.5$ mm

b. Inner diameter of the upper head without sleeve

$d = d_\delta = 27$ mm

c. Outer diameter of the upper head

$d_o = (1.25 \sim 1.65) \times d$

$= 1.63 \times 27 = 44$ mm

d. Minimal radial thickness of the upper head

$h_o = (0.16{\sim}0.27) \times d$

$= 0.26 \times 27 = 7 \text{ mm}$

e. Minimal height of the profile

$h_{m_{min}} = (0.5{\sim}0.55) \times d$

$= 0.55 \times 27 = 24 \text{ mm}$

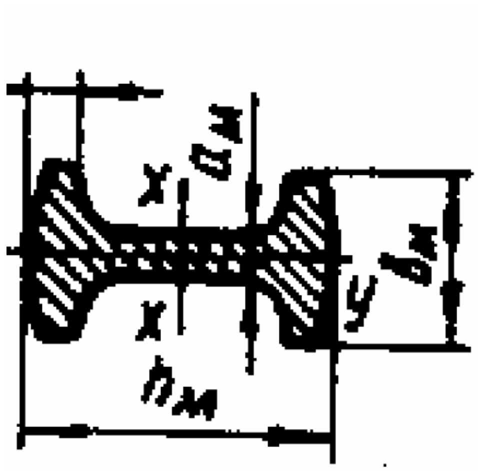

Figure (4.18): Cross-section of the connecting rod

$h_m = (1.2{\sim}1.4) \times h_{m.min}$

$= 1.4 \times 24 = 33.6 \text{ mm}$

$b_m = (0.5{\sim}0.6) \times l_m$

$= 0.6 \times 36.5 = 22 \text{ mm}$

$a_m = (2.5{\sim}6) = 6 \text{ mm}$

f. Diameter of connecting rod neck

$d_{mu} = (0.56{\sim}0.75) \times D$

$= 0.75 \times 96.5 = 70 \text{ mm}$

g. Thickness of the bearing shells

$t_{sh} = (0.03 \sim 0.05) \times \mathrm{d}_{mu}$

$= 0.05 \times 70 = 3.5 \text{ mm}$

h. Distance between connecting rod bolts

$C = (1.3 \sim 1.75) \times d_{mu}$

$= 1.75 \times 70 = 122 \text{ mm}$

i. Length of the low head

$l_k = (0.45 \sim 0.65) \times d_{mu}$

$= 0.6 \times 70 = 42 \text{ mm}$

j. Length of the connected rod

$L = \frac{D}{\delta}$

$= \frac{96.5}{0.3} = 321.6 \text{ mm}$

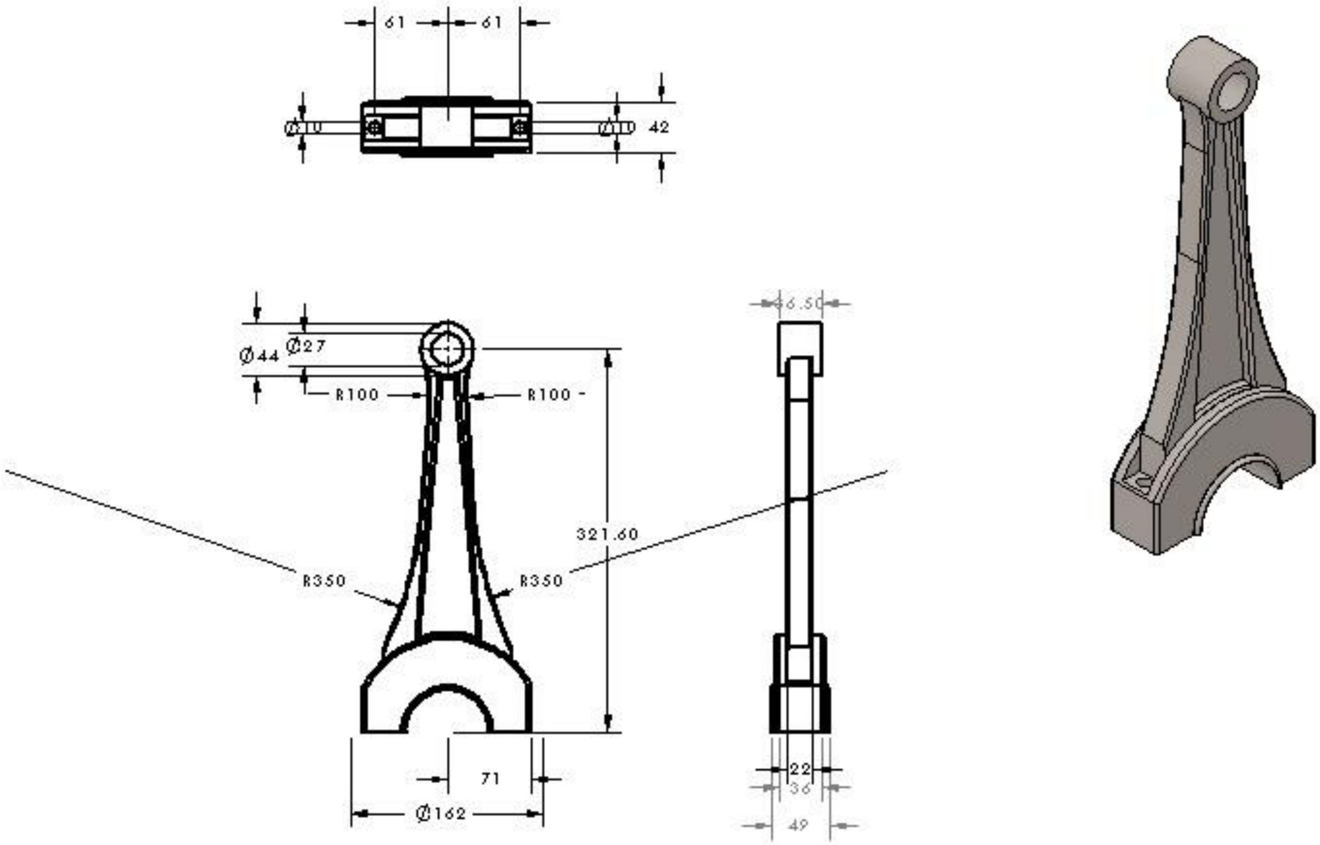

Figure (4.19) SOLIDWORKS drawing of the connecting rod

4.4.3 Calculation of the crankshaft dimension:

a. Distance between the circles of the main journals

$l = (1.1 \sim 1.25) \times D$

$= 0.5 \times 96.5 = 48.25 \text{ mm}$

b. Diameter of the main journal

$d_{ou} = (0.5 \sim 0.8) \times D$

$= 0.8 \times 96.5 = 77 \text{ mm}$

c. Length of the main journal

$l_{ou} = (0.5 \sim 0.6) \times d_{ou}$

$= 0.6 \times 77 = 46$ mm

d. Diameter of the rod journal

$d_{mu} = 70$ mm

e. Length of the rod journal

$l_{mw} = (0.45\sim0.65) \times d_{mw}$

$= 0.65 \times 70 = 45.5$ mm

f. Thickness of the crank

$h = (0.15\sim0.35) \times d_{mu}$

$= 0.35 \times 70 = 24.5$ mm

g. Width if the crank

$b = (1.7\sim2.9) \times d_{mu}$

$= 2.9 \times 70 = 200$ mm

h. Radius of the rounded

$r = (0.06\sim0.1) \times d_{mw}$

$= 0.1 \times 70 = 7$ mm

4.4.4 Calculation of the engine block:

4.4.4.1 Cylinders:

a. Allowable tensile stress for aluminum

Aluminum was used as a material

$\sigma_{on} = 151.658$ Mpa

With factor of safety of 2.25

$$\sigma_{on} = \frac{151.658}{2.25} = 67.4 \text{ MPa}$$

b. The distance between the axis of two cylinders

Take $\frac{L_o}{D} = 1.3$

$L_o = D \times 1.3$

$= 96.5 \times 1.3 = 125$ mm

c. The minimum thickness of the cylinder

$$t_{c.min} = 0.5 \times \frac{p_z \times D}{\sigma_{on}} = \frac{0.5 \times 17.263 \times 0.0965}{67.4} = 0.0124 \text{ m}$$

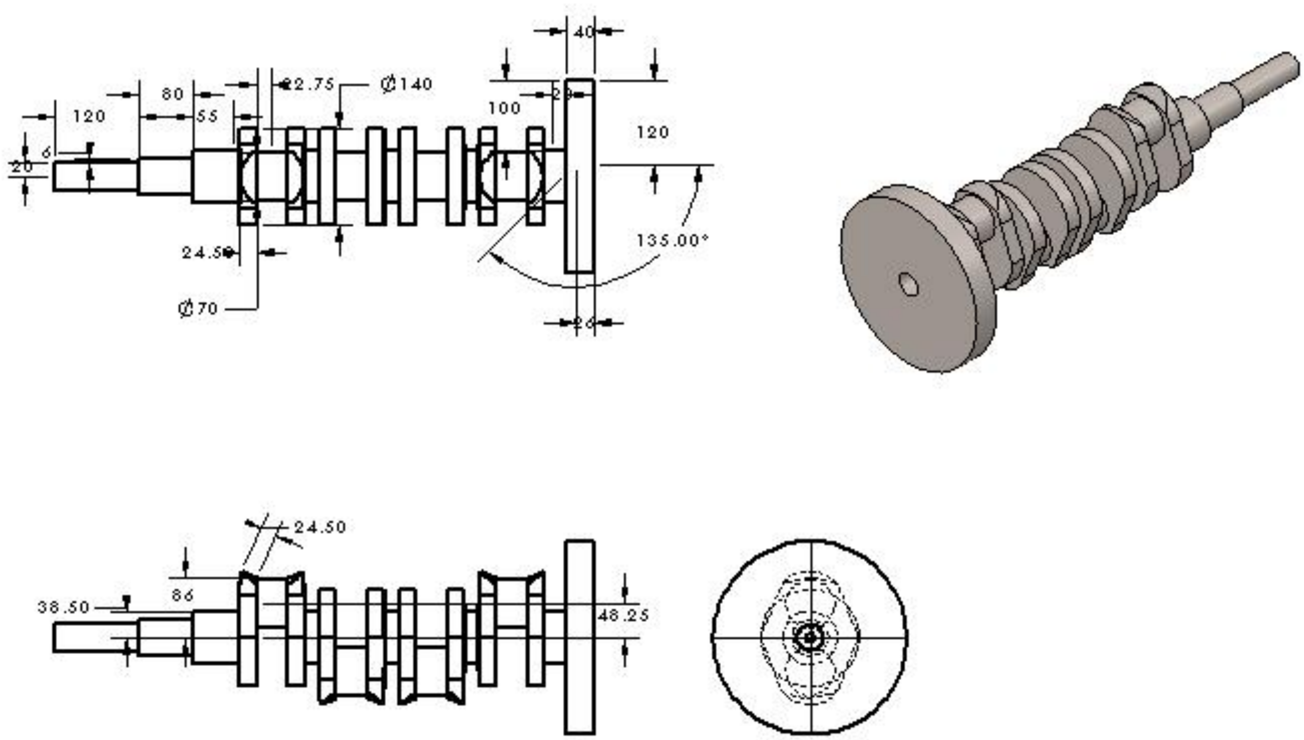

Figure (4.20): SOLIDWORKS drawing of the crankshaft

4.4.4.2 Cylinder head

a. Height of cylinder head

$H_h = (0.95 \sim 1.2) \times D$

$= 1.2 \times 96.5 = 115.8 \text{ mm}$

b. The thickness of the lower support wall

$t_{hl} = 0.09 \times D + 2$

$= 0.09 \times 96.5 + 2 = 10.7 \text{ mm}$

c. Thickness of the cooler area of aluminum cylinder heads

$t_{hc} = 0.03 \times D + 4.2$

$= 0.03 \times 96.5 + 4.2 = 6.63 \text{ mm}$

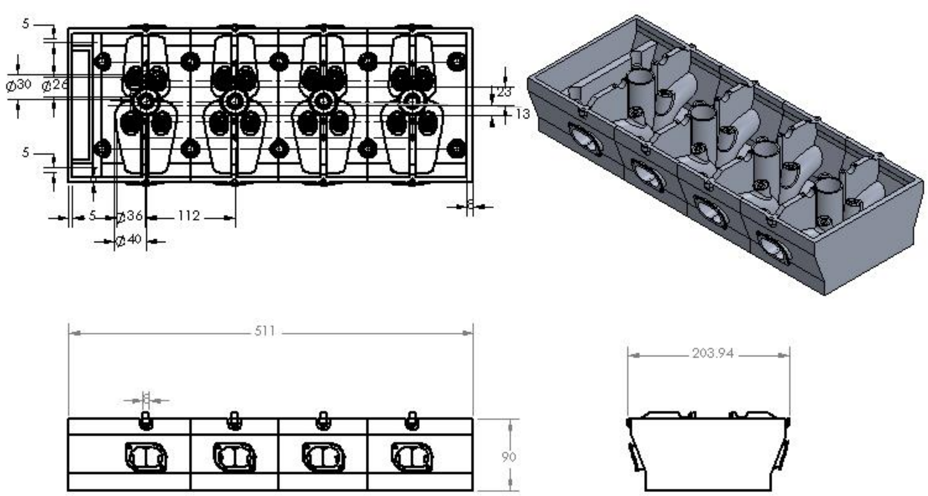

Figure (4.21) SOLIDWORKS drawing for the engine head

4.5 Cooling system

Put a suggestion to Design a cooling system after adding the turbocharger to make the engine work stable:

4.5.1 Cooling water considerations

$T_{w_{out}} = (90\sim95℃) = 95\ ℃$

$\Delta T_w = (6\sim12℃) = 8\ ℃$

$T_{w_m} = T_{lq_{out}} - \frac{\Delta T_{lq}}{2} = 95 - \frac{8}{2} = 91\ ℃$

4.5.2 Ambient air

$T_{a_{in}} = 50\ ℃$

$T_{a_{out}} = 85\ ℃$

$T_{a_m} = \frac{50+85}{2} = 67.5\ ℃$

4.5.3 Heat transfer calculations

$Q_w = \frac{0.53\times i\times D^{1+2m}\times N^m}{\alpha}$

Where

D = Piston diameter

m = constant (0.6~0.7)

i = number of sylinders

$Q_w = \frac{0.53\times i\times 96.5^{1+2\times0.7}\times N^{0.7}}{1.8} = 22.66\times10^6$ W

$\dot{m}_w = \frac{Q_w}{Cp_w\times\rho_w\times\Delta T_w} = \frac{22.66\times10^6}{4187\times1000\times8} = 0.676\ \text{m}^3/s$

$\dot{m}_{w_{th}} = \frac{0.676}{0.8} = 0.845\ \text{m}^3/s$

4.5.4 Radiator calculations

4.5.4.1 Area of radiator

$$A = \frac{Q_w}{U\left[T_{w_m} - \left(T_{a_m} + \frac{\Delta T_a}{2}\right)\right]}$$

Where

U = Coefficient of heat transfer

= 160 k W/(m^2 K)

$$A = \frac{22.66\times10^6}{160\times10^3\left[91-\left(67.5+\frac{35}{2}\right)\right]} = 23.6\ \text{m}^2$$

4.5.4.2 Fan calculation:-

a. Air flow rate:-

$$\dot{m}_a = \frac{Q_a}{\rho_a \times cp_a \times \Delta T_a}$$

$$= \frac{22.66\times10^6}{1.16\times1.005\times35} = 555.35\ \text{m}^3/\text{s}$$

Aerodynamic resistance it's in range of (600~1000) Pa. take it 1000 Pa

Take the fan efficiency = 50%

b. The power needed to run the fan is:-

$$N_{fan} = \frac{\dot{m}_a \times \Delta P_{air\ resistance}}{\eta_{fan} \times 1000}$$

$$= \frac{555.35\times1000}{0.5\times1000} = 1.117\ \text{kW}$$

c. The fan area:-

ω_a = (6~24) m/s

$A_{fan} = \frac{\dot{m}_a}{\omega_a}$ (Take $\omega_a = 24$ m/s)

$$A_{\text{fan}} = \frac{555.35}{24} = 23.1\ \text{m}^2$$

3. The diameter of the fan:-

$$D_{fan} = 2 \times \sqrt{\frac{A_{\text{fan}}}{\pi}}$$

$$= 2 \times \sqrt{\frac{23.1}{\pi}} = 5.42\ \text{m}$$

The fan has 6 blades

∴ The diameter of the fan will be $\frac{5.42}{6} = 0.903\ m$

4. The speed of the fan:-

$$u_{fan} = \Psi \times \sqrt{\frac{\Delta P_a}{\rho_a}}$$

$\Psi \equiv$ Factor depended on the shape of the fan (2.8~3.5) take it equals to 3

$$= 3 \times \sqrt{\frac{1000}{1.16}} = 88.08\ \text{m/s}$$

∴ The rotating speed of fan

$$n_f = \frac{60 \times u_{fan}}{\pi \times D_{fan}} = \frac{60 \times 88.08}{\pi \times 0.903} = 1861.42\ \text{rpm}$$