YILDIZ TECHNICAL UNIVERSITY

DEPARTMENT OF MECHANICAL ENGINEERING

LINEAR RANGE EXTENDER ENGINE CONSTRUCTION

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1. Linear Range Extender Introduction

The first modern free piston engine (FPE) was designed by Argentine engineer Raúl Pateras Pescara. Although the first design was made for a compressor developed and marketed by the Pescara Auto-Compressor company, which was released in 1933, the development of the product was focused on generator-based systems in the ongoing process. Today, it can be used as a Linear Range Extender, which we hear frequently, and which is open to technological development. Linear range extenders (LREs) are thought to have an important place in hybrid vehicle technology. As a basic principle, it aims to increase the vehicle movement distance by supporting the electric motor working together with the classical internal combustion engine in hybrid vehicles.

Linear range extender (LRE) is a crankshaft, camshaft, flywheel gear, etc., where the piston assembly has free and linear motion. It is a linear motor in which the mechanisms are eliminated. According to research, the non-angular movement and the absence of unnecessary transmission elements that will cause friction losses on the engine make the free piston engine about 10% more thermally efficient compared to conventional internal combustion engines. The engine can be designed to be two or four stroke. The air-fuel mixture is sprayed into the cylinder at the ideal rate during suction, and then while the compression occurs, the spark plugs are ignited and combustion takes place when the piston approaches the top dead point. The energy released during the combustion phase and the thrust applied to the piston surface cause the back and forth linear movement of the arm located between the two pistons (Figure 1). The coil, which is wound on the arm, transforms the linear motion into electrical energy, and this electrical energy is stored in large batteries to be used to increase the distance in the hybrid vehicle.

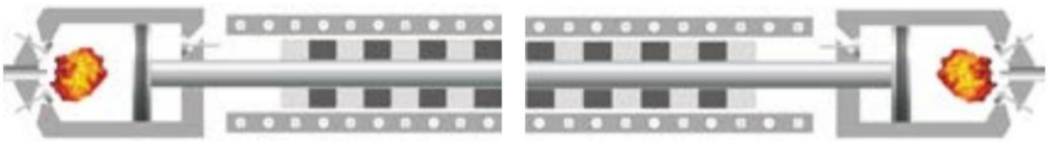
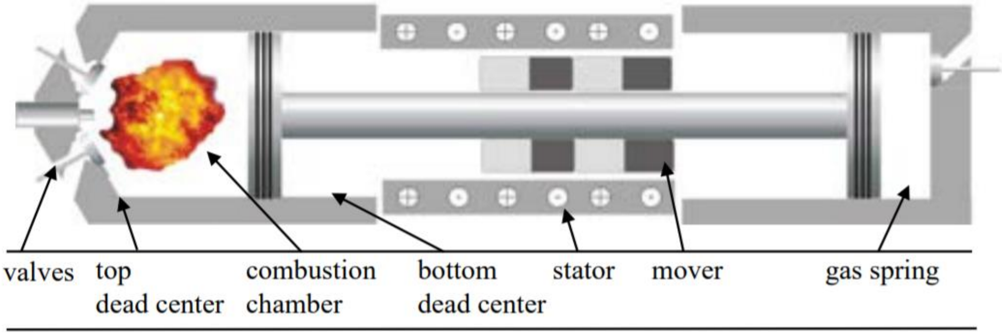


Figure-1

The key point here is that the counterweights on the crank, which provide the piston back movement in conventional internal combustion engines, are performed by the compression and expansion phases in the oppositely positioned counter piston cylinder assembly. In some designs, although there is only one combustion chamber (Figure 2), there is a gas chamber that provides the continuous movement of the system and acts as a spring. Another design model is the central combustion system, where the combustion chamber, which is considered the most advanced, is in the center of the cylinders (Figure 3).

We used a design similar to Figure 2 in our Linear Range Extender.



Şekil 2

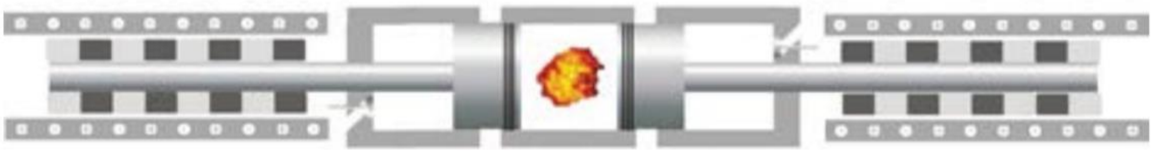


Figure 3

Desing and Calculation Values

$D = 86\ mm$
$S = 86\ mm$
$P_1 = 1{,}05\ bar$
$m_y = 0{,}003\ g/cycle$
$H_u = 10000\ kcal/kg = 41840\ kj/kg$
$Compression\ Ratio = 10{,}2$
$Initial\ Temperature = T_1 = 300\ K$

2. Thermal Calculations

$$V_H = \frac{\pi}{4} \times (0{,}086)^2 \times (0{,}086)$$
$$V_H = 0{,}5\ liter$$
$$Efficiency\ of\ combustion = 0{,}9$$
$$Q = 41840 \times 3 \times 10^{-6} \times 0{,}9$$
$$Q = 0{,}1129\ kj$$

<u>Finding the Fill Weight</u>

$$P_1 \times V_1 = m \times R \times T_1$$
$$R = 287\, J/kg.K$$
$$1{,}05 \times 5 \times 10^{-4} = m \times 287 \times 300$$
$$m = 0{,}60975\ g$$
$$m = m_{air} + m_{fuel}$$
$$m_{hava} = 0{,}60675\ g$$

<u>Amount of Oxygen</u>

$$m_{oxygen} = 0{,}232 \times m_{air}$$
$$m_{oxygen} = 0{,}14094\ g$$

<u>Compression Process (1-2)</u>

$$T_1 = 300\ K$$
$$k_1 = 1{,}4$$
$$P_2 = P_1 \times \varepsilon^k = 1{,}05 \times (10{,}2)^{1{,}4}$$
$$P_2 = 27{,}11\ bar$$
$$T_2 = T_1 \times \varepsilon^{k-1} = 300 \times (10{,}2)^{0{,}4}$$
$$T_2 = 759{,}55\ K$$

<u>Combustion Process (2-3)</u>

$$\frac{759{,}55 - 750}{800 - 750} = \frac{c_{v_2} - 0{,}8}{0{,}812 - 0{,}8}$$
$$c_{v_2} = 0{,}8022\ kj/kg\,.K$$
$$Q = m_{oksijen} \times c_{v_2} \times (T_3 - T_2)$$

$$T_3 = 1758{,}55\ K$$
$$\frac{T_3}{T_2} = \frac{P_3}{P_2}$$
$$P_3 = 62{,}76\ bar$$

Expansion Process

$$T_3 = 1758{,}55\ K\ so\ k_2 = 1{,}301\ (EES\ used)$$
$$P_3 = P_4 \times \varepsilon^{k_2}$$
$$P_4 = 3{,}138\ bar$$
$$T_4 = \frac{T_3}{\varepsilon^{k-1}}$$
$$T_4 = 874{,}1\ K$$

Finding of Thermal Efficiency

$$\mu_t = 1 - \frac{T_4}{T_3} = 0{,}502$$

Finding the Average Indicated Pressure

$$P_{mi} = \frac{L_ç}{V_H} = \frac{Q_1 - Q_2}{V_H}$$
$$Q_1 = 0{,}1129\ kj$$
$$Q_2 = \frac{1 - \mu_t}{Q_1}$$
$$Q_2 = 0{,}0561\ kj$$
$$P_{mi} = 1{,}13\ bar$$

Power Calculation

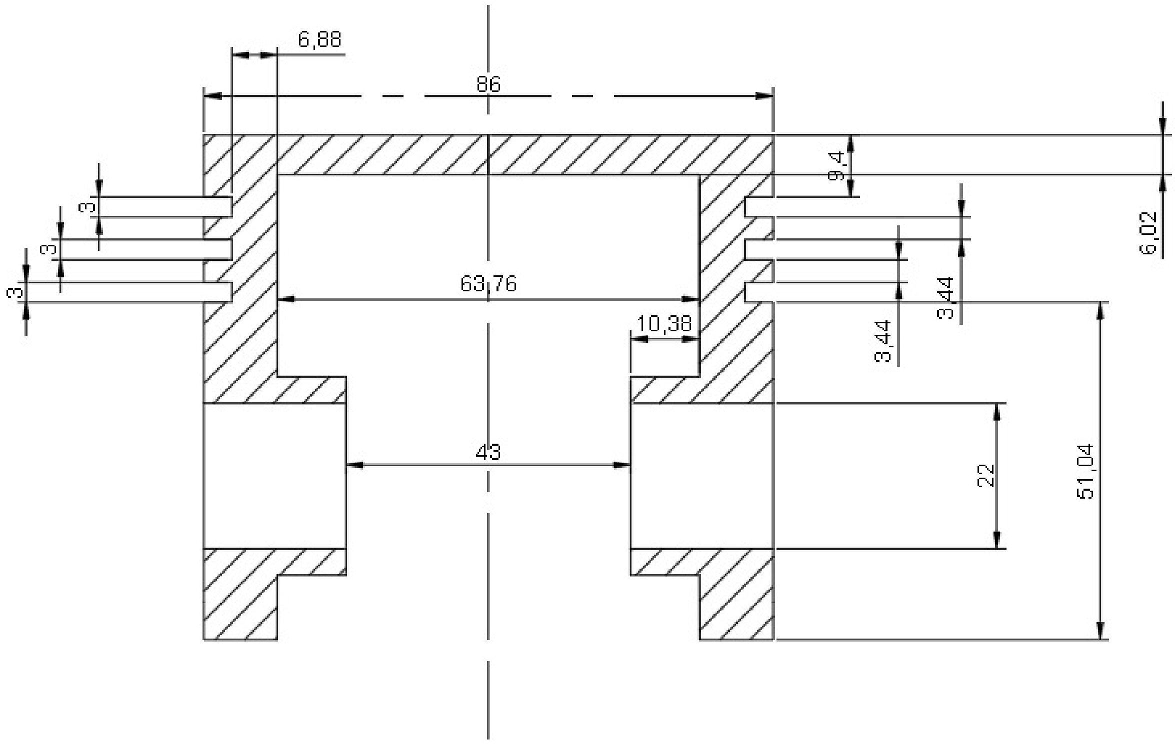
$$Ni = \frac{P_{mi} \times V_H \times n \times Z}{a}$$
$$Ni = \frac{1{,}13 \times 5 \times 10^{-4} \times 3000 \times 2 \times 10^5}{60 \times 2}$$
$$Ni = 2{,}825\ kW$$
$$\mu_m = 0{,}8\ (assumed)$$
$$Ne = Ni \times \mu_m$$
$$Ne = 2{,}26\ kW$$

3. Strength Calculations

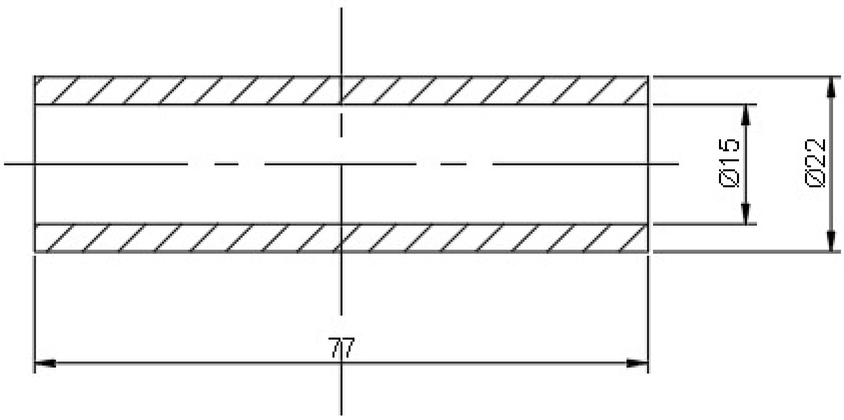
The control of the first selected values was done manually.

Matlab was used for revisions.

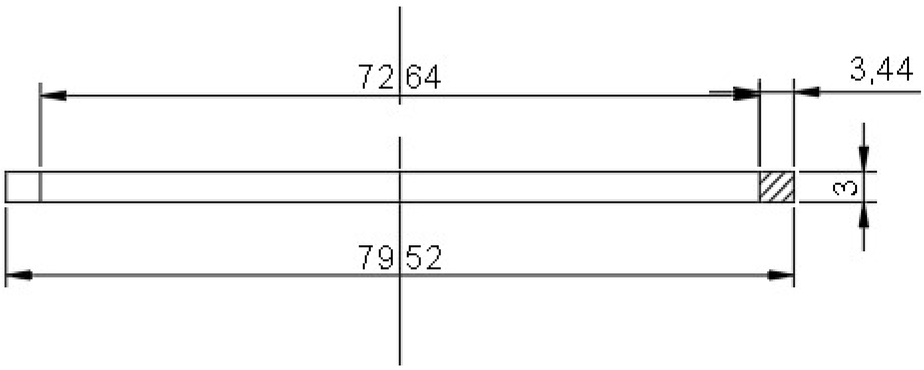
Shape and dimensions are given with technical drawing.



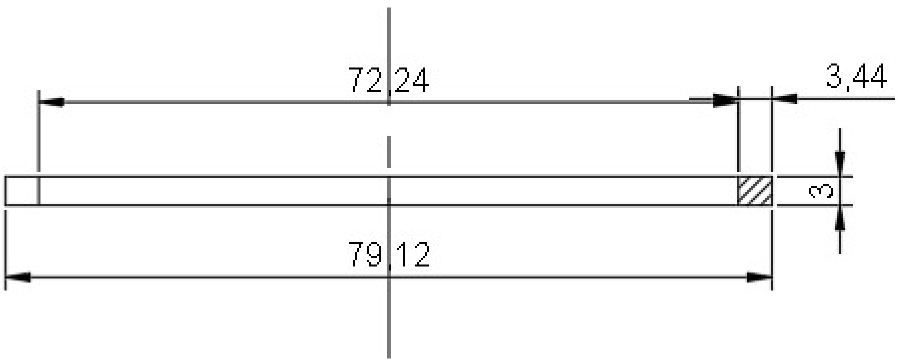
First Drawing of the Piston



Pin Initial Drawing



Compression Ring Initial Drawing



First Drawing of Oil Control Ring

<u>Piston Control</u>

Material: Aluminium

$$n = 3000\ rpm$$
$$Ap = 5{,}808 \times 10^{-3}\ m^2$$
$$P_{max} = 6{,}276\ Mpa$$
$$F_p = Ap \times P_{max}$$
$$F_p = 36451\ N$$

<u>Piston Head Bending</u>

$$\sigma_e = P_{max} \times \frac{r_i^2}{\delta^2}$$
$$\sigma_e = 6{,}276 \times \frac{(31{,}88)^2}{(6{,}02)^2}$$

$$\sigma_e = 176\ Mpa$$

Stress Due to Heat

$$\sigma_h = \frac{\alpha_{Al} \times E \times q \times \delta}{200 \times \lambda_h}$$
$$\alpha_{Al} = 22 \times 10^{-6}\ 1/K$$
$$q = 11{,}63 \times (6000 + 26 \times n) \times P_{mi} = 123091{,}92$$
$$\lambda_h = 205 W/m.K$$
$$E = 70\ GPa$$
$$\sigma_h = 0{,}0293\ Mpa$$
$$\sigma_\Sigma = \sigma_e + \sigma_h$$
$$\sigma_\Sigma = 176{,}034\ Mpa$$
$$\sigma_\Sigma > 150\ Mpa\ (unsafe)$$

Cross Section of Oil Holes

Number of Oil Holes =$n_{oil\ holes}$=9

Oil Hole Diameter d_{yd}=1,2 mm

$$A_{x-x} = \frac{\pi}{4} \times \left({d_g}^2 - {d_i}^2\right) - (n_{oil\ hole} \times F')$$
$$n_{oil\ hole} = 9$$
$$d_{yd} = 1{,}2\ mm$$
$$d_g = D - 2 \times (t - \Delta t)$$
$$d_g = 86 - 2 \times (3{,}44 - 0{,}8)$$
$$d_g = 77{,}52\ mm$$
$$d_i = 63{,}76\ mm$$
$$F' = \frac{d_g - d_i}{2} \times d_{yd}$$
$$F' = 8{,}526\ mm^2$$
$$A_{x-x} = 1452{,}52\ mm^2$$
$$\sigma_{com} = \frac{F}{A_{x-x}} = \frac{36451}{1452{,}52}$$
$$\sigma_{com} = 25{,}09\ Mpa$$
$$\sigma_{com} < 30\ Mpa\ (safe)$$

First Ring Position Check

$$\tau = \frac{0{,}0314 \times P_{max} \times D}{h_r}$$

$$h_r = 3{,}44\ mm$$
$$\tau = 4{,}92\ Mpa$$
$$\sigma_b = \frac{0{,}0045 \times P_{max} \times D}{{h_r}^2}$$
$$\sigma_b = 17{,}65\ Mpa$$
$$\sigma_\Sigma = \sqrt{{\sigma_b}^2 + 4 \times \tau^2}$$
$$\sigma_\Sigma = 20{,}208\ Mpa$$
$$\sigma_\Sigma < 30\ Mpa\ (safe)$$

Thermal Expansion

A water-cooled LRE design was made.

Cylinder material: Cast iron

$$\Delta c = 0{,}007 \times D = 0{,}602\ mm$$
$$D = 86\ mm$$
$$D_c = 85{,}398\ mm$$
$$\alpha_{st} = 11 \times 10^{-6}\ 1/K$$
$$T_c = 523\ K$$
$$T_{cyl} = 385\ K$$
$$T_0 = 300\ K$$
$$\Delta c' = D \times \left(1 + \alpha_{cly} \times \left(T_{cyl} - T_0\right)\right) - D_c \times \left(1 + \alpha_p \times (T_c - T_0)\right)$$
$$\Delta c' = 0{,}27\ mm$$

Checking the Segments

Material: Steel

$$E = 2 \times 10^5\ Mpa$$
$$A_0 = 3 \times t$$
$$P_{av} = 0{,}152 \times E \times \frac{\frac{A_0}{t}}{\left(\frac{D}{t_k} - 1\right)^3 \times \left(\frac{D}{t_k}\right)}$$
$$P_{av} = 0{,}26\ Mpa$$
$$0{,}11 < P_{av} < 0{,}37\ appropriate\ as\ a\ pressure\ value$$

Bending Stress

In working conditions;

$$\sigma_{b1} = 2{,}61 \times P_{av} \times \left(\frac{D}{t_k} - 1\right)^2$$
$$\sigma_{b1} = 396{,}72\ Mpa$$
$$200 < \sigma_{b1} < 450\ (safe)$$

$$\sigma_{b2} = \frac{4 \times E \times \left(1 - 0{,}114 \times \frac{A_0}{t}\right)}{m \times \left(\frac{D}{t} - 1{,}4\right) \times \left(\frac{D}{t}\right)}$$

$$m = 1{,}57\ taken\ from\ book$$

$$\sigma_{b2} = 568{,}28\ Mpa$$

Distance Between Segment Ends

$$\Delta r = \Delta r' + \pi \times D \times \left(\alpha_r \times (T_r - T_0)\right) - \alpha_{cyl} \times \left(T_{cyl} - T_0\right)$$

$T_{cyl} = 385\ K$

$T_r = 500\ K$

$\alpha_r = \alpha_{st} = 11 \times 10^{-6}\ 1/K$

$\Delta r' = 0{,}08\ mm(0{,}06 - 0{,}1\ chosen)$

$\Delta r = 0{,}45mm$

Pin Check

Material: Steel

$d_p = 22\ mm$

$d_{pi} = 15\ mm$

$L_p = 77\ mm$

$b = 43\ mm$

$L_b = 34\ mm$

$$q_{cr} = \frac{F}{d_p \times L_p} = 21{,}51\ Mpa$$

$20 < q_{cr} < 60\ (appropriate)$

$$q_b = \frac{F}{d_p \times \left(L_p - b\right)} = 45{,}53\ Mpa$$

$15 < q_b < 50\ (appropriate)$

$$\alpha_{pim} = \frac{d_{pi}}{d_p} = 0{,}81$$

$$\sigma_{pim} = \frac{F \times \left(L_p + 2 \times b - 1{,}5 \times L_b\right)}{1{,}2 \times \left(1 - {\alpha_p}^4\right) \times d_p}$$

$\sigma_{pim} = 407{,}58\ Mpa$

$\sigma_{pim} > 250\ Mpa\ (unsafe)$

$$\tau = \frac{0{,}85 \times F \times (1 + \alpha + \alpha^2)}{(1 - \alpha^4) \times {d_p}^2} = 174{,}91\ Mpa$$

$60 < \tau < 250\ (appropriate)$

Ovalization Control of Pin

$$\Delta d_{max} = \frac{1{,}35 \times F}{E \times L_p} \times \left(\frac{1+\alpha}{1-\alpha}\right)^3 \times (0{,}1 - (\alpha - 0{,}4)^3)$$
$$\Delta d_{max} = 0{,}036\ mm$$
$$\Delta d_{max} < 0{,}05\ (appropriate)$$

The highest ovalization stress occurs on the inner-horizontal side of the pin.

$$\sigma_0 = \frac{1{,}5 \times F}{L_p \times d_p} \times \left[0{,}19 \times \frac{(1 + 2 \times \alpha) \times (1+\alpha)}{(1-\alpha)^2 \times \alpha} + \frac{1}{1-\alpha}\right] \times (0{,}1 - (\alpha - 0{,}4)^3)$$
$$\sigma_0 = 352{,}13\ Mpa$$
$$\sigma_0 > 300\ Mpa\ (unsafe)$$

Cylinder Calculation

Material: Cast Iron

$$\delta_S = 0{,}5 \times B \times \left[\sqrt{\frac{\sigma_z + 0{,}4 \times P_{max}}{\sigma_z - 1{,}3 \times P_{max}}} - 1\right]$$
$$\sigma_z = 60\ Mpa$$
$$\delta_S = 4{,}21\ mm$$
$$\delta_{S,Chosen} = 7\ mm\ (appropriate)$$

Expansion Stress in Cylinder Wall

$$\sigma_{ex} = \frac{P_{max} \times B}{2 \times \delta_S}$$
$$\sigma_{ex} = 38{,}55\ Mpa$$

Temperature Stress in Cylinder Wall

$$\sigma_t = \frac{E \times \alpha \times \Delta T}{2 \times (1-\nu)}$$
$$\Delta T = 120\ K$$
$$E = 10^5$$
$$\nu = 0{,}25\ poisson\ ratio$$
$$\alpha = 11 \times 10^6$$
$$\sigma_t = 88\ Mpa$$

Total Stress in Cylinder Wall

$$\sigma_{\sum d\imath ş} = \sigma_{ex} + \sigma_t = 126{,}55\ Mpa$$
$$\sigma_{\sum d\imath ş} < 130\ Mpa\ (appropriate)$$
$$\sigma_{\sum iç} = \sigma_x - \sigma_t = -49{,}45\ Mpa$$

4. Matlab Codes

motor.m

```
%% Values
P3 = 6.276;                 %MPa, combustion end pressure
Pmi = 0.0113;               %Mpa, average indicated pressure
piston_head = 7;            %mm, wall thickness of piston head
D = 86;                     %mm, piston diameter
hr = 2.58;                  %mm, location of the first segment
tk = 3.87;                  %mm, the thickness of the segment
delta_tk = 0.95;            %mm, distance between compression ring and piston
s = 5.56;                   %mm, wall thickness of piston
Di = D - 2*(s+tk+delta_tk); %mm, piston inner diameter
ty = 3.698;                 %mm, oil ring thickness
delta_ty = 1;               %mm,
n = 10;                     %number of oil holes
dyd = 1.5;                  %mm, diameter of oil holes
% Floating pin
dp = 25;                    %mm, pin diameter
dpi = 15;                   %mm, pin inner diameter
Lp = 77;                    %mm, pin lenght
b = 38;                     %mm, distance between boss
Lb = 32;                    %mm,
%
alfa_al = 22*10(-6);        %1/K, linear expansion coefficient
lambda_al = 205000;         %W/mmK, Al. heat transfer coefficient
revolution = 3000;          %rpm
E_al = 70000;               %MPa, Al. elasticity modulus
dg = D-2*(tk+delta_tk);     %
alfa_st = 12*10^(-6);       %1/K
alfa_ci = 11*10(-6);        %1/K
Tc = 523;                   %K, temperature of piston head at the end of the combustion
Tcyl = 385;                 %K, temperature of cylinder at the end of the combustion
delta_c = 0.516;            %mm, distance between cylinder
Dc = D-Delta_c;             %
To = 300;                   %K, initial temperature
```

```
motor.m
delta_c = 0.516;            %mm, distance between cylinder
Dc = D-Delta_c;             %
To = 300;                   %K, initial temperature
E_st = 200000;              %MPa
Ao = 2.5*tk;                %
Tr = 500;                   %K
E_ci = 10^5;                %MPa


%% Piston Calculations
%% Finding Forces
F = (P3*pi*(D^2)/4);            %Force exposured to piston, N
fprintf("Force exposured to upper side of the piston during combustion %2f N \n", F)

%% Piston Control
sigma_e=P3*((Di/2)^2)/piston_head^2;
q=11.63*(6000+26*revolution)*Pmi;
sigma_h=(alfa_al*E_al*q*piston_head)/(200*lambda_al);
sigma_pistontotal= sigma_h+sigma_e;
if sigma_pistontotal> 150
    fprintf("Piston is not resistant to stresses. Value: %2f MPa \n", sigma_pistontotal)
elseif sigma_pistontotal<30
    fprintf("Piston is safe against stresses. Value: %2f MPa \n", sigma_pistontotal)
else
    fprintf("Piston is appropriate against the stresses. Value: %2f \n", sigma_pistontotal)
end
%% Oil Holes' Cross-Sections Control
A2=((dg-Di)/2)*dyd;
Axx=(pi/4)*(dg^2-Di^2)-n*A2;
sigma_com=F/Axx;
if sigma_com >40
    fprintf("X-X cross-section is not resistant to stresses. Value: %2f MPa \n", sigma_com)
elseif sigma_com<30
```

```
motor.m
if sigma_com >40
    fprintf("X-X cross-section is not resistant to stresses. Value: %2f MPa \n", sigma_com)
elseif sigma_com<30
    fprintf("X-X cross-section is safe against stresses. Value: %2f MPa \n", sigma_com)
else
    fprintf("X-X cross-section is appropriate against the stresses. Value: %2f \n", sigma_com)
end
%% First Ring Location Check
to_hr=(0.0314*P3*D)/hr;
sigma_ring=(0.0045*P3*D^2)/hr^2);
sigma_ringtotal=sqrt(sigma_ring^2+4*to_hr^2);
if sigma_ringtotal> 40
    fprintrf("First ring place is not resistant to stresses. Value: %2f MPa \n", sigma_ringtotal)
elseif sigma_ringtotal<30
    fprintf("First ring place is safe against stresses. Value: %2f MPa \n", sigma_ringtotal)
else
    fprintf("First ring place is appropriate against the stresses. Value: %2f \n", sigma_ringtotal)
end
%% Thermal Expansion
% Water cooling, piston cylinder was made of cast iron.
delta_c2=D*(1+alfa_ci*(Tcyl-To))-Dc*(1+alfa_al*(Tc-To));
fprintf("Value of piston expansion: %2f mm \n", delta_c2);

%% Ring Control
Pav=0.152*E_st*(Ao/tk)/((D/tk)-1)^3*(D/tk));
if Pav<0.11 || Pav>0.37
    fprintf("Ring is not appropriate in terms of pressure. Value: %2f MPa \n", Pav)
else
    fprintf("Ring is appropriate in terms of pressure. Value: %2f MPa \n", Pav)
end
%%Bending Stress
%%Operating State
sigma_b1=2.61*Pav*((D/tk)-1)^2;
```

motor.m

```
%%Bending Stress
%%Operating State
sigma_b1=2.61*Pav*((D/tk)-1)^2;
if sigma_b1<200
    fprintf("Ring is too safe against to stresses. Value: %2f MPa \n", sigma_b1)
elseif sigma_b1>450
    fprintf("Ring is not safe. Value: %2f MPa \n", sigma_b1)
else
    fprintf("Ring stress is appropriate. Value: %2f MPa \n", sigma_b1)
end
m=1.57;
%during sliding on piston
sigma_b2=(4*E_st*(1-0.114*Ao/tk))/(m*((D/tk)-1.4)*(D/tk));
fprintf("ring stress while sliding on piston: %2f MPa \n", sigma_b2)
%butting clearance between ring ends
delta_r2=0.08; %mm
delta_r=delta_r2+pi*D*(alfa_st*(Tr-To)-alfa_ci*(Tcyl-To);

%% Pin
qcr=F/(dp*Lp);
if qcr<20
    fprintf("qcr value is less than it must be. Value: %2f MPa \n", qcr)
elseif qcr>60
    fprintf("qcr value is more than it must be. Value: %2f MPa \n", qcr)
else
    fprintf("qcr value is at the level it should be. Value: %2f \n", qcr)
end
qb=F/(dp*(Lp-b));
if qb<15
    fprintf("qb value is less than it must be. Value: %2f MPa \n", qb)
elseif qb>60
    fprintf("qb value is more than it must be. Value: %2f MPa \n", qb)
else
```

motor.m

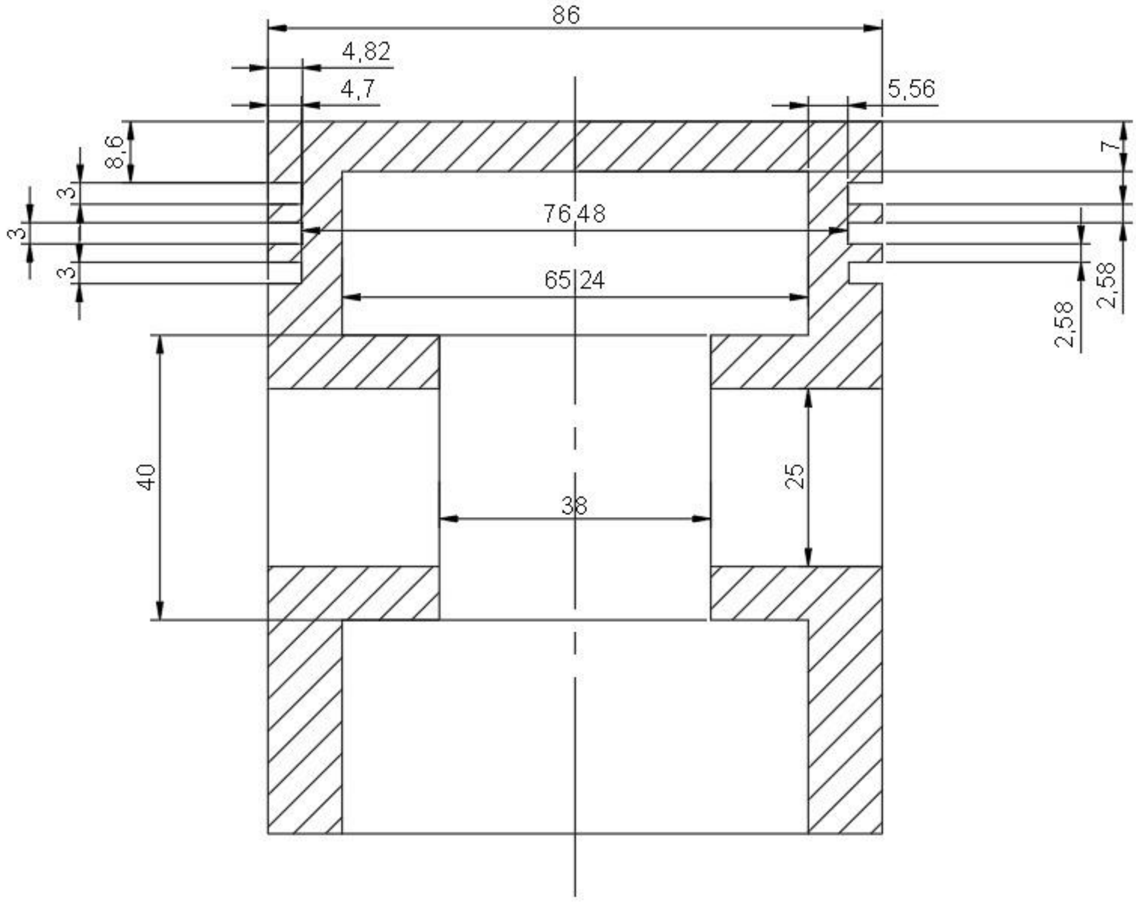
```
elseif qb>60
    fprintf("qb value is more than it must be. Value: %2f MPa \n", qb)
else
    fprintf("qb value is at the level it should be. Value: %2f \n", qb)
end
alfa_pin=dpi/dp;
sigma_pin=F*(Lp+2*b-1.5*Lb)/(1.2*(1-alfa_pin^4)*dp^3);
if sigma_pin<100
    fprintf("Pin is too safe against to stresses. Value: %2f MPa \n", sigma_pin)
elseif sigma_pin>250
    fprintf("Pin is not safe. Value: %2f MPa \n", sigma_pin)
else
    fprintf("Pin stress is appropriate. Value: %2f MPa \n", sigma_pin)
end
to_pin=0.85*F*(1+alfa_pin^2)/((1-alfa_pin^4)*dp^2);
if to_pin<60
    fprintf("Pin is too safe against shear. Value: %2f MPa \n", to_pin)
elseif to_pinto_pin>250
    fprintf("Pin is unsafe against shear. Value: %2f MPa \n", to_pin)
else
    fprintf("Pin is at the level it should be against shear. Value: %2f MPa \n", to_pin)
end

%Pin ovalization control of the pin
delta_dmax=((1.35*F)/(E_st*Lp))*(((1+alfa_pin)/(1-alfa_pin))^3)*(0.1-alfa_pin)
if delta_dmax<0.05
    fprintf("Ovalization is at normal level. Value: %2f MPa \n", delta_dmax)
else
    fprintf("Ovalization is too much, must be dropped. Value: %2f mm \n", delta_dmax)
end
%%Ovalization occurs where the highest pin located(on the inner side)
%%It must be controlle
sigma_oval1=((15*F)/(Lp*dp));
```

```
motor.m  ×  +
    %%It must be controlle
    sigma_oval1=((15*F)/(Lp*dp));
    sigma_oval2=((0.19*(1+2*alfa_pin))/((1-alfa_pin)^2*alfa_pin))
    sigmaoval_13=0.1-(alfa_pin-0.4)^3;
    sigmaoval=sigma_oval1*sigma_oval2*sigma_oval3;
    if sigmaoval<300 || sigmaoval>200
        fprintf("Pin is safe against ovalization stresses. Value: %2f MPa \n", sigmaoval)
    else
        fprintf("Pin is not appropriate against ovalization stresses. Value: %2f MPa \n", sigmaoval)
    end
    %% Cylinder Head Calculations
    %Material is cast iron
    sigma_z=60;
    sigma_s_secim=7;
    delta_T=120;
    nu=0.25;

    Sigma_s=0.5*D*(sqrt((sigma_z+0.4*P3)/(sigma_z-1.3*P3))-1;
    if Sigma_s<sigma_s_secim
        fprintf("Piston wall thickness is appropriate. Value: %2f mm \n", Sigma_s)
    else
        fprintf("Select piston wall thickness again. Value: %2f mm \n", Sigma_s)
    end
    sigma_ex=((P3*D)/(2*sigma_s_secim));
    sigma_t=((E_ci*alfa_ci*delta_T)/(2*(1-nu)));
    sigma_toplam_dis=sigma_ex+sigma_t;
    sigma_toplam_ic=sigma_ex-sigma_t;
    if sigma_toplam_dis>130
        fprintf("Cylinder is not safe against the stress where occurs out of its head. Value: %2f \n", sigma_toplam_dis)
    elseif sigma_toplam_dis<100
        fprintf("Cylinder is too safe against the stress where occurs out of its head. Value: %2f \n", sigma_toplam_dis)
    else
        fprintf("Cylinder is safe against the stress where occurs out of its head. Value: %2f \n", sigma_toplam_dis)
```

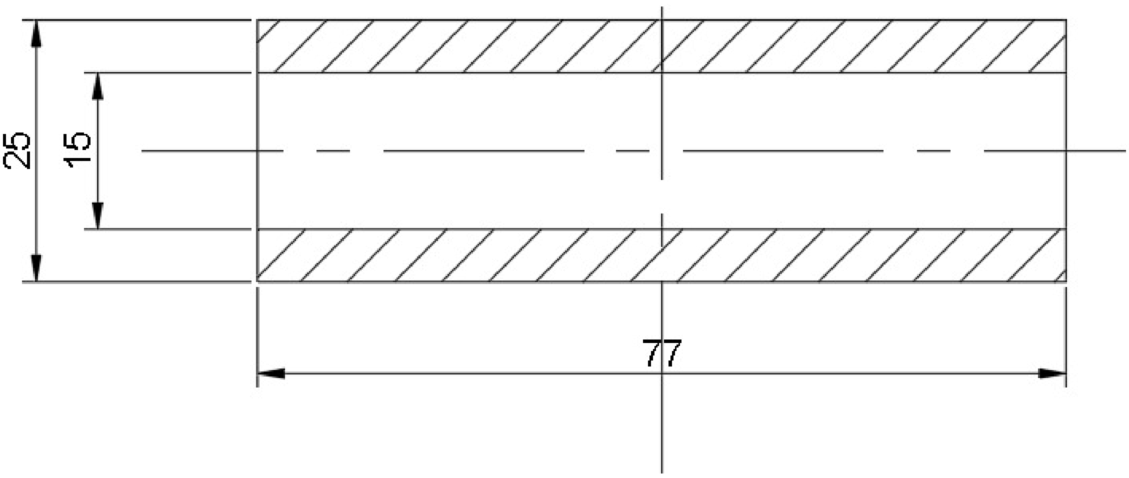
When program is run;

```
>> motor
Force exposured to upper side of the piston during combustion 36456.059028 N
Piston is appropriate against the stresses. Value: 136.290008
X-X cross-section is appropriate against the stresses. Value: 31.610716
First ring place is appropriate against the stresses. Value: 34.019188
Value of piston expansion: 0.177025 mm
Ring is appropriate in terms of pressure. Value: 0.357811 MPa
Ring stress is appropriate. Value: 420.606283 MPa
ring stress while sliding on piston: 787.375348 MPa
qcr value is less than it must be. Value: 18.938212 MPa
qb value is at the level it should be. Value: 37.390830
Pin stress is appropriate. Value: 234.551850 MPa
Pin is at the level it should be against shear. Value: 77.469125 MPa

delta_dmax =

   -0.1023

Ovalization is at normal level. Value: -0.102266 MPa

sigma_oval2 =

    4.3542

Pin is safe against ovalization stresses. Value: 113.794984 MPa
Piston wall thickness is appropriate. Value: 4.217944 mm
Cylinder is safe against the stress where occurs out of its head. Value: 126.552571
```

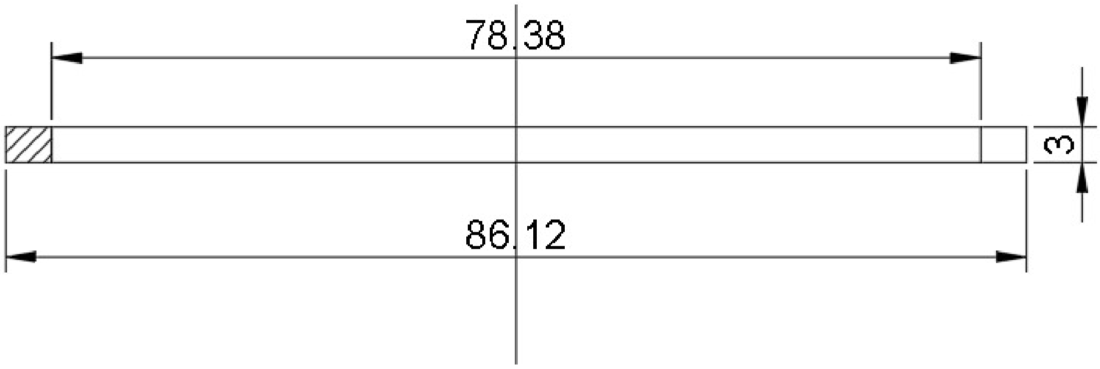
Drawings After Calculations and Matlab Codes



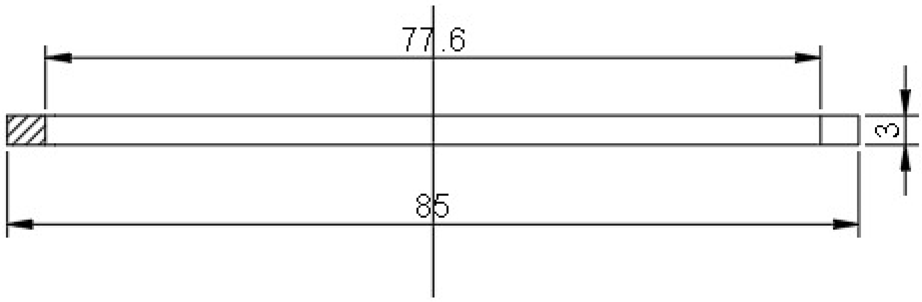
Last Drawing of Piston



Last Drawing of Pin

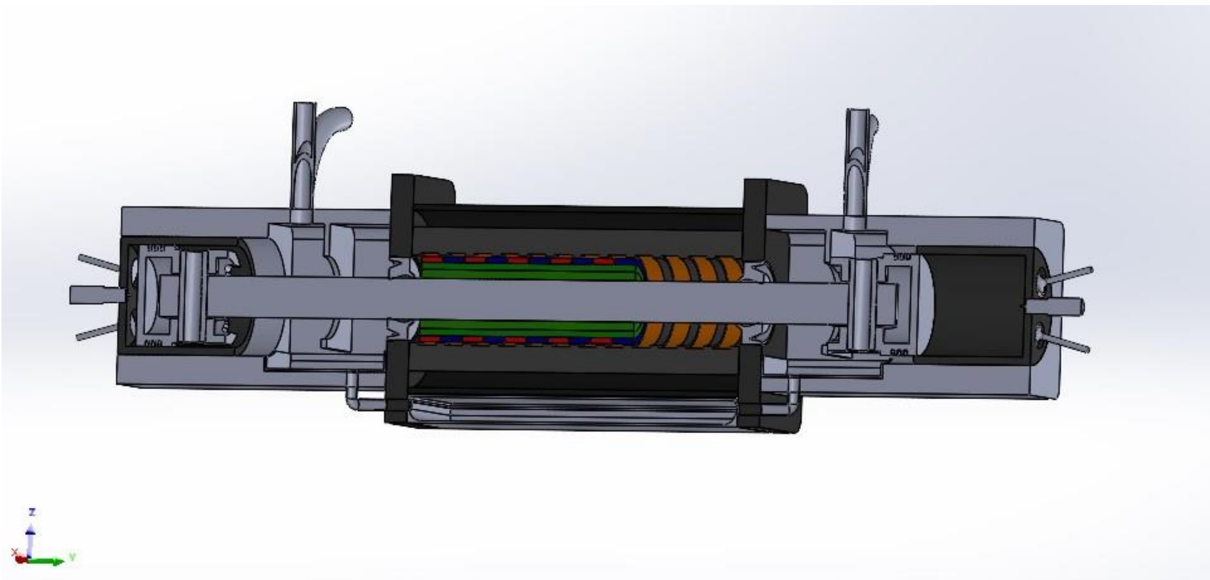


Last Drawing of Compression Ring



Last Drawing of Oil Control Ring

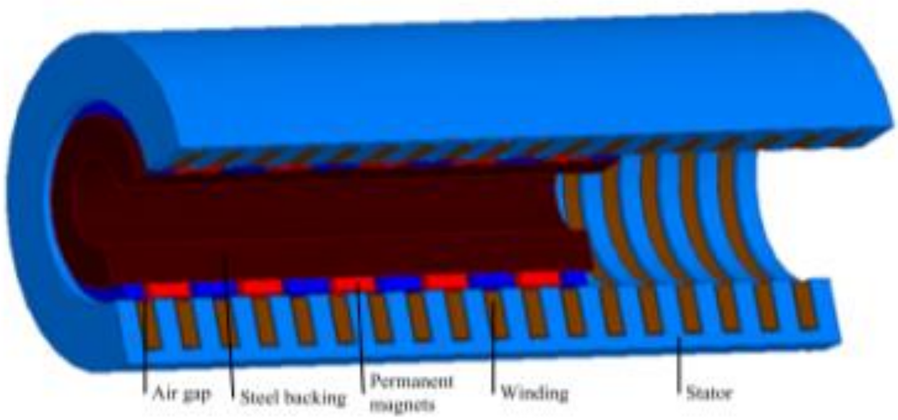
5. Concept 2-Cylinder Engine Design



Assembly content:

1. Sump Upper
2. Sump Bottom
3. Oil Seal x2
4. Electric Motor
5. First Chamber x2
6. Cylinder Head x2
7. Hose x2
8. Piston Guard x2
9. Spark Plug x2
10. Permanent Magnet (Including Rod)
11. Intake Valve x4
12. Exhaust Valve x4
13. Pin x2
14. Compression Ring x4
15. Oil Control Ring x2
16. Piston x2

6. Linear Generator Basic Design



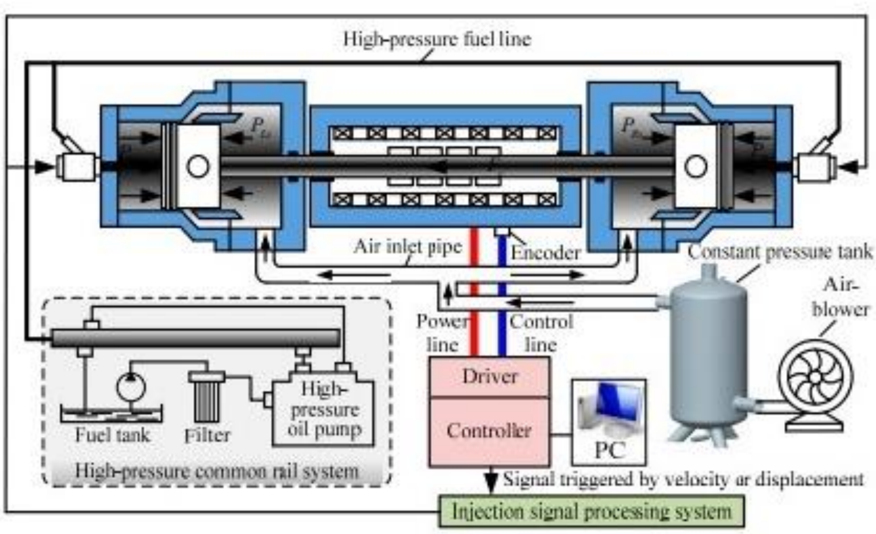
The reciprocating motion of a linear generator produces pulsed power, varying voltage and frequency. The velocity of motion is not sinusoidal and the average velocity of each half-period differs due to the different forces applied during the combustion and expansion process. The analysis of the linear generator driven by the free piston motor should consider the behavior of the generator prime mover. The output power of the generator must be reduced to compensate for the pulsating power. A high capacitive energy storage device is required to provide constant power. The configuration of such a power regulator provides additional design requirements to the linear generator, such as allowable induced voltage. In a range-extender vehicle, the power management controller determines the output power of the REX as the power supplied to the electric motor is the combined power of the REX and the battery. Therefore, a vehicle simulation with a power management controller is required to verify the operating conditions of the REX, and hence the generator.

A 3 KW electric motor was deemed suitable for the system and was sized based on the parameters on the next page. The electric motor is positioned between two pistons and is designed in such a way that it reciprocates inside the rod and creates a magnetic field with the help of magnets.

Parameters	Value
Power/kW	3
Stator length/mm	296
Outer diameter of stator/mm	122
Inner diameter of stator/mm	74
Slot depth of stator/mm	19
Slot pitch of stator /mm	16
Tooth width of stator /mm	8
Pole pitch of permanent magnet /mm	19.2
Radial height of permanent magnet /mm	5
Width of air gap /mm	1
Number of coil turns per slot	21

7. Initial Motion System Design

In this energy conversion machine, which we know as Linear Range Extender or Free Piston Engine, unlike conventional internal combustion engines, connecting rod, crankshaft, camshaft, flywheel, starter motor, etc. There is no such equipment. In the same direction, the mechanical energy obtained by the expansion of the piston as a result of the combustion of liquid fuel in the two opposite piston-cylinder assembly is transformed into electrical energy by the back and forth movement of the arm connected with the pin from the lower parts of both pistons, thanks to the coil wrapped around the arm.



Şekil 7.1

A more ergonomic Pneumatic system was designed to support the first movement of the system by making a detailed literature review for a machine that will operate on this principle. As can be seen in Figure 7.1, the Free Piston Engine first motion mechanism, which was thought to be a two-stroke, was adapted to our project, the two-cylinder, four-stroke Linear Range Extender, as a benchmark. The system was designed and tested in FluidSIM.

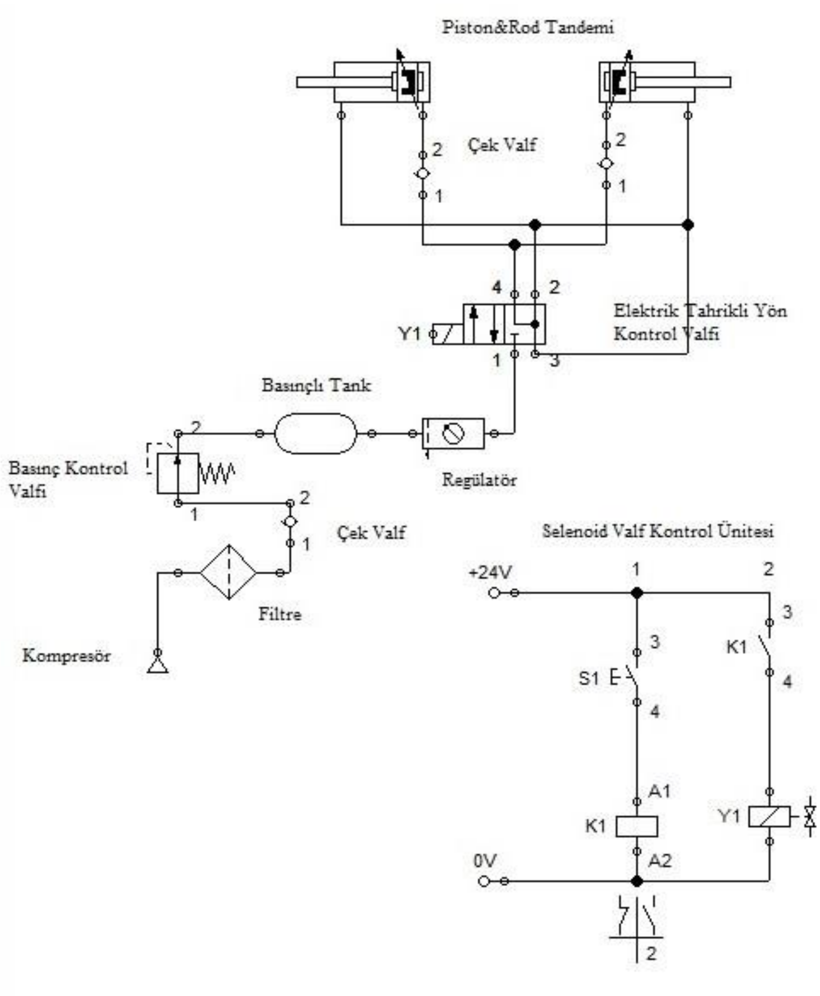


Figure 7.2

The working principle of the system is as follows;

The air taken from the atmosphere is compressed in the compressor and sent to the pressurized tank. From here, the desired pressure value is adjusted with the help of the conditioner (regulator) and transferred to the solenoid controlled directional valve. Compressed air at the level of 1.5-2 bar is sent to the lower part of both pistons (arm and pin connection area), respectively, to a right piston and a left piston in series. In the meantime, the system is turned off when the engine is started and catches its full speed. Although it seems to be a problem to send compressed air to a closed container filled with oil in basic principle, we have overcome this problem by placing check valves on the piston inlets. In addition, a pressure control valve has been placed in order to prevent our system from being damaged against possible excessive pressure values. The system diagram is shown in Figure 7.2.

8. References

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