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Technical Aspect and Simulation of Maritime Systems

Simulation of a Single-Stage-Compressor

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1. Scope

Simulating a single-stage compressor with increasing pressure and air pressure bottles is the aim of this study. An integrated diagram that illustrates all three steps will be provided.

In addition, the following variables are computed and taken into account:

- temperature behavior with respect to pressure
- temperature rise in the air bottle vs. time
- mass flow of air in the air bottle vs. Time
- work done on the compressor

Basic understanding of MATLAB and the technical layout of the compressor are both helpful and will be combined to complete this challenge.

A conclusion that follows the simulation's execution and expansion will list the results.

2. Background Knowledge

It is crucial to have background knowledge for the simulation. The key points to comprehend the entire process are outlined in the paragraphs that follow.

Air compressors

A mechanical device called an air compressor transforms power, usually from an internal combustion engine or electric motor, into the potential energy contained in compressed air. It is widely employed in many different fields and contexts, such as manufacturing, building, transportation, and pneumatic tools. An overview of air compressors, their varieties, and common applications is given by this background information.

Working Principal:

The basic operation of an air compressor is to compress the air while raising the pressure. They pull in atmospheric air and increase the pressure on it, which reduces the amount of air. After that, the compressed air is either used immediately for various uses or stored in a tank.

Types of Air Compressors:

There are several types of air compressors available, each with its own advantages and applications. The main types include:

Reciprocating Air Compressors:

Air is compressed using reciprocating compressors using a piston and cylinder setup. They work with either a single stage or multiple stages of compression. Both lubricated and oil-free versions of reciprocating compressors are suited for high-pressure applications.

Diagram 1: Reciprocating Air Compressor

Rotary Screw Air Compressors:

Air is compressed using two interlocking helical rotors in rotary screw compressors. Compressed air is created as a result of the air being trapped between the rotating rotors, which gradually reduces its volume. The advantages of rotary screw compressors include their great efficiency, continuous operation, and minimal noise.

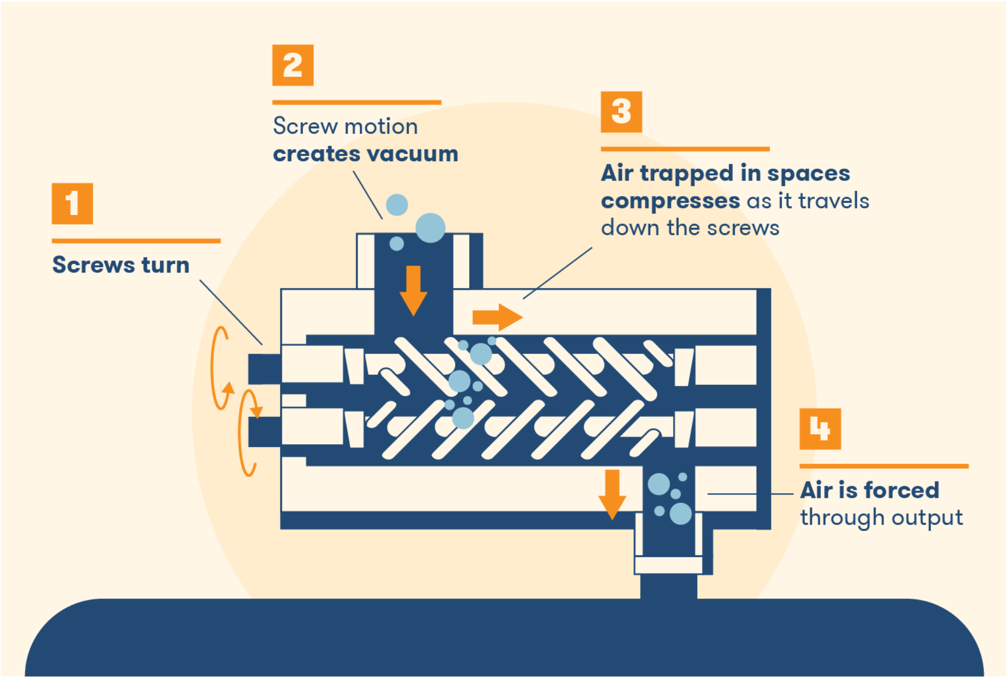


Diagram 2: Rotary Screw Air Compressor

Centrifugal Air Compressors:

A rotating impeller in centrifugal compressors accelerates air, which is then transformed into pressure energy by a diffuser. They frequently deliver enormous volumes of compressed air and are employed in extensive industrial applications.

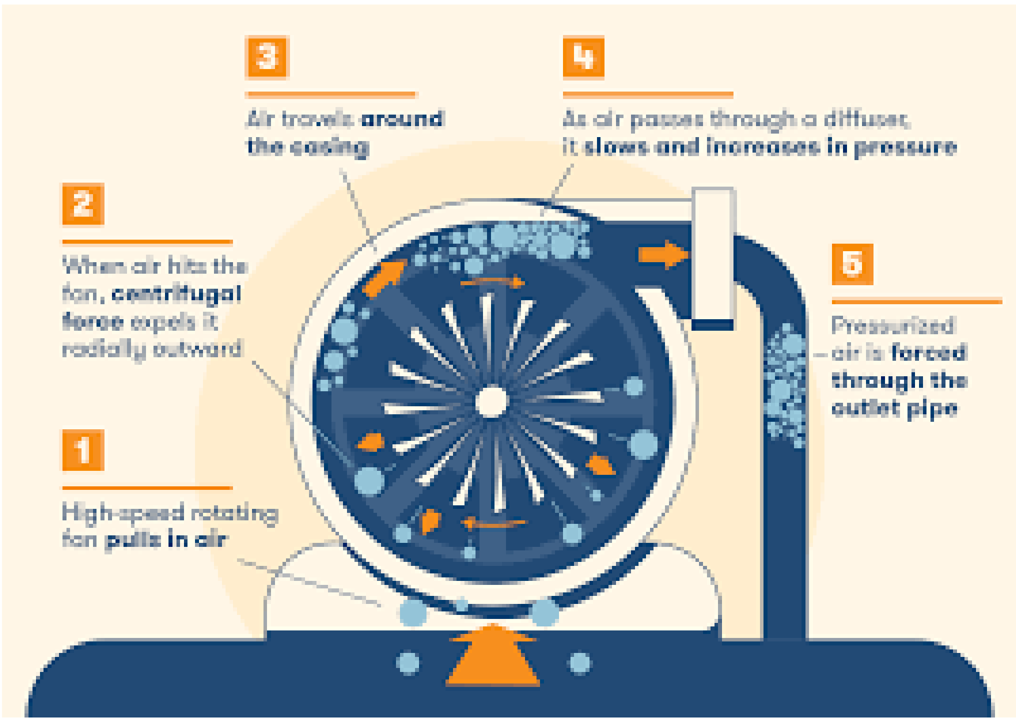


Diagram 3: Centrifugal Air Compressor

Common Applications:

Air compressors are used in a wide range of industries, including:

Pneumatic Tools: A variety of pneumatic tools, including impact wrenches, nail guns, spray guns, and pneumatic drills, are powered by air compressors.

Industrial Manufacturing: Pneumatic conveyance, packing, air blowers, and air-powered equipment all make use of compressed air.

Construction and mining: Air compressors operate pneumatic tools like jackhammers, rock drills, and sandblasting equipment on building sites and during mining operations.

Heating, ventilation, and air conditioning (HVAC) systems use air compressors to circulate air, cool it, and refrigerate it.

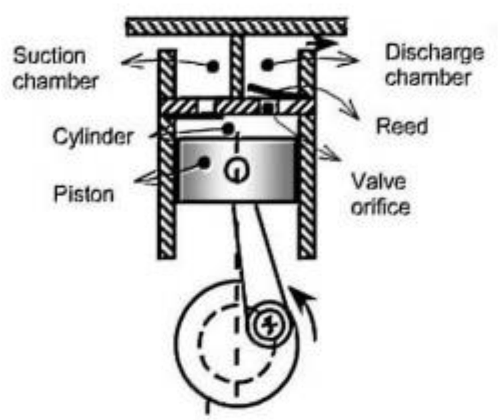
Automotive Industry: Pneumatic brake systems, tire inflation, and assembly lines for automobiles all use compressed air.

Single-stage air compressors

A single stage reciprocating air compressor is a type of air compressor that compresses air in one step using a piston and cylinder setup. It is a typical kind of compressor that is utilized in a variety of contexts, from small-scale activities to industrial ones. This background information gives a general understanding of the components, working theory, and advantages and disadvantages of a single stage reciprocating air compressor.

Working Principle:

A piston that reciprocates back and forth inside a cylinder powers a single stage reciprocating air compressor. A motor, often an electric motor, which transforms electrical energy into mechanical energy, drives the piston. A vacuum is created as the piston descends, drawing air into the cylinder. The air is compressed by the piston during the upward stroke, which lowers its volume and raises its pressure. After that, the compressed air is released into a storage tank or used immediately for a variety of purposes.



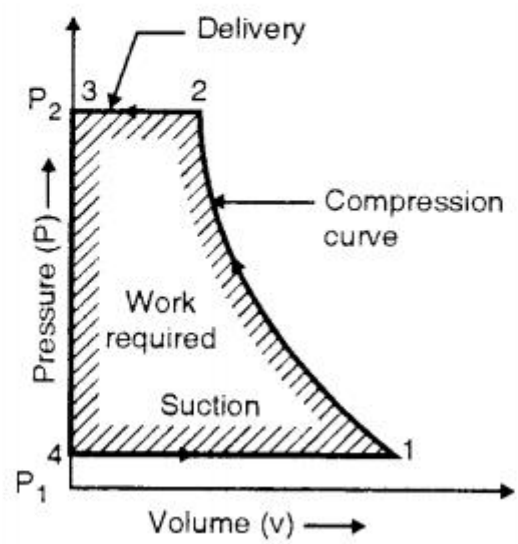


Figure 4: Single Stage Reciprocating Air Compressor

Components:

A single stage reciprocating air compressor consists of several key components:

Cylinder: The main chamber in which the piston oscillates back and forth to compress the air is called the cylinder.

Piston: The cylindrical piston, which is attached to the crankshaft, is a part that fits inside the cylinder. It reciprocates to produce the required compression.

Crankshaft: The piston moves linearly as a result of the crankshaft translating the motor's rotating motion.

Valves: The intake and discharge valves on the air compressor regulate the amount of air that enters and exits the cylinder. During the intake stroke, the intake valve opens to let air into the cylinder, and during the compression stroke, the discharge valve opens to let the compressed air out.

Pros of Single Stage Reciprocating Air Compressor:

Simplicity: Due to their simple construction and minimal number of parts, single stage reciprocating air compressors are simple to use and maintain.

Cost-Effective: They are a cost-effective option for small-scale applications since they are often more cheap than multi-stage compressors.

Suitable for Low to Medium Pressure Applications: Single stage compressors are ideal for tasks requiring low to moderate pressures, such as running pneumatic tools, little workshops, and do-it-yourself projects.

Cons of Single Stage Reciprocating Air Compressor:

Limited Pressure Range: Applications requiring high pressure levels are not suited for single stage compressors. They are usually made to function just within a certain pressure range.

Higher Heat Generation: Due to the compression process occurring in a single step, single stage compressors typically produce greater heat. The compressor's effectiveness and durability may be impacted by this.

Pulsating Airflow: Pulsating airflow produced by the single stage compression process may lead to changes in air pressure downstream and impair the functionality of air-powered products and equipment.

3. Initial values for the basic calculations

Following assumptions are made in mathematical analysis:

- Index of compression is same in all stages and there is no pressure drop in suction and delivery of air across any stage.
- There is perfect intercooling between compression stages.
- Mass handled in different stages is same.
- Air behaves as perfect gas during compression.
- Other friction losses are neglected.

Ambient parameters

The ambient parameters are information required for the whole set-up conditions. Throughout the process the pressure is rising. The temperature is constant due to the intercooler.

```
% ambient parameters:
p_amb= 1 * 10^5;
T_amb = 20 +273.15;
```

Compressor values

To implement the compressor into our simulation it is necessary to determine the details of the compressor as well as different data. Those are the size, volume, area, size of the push rod and the pressure ratio at discharge to suction pressure (Compress Ratio). The compression ratio is the ratio between the maximum and minimum volume V.

```
% Parameters of Compressor1:
D1 = 0.05;     % Diameter of cylinder [m]
H = 0.20;     % Stroke of piston [m]
PushRodRatio = 0.25;
CompressRatio = 12;
A1 = 0.25*pi*D1^2;
Vh1 = A1*H;
Vc1 = Vh1/(CompressRatio - 1);
PolyExp = 1.35; % for the first part of the process: Compression
```

Crank angle values per revolution

Those values need to be calculated in relation with the volume, area and the push rod ratio to gain the crank angle for the volume v1. In total we have 100 revolutions.

```
% Crank angle values covering one revolution:
f = 0:1:360;     % [°]
V1 = Vc1 + A1*(H/2)*( 1 - cosd(f-180) + (1-cosd(2*(f-180)))*PushRodRatio/4 );

i = 1;
```

This diagram shows an example of a crank angle curve with the typical cosinus curve and a constant rod length.

Pressure in the air bottle

This bottle is necessary as a reservoir to store the compressed air. With its high pressure it is possible to start marine I.C. engines.

It is connected to the air compressor with a filling valve, to the main engine with an outlet valve. A relief valve relieves excess pressure and a drain valve drains condensate.

The pressure, air temperature as well as the bottle volume are needed for the calculations.

```
% initial parameters of compressed air bottle:
p_B1 = 15 * 10^5;    % pressure in the bottle [Pa]
T_1 = T_amb ;
V_B = 8;            % volume [m³]
```

4. Calculation of Single-Stage-Compressor

We used the following code to calculate the system diagram for the final point while filling the air bottle. The pressure vs. volume graph in the system diagram is generally determined by this code.

We can use following relation between pressure and volume to find the values for system diagram:

P2/P1=(V2/V1)^(-n)

```
while p_12(end) <= p_B1
    p_12(i+1) = p_12(i) * (V1(i+1) / V1(i))^-PolyExp;
    V_12(i+1) = V1(i+1);
    i = i + 1;
end

% second stage: 2 --> 3 air delivery 1
p_23(1) = p_12(end);
V_23(1) = V_12(end);
while f(i) < 180
    p_23(end+1) = p_23(1);
    V_23(end+1) = V1(i+1);
    i=i+1;
end

% 3'rd stage: 3 --> 4 re-expansion 1
p_34(1) = p_23(end);
V_34(1) = V_23(end);
while p_34(end) >= p_amb
    p_34(end+1) = p_34(end) * (V1(i+1) / V1(i))^-PolyExp;
    V_34(end+1) = V1(i+1);
    i=i+1;
end

% 4'th stage: 4 --> 1 air intake 1
p_41(1) = p_34(end);
V_41(1) = V_34(end);
while f(i) < 360
    p_41(end+1) = p_41(1);
    V_41(end+1) = V1(i+1);
    i=i+1;
end
```

All processes are combined with the following command in single vector.

```
% combine all parts to one pressure vector1:
p_WholeProcess1 = [p_12 p_23 p_34 p_41];
V_WholeProcess1 = [V_12 V_23 V_34 V_41];
```

A single-stage compressor system diagram, the end product of the procedure, is shown in the graph below.

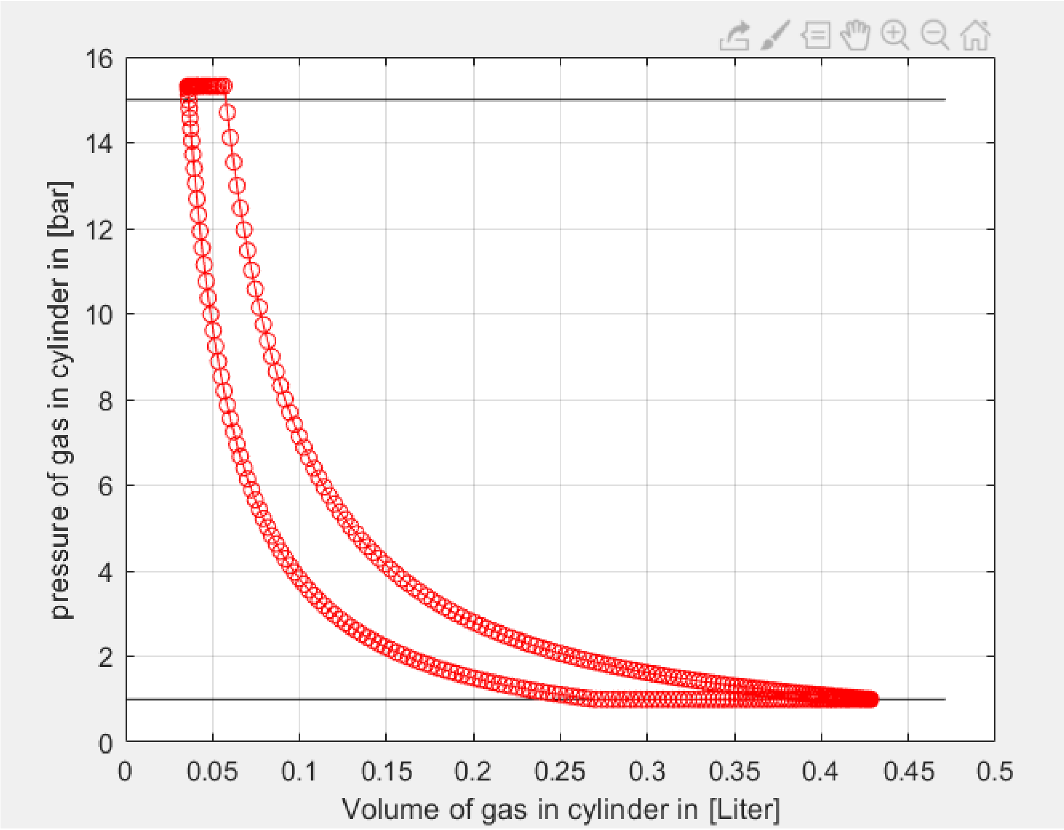


Figure: System Diagram of Single-Stage-Compressor

5. Simulation of temperature behavior with respect to pressure.

To determine temperature on each stroke we can use temperature is directly proportional to the pressure inside compressor chamber.

- Equation: T2 / T1 = (P2 / P1) ^ (n – 1 / n)

Where,

T = Temperature in kelvin.
P = Pressure in pascal
n = Polytropic exponent

We can determine P from equation;

- Equation: P2/P1 = (V2/V1) ^(-n)

Therefore, Temperature rise in each state is calculated with:

```
% first stage: 1 --> 2 Compression
p_12 = p_amb;   % pressure in the compressor
V_12 = V1(1);


while p_12 <= p_B1
    p_12(i+1) = p_12(i) * (V1(i+1) / V1(i))^-PolyExp;
    T_1(i+1) = T_1(i)*(p_12(i+1)/p_12(i))^((PolyExp-1)/(PolyExp));
    V_12(i+1) = V1(i+1);
    i = i + 1;
end
```

This calculation will be made throughout the process to comprehend how pressure-related temperature changes. We will see the results shown below.

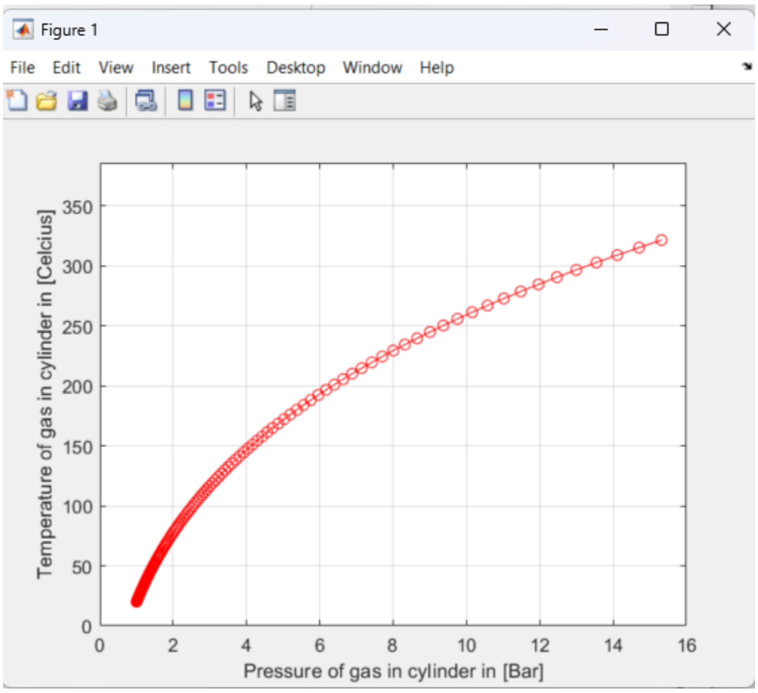


Figure: Temperature changes with respect to Pressure

6. Calculations for system effects on air bottle:

The air bottle's pressure rise is first calculated with relation to time. We must take into account the mass flow rate of compressed air from the compressor to the air bottle in order to compute that. We have established a few characteristics of the gas to utilise with the gas laws:

```
R = 287;    % [J/kg.K] individual Gas constant for air
cv = 718;   % [J/kg.K] specific heat capacity at constant volume for air
cp = 1003;  % [J/kg.K] specific heat capacity at constant pressure for air
```

Initial parameters of air bottle:

```
% initial parameters of air bottle:
p_B = 2 * 10^5;  % pressure in the bottle [Pa]
T_B = T_amb;
V_B = 0.1;          % volume [m³]
A_B = 2;          % surface size of the bottle [m²]
m_B = p_B*V_B/(R*T_B);   % initial mass in the bottle
k = 50;   % heat transmition coefficient of the wall of the bottle
```

Initial air mass in the cylinder is calculated by:

- Equation: m1 = Pamb * (Vc+Vh) / (R*Tamb)

```
% Air mass in the cylinder:
m1 = p_amb*(Vc+Vh)/(R*T_amb);
```

Rate of change of temperature was calculated by energy conservation principles. We obtained an equation:

- Equation: dT / dt = (1 / m1. cv) * [-k * A * (Tb – T1) + m2 * (cp (T3 – Tb) + R * Tb)]

Where,
m1 = mass flow rate of air in bottle;
m2 = mass flow rate from compressor;
Tb = Temperature of air in bottle;
T1 = Ambient temperature;
T3 = Temperature of ai from compressor;
Cv = Specific heat capacity at constant volume of air
Cp = Specific heat capacity at constant pressure of air.

Here we can determine temperature and mass flow by using equation PV=mRT;

- Equation: dm/dT = RT/PV
- Equation: dP/dt = mRT/V

```
for i=1:60000
    if p_B(i) <= 15*10^5
    [p,V,Dm(i),T23] = CylinderProcess_function( f , p_amb , p_B(i) , DeliveryValve , IntakeValve , Vc , A , H , PushRodRatio , PolyExp , m1 , T_amb );
    m_flow = Dm(i)/Dt;   % mass flow form compressor to bottle
    dmB_dt = m_flow;
    dTB_dt = (-k*A_B*(T_B(i) - T_amb) + m_flow*(cp*(T23 - T_B(i)) + R*T_B(i)))/(m_B(i)*cv);
    T_B(i+1) = T_B(i) + dTB_dt*Dt;
    m_B(i+1) = m_B(i) + dmB_dt*Dt;
    p_B(i+1) = R*m_B(i+1)*T_B(i+1)/V_B;
    t(i+1) = t(i) + Dt;
    else
        break
    end

end
```

By running this code, we will get following outputs:

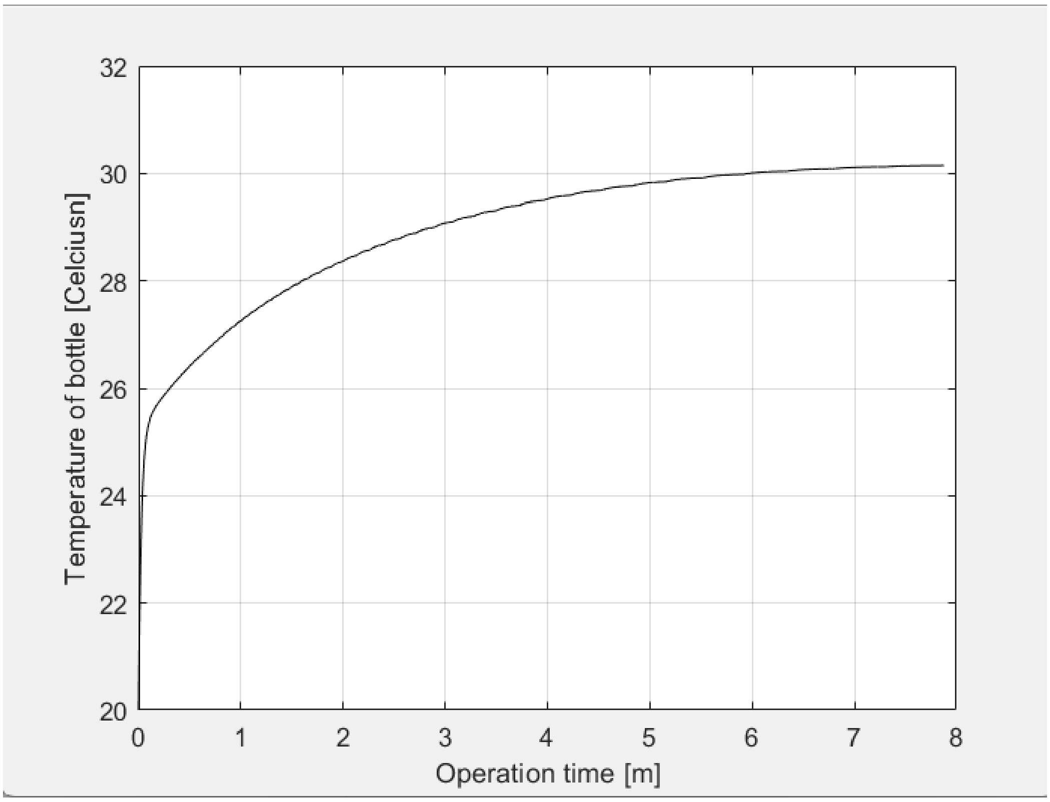


Figure: Tempreture Vs Time

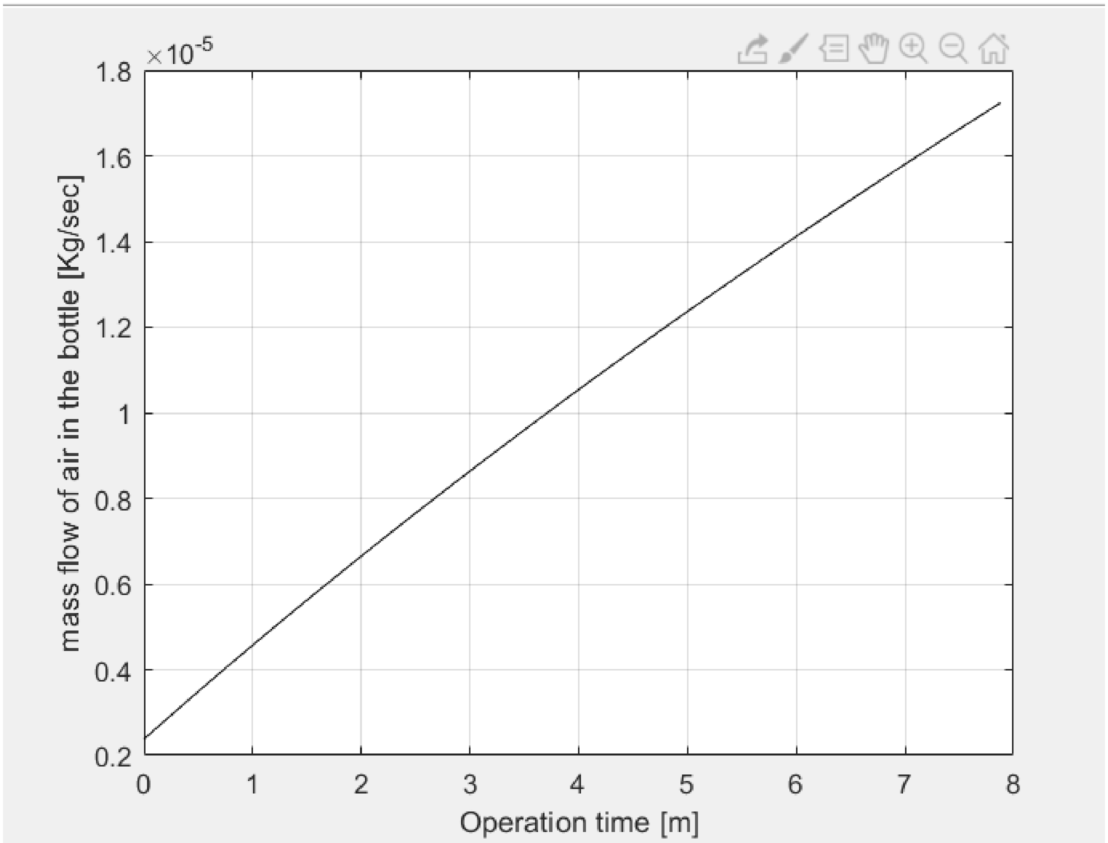


Figure: Mass Flow Vs Time

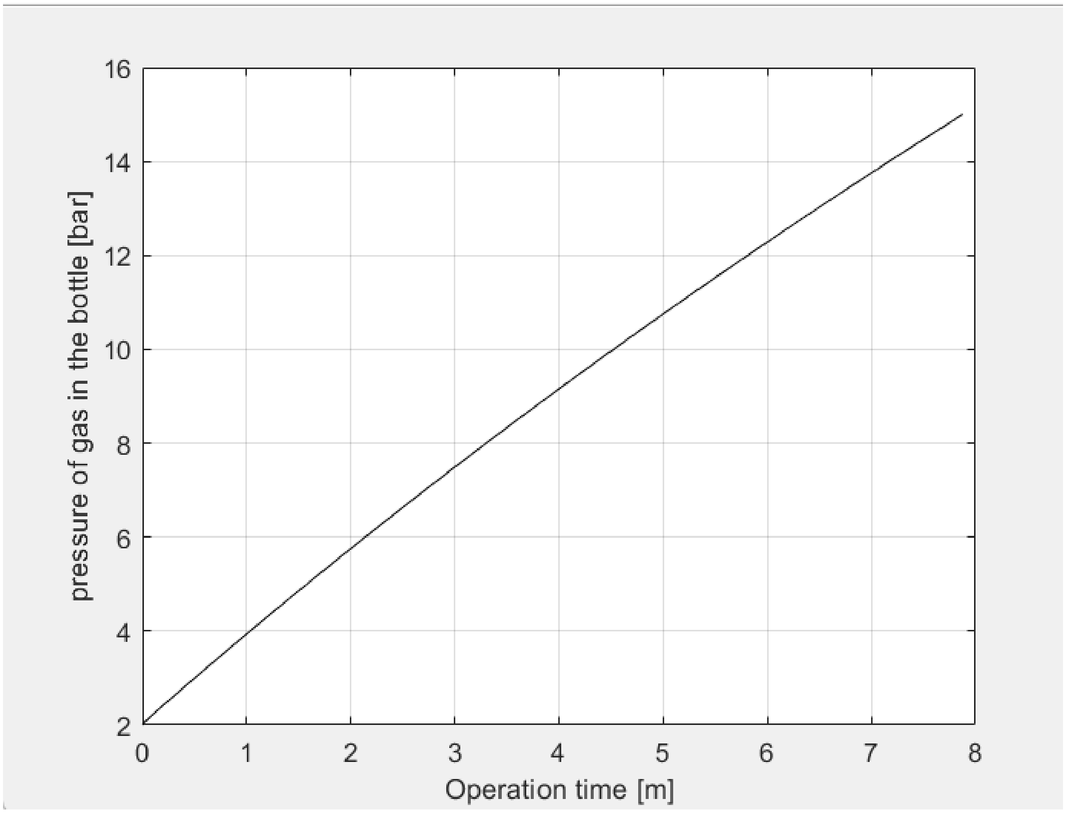


Figure: Pressure Vs Time

7. WORK DONE IN A SINGLE STAGE RECIPROCATING COMPRESSOR WITH CLEARANCE VOLUME:

Considering clearance volume: With clearance volume the cycle is represented on Figure. The work done for compression of air polytropically can be given by the are a enclosed in cycle 1-2-3-4.

Clearance volume in compressors varies from 1.5% to 35% depending upon type of compressor.

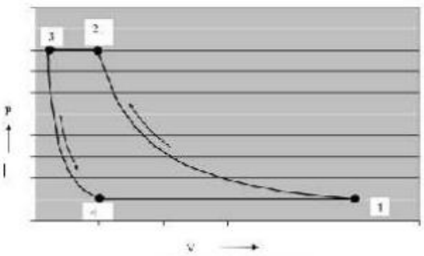


Fig1: PV Diagram

$W_{c,with\,CV}$ = Area 1234

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right] - \left(\frac{n}{n-1}\right)(p_4V_4)\left[\left(\frac{p_3}{p_4}\right)^{\frac{n-1}{n}} - 1\right]$$

Here $P_1 = P_4$, $P_2 = P_3$

$$= \left(\frac{n}{n-1}\right)(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right] - \left(\frac{n}{n-1}\right)(p_1V_4)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$$

$$= \left(\frac{n}{n-1}\right)(p_1)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right](V_1 - V_4)$$

In the cylinder of reciprocating compressor (V1-V4) shall be the actual volume of air delivered per cycle. Vd = V1 – V4. This (V1 – V4) is the volume of air in hated in the cycle and delivered subsequently.

$$W_{c,with\,CV} = \left(\frac{n}{n-1}\right)(p_1V_d)\left[\left(\frac{p_2}{p_1}\right)^{\left(\frac{n-1}{n}\right)} - 1\right]$$

During intake and air delivery the pressure will remained unchanged so we can take it constant.

Work done during Compression:

```
% first stage: 1 --> 2 Compression 1
p_12(1) = p_amb;   % pressure in the compressor
V_12(1) = V1(1);
Workdone_compression_12 = 0;
Total_work_1 = 0;
x = 0;
while p_12(end) <= p_B1
    p_12(i+1) = p_12(i) * (V1(i+1) / V1(i))^-Poly_n;
    V_12(i+1) = V1(i+1);
    Workdone_compression_12(i) =  (Poly_n)/(Poly_n - 1) * (V_12(i)) * p_12(i) *( ((p_12(i+1)/p_12(i))^((Poly_n - 1)/(Poly_n)))- 1 );


    Total_work_1 = Total_work_1 + Workdone_compression_12(i);

    figure(3); clf; hold on; grid on; box on;
    ylim([0 1000])
    xlim([-0.2 1.2])
    plot( f,  Total_work_1  , 'r.')
    ylabel('Instantenuous Work done')

    i = i + 1;
end
```

Work done during expansion:

```
% 3'rd stage: 3 --> 4 re-expansion 1
p_34(1) = p_23(end);
V_34(1) = V_23(end);
 Workdone_expansion_34 = 0;

while p_34(end) >= p_amb
    p_34(end+1) = p_34(end) * (V1(i+1) / V1(i))^-Poly_n;
    V_34(end+1) = V1(i+1);
    Workdone_expansion_34(i) =  (Poly_n)/(Poly_n - 1) * (V_34(end)) * p_34(end) *( ((p_34(end-1)/p_34(end))^((Poly_n - 1)/(Poly_n)))- 1 );
    Total_work_1 = Total_work_1 - Workdone_expansion_34(i);

    figure(3);clf; hold on; grid on; box on;
    plot( f ,  Total_work_1 , 'r.')

    ylabel('Instantenuous Work done')

    i=i+1;
end
```

The resulted graph is shown below.

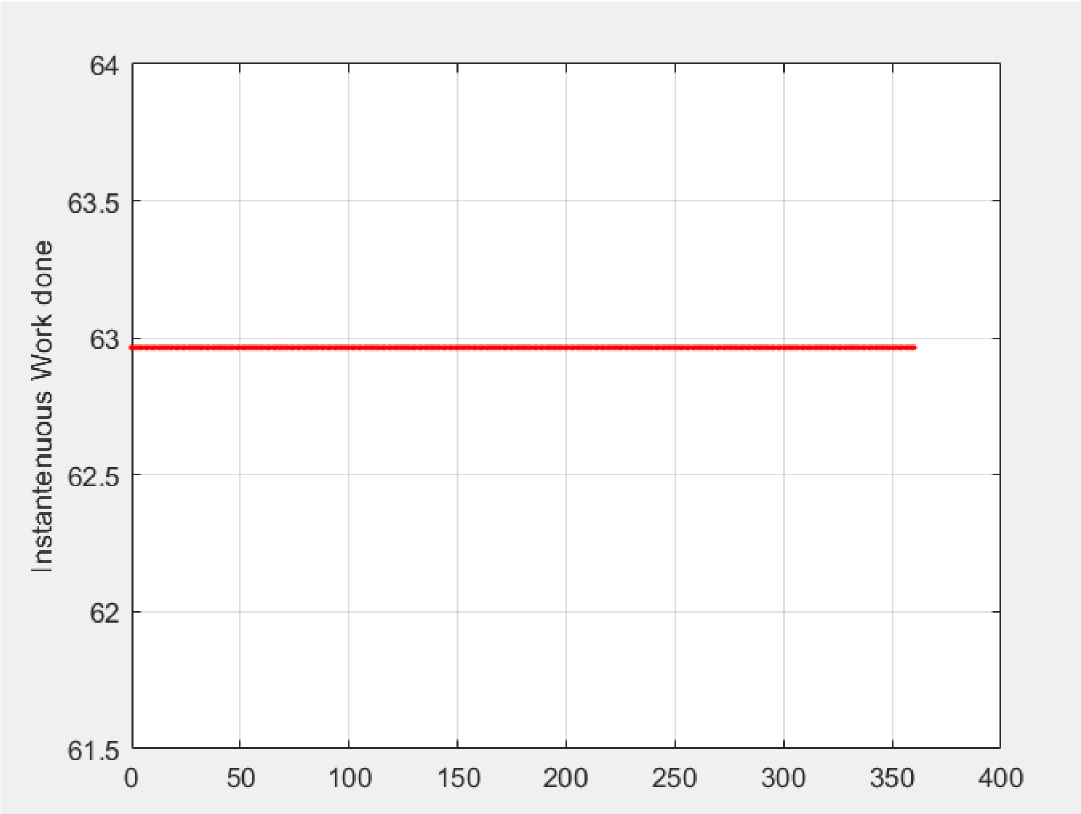


Figure: Total Work done

8. Findings:

- Hot air compressed from atmospheric temperature: Tamb = 20 C.
- Outlet Compressor Temperature = 321 C
- Over time, the rate of pressure increase in the bottle is reducing. The air bottle must be filled from 2 bar to 15 bar in a total of 7.86 minutes.
- The pace at which the mass flow tare in bottles is increasing is likewise declining over time. The mass flow rate was 1.72 * 10-5 Kg/sec at the final location.
- The temperature of the air within the bottle as it fills with compressed air. The thermometer shows a rise in temperature to 30.14 Celsius.
- Total Workdone = 62.96 KJ

9. Conclusion:

Utilising a single-stage compressor with a reciprocating compressor to pressurise the air is the major goal of the work

Our main objective is to learn the outcomes described in the aforementioned scope.

- temperature behavior with respect to pressure
- temperature rise in the air bottle vs. time
- mass flow of air in the air bottle vs. Time
- work done on the compressor

All the findings and diagram are displayed in the report.

Results with fitting diagrams:

The similarity between the obtained diagrams and the ideal diagrams indicates that the results are accurate. Additionally, air mass flow and pressure are rising steadily as expected and are both logically right. We get the same results while manually calculating the quantities with a calculator.

Comparison of findings with real data:

I used energy conservation equations to compare the data from the simulation to the analytical calculations. The exercise's findings are in line with the data from real time.

The air could not, however, be cooled to suction temperature due to real-world intercooler characteristics. Positively, data variation is significantly below the tolerance level.

The other figures are difficult to compare because they are always dependent on environmental factors such as circumstances, ambient temperatures, air bottle size, and more.

Benefits of using MATLAB:

Companies who seek to compute results and efficiency to make final judgements can benefit from the simulation. They can determine which compressor best suits their demands by comparing the values of single-stage, two-stage, and three-stage compressors.

Learnings:

I gained insight into the individual phases and operational methods of a compressor throughout the process. Small adjustments can have a significant effect on the entire system. Additionally, this system's advantage over the one-stage compressor, which has higher power, performance, and complexity, is readily apparent.

10. References:

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