FUEL-AIR CYCLE ANALYSIS
Introduction

- Ideal Gas Cycle (Air Standard Cycle)
  - Idealized processes
  - Idealize working Fluid

- Fuel-Air Cycle
  - Idealized Processes
  - Accurate Working Fluid Model

- Actual Engine Cycle
  - Accurate Models of Processes
  - Accurate Working Fluid Model
Contents

- Factors considered
  - Composition of cylinder Gases
  - Variable Specific Heat
  - Dissociation
  - Number of Moles
- Comparison with Air-Standard Cycle
- Effect of Operating Variables
  - Compression ratio
  - Fuel-Air ratio
The theoretical cycle based on the actual properties of the cylinder contents is called the fuel – air cycle.

- The fuel – air cycle take into consideration the following:

1. The actual composition of the cylinder contents.
2. The variation in the specific heat of the gases in the cylinder.
3. The dissociation effect.
4. The variation in the number of moles present in the cylinder as the pressure and temperature change.
Fuel-Air Cycle contd

5. Compression & expansion processes are frictionless

6. No chemical changes in either fuel or air prior to combustion.

7. Combustion takes place instantaneously at top dead center.

8. All processes are adiabatic.

9. The fuel is mixed well with air.

10. Subsequent to combustion, the change is always in chemical equilibrium.
Composition of Cylinder Gases

1. The actual composition of the cylinder contents are
   - (Fuel + Air + Water vapor + residual gas)
   - The fuel air ratio changes during the engine operation
     - The change in air-fuel ratio affects the composition of gases before and after combustion particularly the percentage of \( \text{CO}_2, \text{CO}, \text{H}_2\text{O} \) etc. in the exhaust gas.
   - The amount of exhaust gases in the clearance volume various with speed and load on the engine.
     - The fresh charge composition varies its composition because when it enters in the cylinder comes in contact with the burnt gases.
## Composition of Cylinder Gases

The composition of the working fluid, which changes during the engine operating cycle, is indicated in the following table.

<table>
<thead>
<tr>
<th>Process</th>
<th>SI Engine</th>
<th>CI Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intake</td>
<td>Air, <strong>Fuel</strong>, Recycled exhaust &amp; Residual gas</td>
<td>Air, Recycled exhaust &amp; Residual gas</td>
</tr>
<tr>
<td>Compression</td>
<td>Air, <strong>Fuel</strong> Vapor, Recycled exhaust &amp; Residual gas</td>
<td>Air, Recycled exhaust &amp; Residual gas</td>
</tr>
<tr>
<td>Expansion</td>
<td>Composition products (CO₂, CO, H₂, O₂, NO, OH, O, H,...)</td>
<td>Composition products (CO₂, CO, H₂, O₂, NO, N₂, OH, H₂O, O, H,...)</td>
</tr>
<tr>
<td>Exhaust</td>
<td>Composition products (mainly N₂, CO₂, H₂O) If Φ&lt;1 O₂ or If Φ&gt;1 CO &amp; H₂</td>
<td>Composition products (mainly N₂, CO₂, H₂O &amp; O₂)</td>
</tr>
</tbody>
</table>
The effect of cylinder composition on the performance of the engine can easily computed by means of suitable numerical techniques.

The computer analysis can produce fast and accurate results.

Thus, fuel-air analysis can be done more easily through computer rather than manual calculations.
2. The variation of specific heat with temperature

- All gases except mono-atomic gases, show an increase in specific heat with temperature.

- The increase in specific heat does not follow any particular law.

- However between the temperature range 300 K – 1500 K the specific heat curve is nearly a straight line which may be approximately expressed in form

\[
C_P = a_1 + K_1 T \\
C_V = b_1 + K_1 T
\]

- Where \(a_1\), \(b_1\), and \(k_1\) are constants

- The gas constant \(R = C_P - C_V = a_1 - b_1\)
Above 1500 K the specific heat increases is much more rapid and may be expressed in the form

\[ C_P = a_1 + K_1T + K_2T^2 \]
\[ C_V = b_1 + K_1T + K_2T^2 \]

Since the difference between \( C_P \) & \( C_V \) is constant, the value of \( k \) decreases with increase in temperature.

\[ K = \frac{C_P}{C_V} = \frac{R + C_V}{C_V} = 1 + \frac{R}{C_V} \]

Thus, if the variation of specific heats is taken into account during the compression stroke, the final temperature and pressure would be lower compared to the value obtained at constant specific heat.
Loss Due to Variable Specific Heats

- The magnitude of drop of temperature at the end of compression is proportional to the drop in values of ratio of specific heats.

  - For process 1-2
    - With constant specific heat
      \[ T_2 = T_1 \left( \frac{v_1}{v_2} \right)^{k-1} \]
    - With variable specific heat
      \[ T'_{2'} = T_1 \left( \frac{v_1}{v_2} \right)^{k-1} \]

  Where
  \[ k = \frac{C_p}{C_v}, \quad v_{2'} = v_2, \quad \left( \frac{v_1}{v_2} \right) = \left( \frac{v_1}{v_{2'}} \right) = r \]
Process 2-3

Constant volume combustion (Heat addition), from point 2’ will give a temperature $T_3'$, with the variation in specific heat, instead of $T_3$.

Q: Why?

A:

\[
m_f Q_{HV} = C_V (T_3 - T_2) = C_{V'} (T_{3'} - T_{2'})
\]

1. $T_{2'} < T_2$  
   \[ \Rightarrow T_{3'} < T_3 \]

2. $C_{V'} > C_V$  

Loss Due to Variable Specific Heats
For the expansion Process

- For process 3’-4” (Con S.H from point 3’)

\[ T_{4''} = T_{3'} \left( \frac{v_3}{v_{4''}} \right)^{k-1} \]

- For the process 3’-4’ (with variable S.H)

\[ T_{4'} = T_{3'} \left( \frac{v_3}{v_{4'}} \right)^{k-1} \]

Q. Why is \( T_{4'} > T_{4''} \)?

A: Because specific heat ratio increase with decrease in temperature.
3. The effect of dissociation

- Dissociation is the disintegration of combustion products, at high temperature above 1600 K

- Dissociation is the reverse process to combustion

- Dissociation is the heat absorption (endothermic process)

- Combustion is heat liberation (Exothermic process)

- In IC engine, mainly dissociation of CO$_2$ and little dissociation of H$_2$O
The dissociation of CO$_2$ in to CO and O$_2$ starts commencing around 1000 °C

$$2CO_2 \rightarrow 2CO + O_2 + \text{Heat}$$

The dissociation of H$_2$O occurs at temperature above 1300 °C

$$2H_2O \rightarrow 2H_2 + O_2 + \text{Heat}$$

The presence of CO and O$_2$ in the gases tends to prevent dissociation of CO$_2$; this is noticeable in a rich fuel mixture which by producing more CO, suppresses dissociation of CO$_2$
Dissociation

- There is no dissociation in the burnt gases of a lean fuel-air mixture.

- This mainly due to the fact that the temperature produced is too low for this phenomenon to occur.

- The maximum dissociation occurs in the burnt gases of the chemically correct fuel-air mixture when the temperature are expected to be high but decreases with the leaner and richer mixtures.
The Effect of Dissociation

On Exhaust Gas Temperature, Fig below shows the reduction in the temperature of the exhaust gas mixtures due to dissociation w.r.t air-fuel ratio

- With no dissociation maximum temperature is attained @ chemically correct A-F ratio

- With dissociation maximum temp is obtained when mixture is slightly rich
The Effect of Dissociation

- On Power output, If there is no dissociation
  - The Brake power output is max @ stoichiometric mix

- If there is dissociation
  - The Brake Power is Max @ slightly Rich Mixture

- The shaded area shows the loss of power due to dissociation
The Effect of Dissociation

- Dissociation effect are not pronounced in CI engine as in an SI engine. This is mainly due to
  - The presence of a heterogeneous mixture and
  - Excess air to ensure complete combustion

- Both these factors tend to reduce the peak gas temperature attained in CI engine
The Effect of Dissociation

- On the p-v diagram of Otto Cycle
  - Because of lower maximum temperature due to dissociation, the maximum pressure is also reduced and state after combustion will be replaced by 3’ instead of 3.
  - If there was no re-association due to fall of temp during Exp proc.
    - It would be represented by 3’ → 4’
  - If there is re-association
    - the Expansion follows the path 3’ → 4’
The number of molecules in the cylinder varies as the pressure and temperature change.

The number of molecule presented after combustion depend upon:
- Fuel-Air ratio
- Pressure and temperature \( (PV=nRT) \)

The number of mole does a direct effect on the amount of work that the cylinder gas impact on the piston.
Comparison of Air-Standard & Fuel-Air cycles

- By Air standard cycle analysis, it is understood how the efficiency is improved by increasing the compression ratio.

- Air standard cycle analysis do not consider the effect of Fuel-Air ratio on the thermal efficiency because the working medium was assumed to be air.

- In general, fuel-air cycle analysis is used to study:
  - The effect of fuel-air ratio on engine thermal efficiency
  - How the peak pressure and temperature during the cycle varying and its influence on many engine operating variables.
Fuel-Air cycle analysis suggest that the thermal efficiency will **deteriorate** as the mixture supplied to the engine is enriched.

Because of :-

- Increasing losses **due to variable specific heats**
- Enrichment **beyond** the chemically correct ratio will lead to incomplete combustion **and loss in thermal efficiency**
Comparison of Air-Standard & Fuel-Air cycles

- Thermal efficiency will increase as the mixture is made leaner.

- Beyond a certain leaning, the combustion become erratic with loss of efficiency.

- In general the maximum efficiency is within the lean zone very near the stoichiometric ratio.
Effect of Operating variables

- The effect of the common engine operating variables on the thermal efficiency, pressure and temperature within the engine cylinder is better understood by fuel-air cycle analysis.

- The major operating variables
  - Compression ratio
  - Equivalence ratio
Fuel air otto cycle model for different equivalent ration and compression ratio

Results obtained using the Furl-air Otto cycle model for different equivalence ratios and different compression ratios are shown in the following figures:
Effect of Compression Ratio

- The fuel-air cycle efficiency increases with the compression ratio in the same manner as the air-standard cycle efficiency, principally for the same reason, due to more scope of the expansion work.

- The indicated thermal efficiency increases with lean mixtures and compression ratios.
Effect of Compression Ratio

- The variation of indicated thermal efficiency with respect to equivalence ratio for various compression ratios.

Table 3.2. Effect of different compression ratios and fuel-air ratios on thermal efficiency in Otto cycle

<table>
<thead>
<tr>
<th>Compression ratio</th>
<th>Air cycle efficiency $\eta_i$</th>
<th>Fuel-air cycle efficiency at $F_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td>7.0</td>
<td>0.540</td>
<td>0.448</td>
</tr>
<tr>
<td>8.0</td>
<td>0.565</td>
<td>0.470</td>
</tr>
<tr>
<td>9.0</td>
<td>0.585</td>
<td>0.488</td>
</tr>
<tr>
<td>10.0</td>
<td>0.602</td>
<td>0.503</td>
</tr>
<tr>
<td>11.0</td>
<td>0.617</td>
<td>0.517</td>
</tr>
<tr>
<td>12.0</td>
<td>0.630</td>
<td>0.530</td>
</tr>
</tbody>
</table>
As the mixture is made lean the temperature rise due to combustion will be not be significant as a result.

- The specific heat is lowered.
- It decreases the losses due to dissociation.

The thermal efficiency therefore, higher and, in fact, approaches the air-cycle efficiency as the fuel-air ratio is reduced.
Effect of Fuel-Air Ratio

- Effect of equivalence ratio (mixture strength) on thermal efficiency.
Effect of Fuel-Air Ratio

- **Maximum Power**

  Fuel-air ratio affects the maximum power of the engine. The variation is as shown in Figure, as the mixture becomes richer, after a certain point both efficiency and power output falls as can be seen from the experimental curve. This is because in addition to higher specific heats and chemical equilibrium losses, there is insufficient air which will result in formation of CO and H₂ during combustion, which represents direct wastage of fuel.
Effect of Fuel-Air Ratio

- Maximum Temperature

- At a given compression ratio the temperature after combustion reaches a maximum when the mixture is slightly rich ($FIA = 0.072$ or $AlF = 14 : 1$)

- At chemically correct ratio there is still some oxygen present because of chemical equilibrium effect a rich mixture will cause more fuel to combine with oxygen at the point thereby raising the temperature $T_3$.

- However, at richer mixtures increased formation of CO counters this effect.
Effect of Fuel-Air Ratio

- **Maximum Pressure**
  - Pressure of a gas in a given space depends upon its *temperature* and the number of molecules: \( PV = nRT \)
  
  - The curve of \( P_3 \), therefore follows \( T_3 \), but because of the increasing number of molecules, \( P_3 \) does not start to decrease until the mixture is somewhat richer than that the maximum \( T_3 \) (at \( FIA = 0.083 \) or \( A/I F 12 : 1 \)), i.e. about 20 percent rich
**Effect of Fuel-Air Ratio**

- **Exhaust gas temperature**
  - The behavior of $T_4$ with compression ratio is different from that of $T_3$.
  - Unlike $T_3$, the exhaust gas temperature $T_4$ is lower at high compression ratios, because the increased expansion causes the gas to do more work and less heat to be rejected at the end of the stroke.
  - The same effect is present in the case of air-cycle analysis also
Mean Effective Pressure (MEP)

- The MEP increases with compression ratio.
- MEP follows the trend of $P_3$ and $P_4$ and hence it is maximum at a fuel-air ratio slightly richer than the chemically correct ratio as shown in Figure.
Fuel air otto cycle model for different equivalent ratio and compression ratio

- Indicated mean effective pressure increases with increasing compression ratio, is maximized slightly rich of stoichiometric, and increases linearly with the initial density (i.e., $\text{imep} \sim P_1$ and $\text{imep} \sim 1/T_1$)

- For a given compression ratio, the peak pressure is proportional to the indicated mean effective pressure.

- Pick temperatures in the cycles are largest for equivalence ratios slightly rich of stoichiometric.
Effect of *Fuel Type vs imep* on Otto Fuel-Air Cycle

- Note that nitromethane is an excellent choice for racing fuel, as it has the largest imep of the fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Chemical Formula</th>
<th>$r$</th>
<th>$\eta_i$</th>
<th>imep (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>C$<em>7$H$</em>{12}$</td>
<td>10</td>
<td>0.44</td>
<td>13.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.495</td>
<td>14.4</td>
</tr>
<tr>
<td>Diesel</td>
<td>C$<em>{14}$H$</em>{24}$</td>
<td>10</td>
<td>0.44</td>
<td>13.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.495</td>
<td>14.9</td>
</tr>
<tr>
<td>Methane</td>
<td>CH$_4$</td>
<td>10</td>
<td>0.44</td>
<td>12.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.496</td>
<td>13.1</td>
</tr>
<tr>
<td>Methanol</td>
<td>CH$_3$OH</td>
<td>10</td>
<td>0.43</td>
<td>13.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.48</td>
<td>14.2</td>
</tr>
<tr>
<td>Nitromethane</td>
<td>CH$_3$NO$_2$</td>
<td>10</td>
<td>0.39</td>
<td>21.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>0.43</td>
<td>23.1</td>
</tr>
</tbody>
</table>

$^1$ $\phi = 1.0, f = 0.10, P_1 = 1.0$ bar, $T_i = 350$ K.
Effect of residual fraction on Otto fuel air characteristics

Notice that $\text{imep}$ falls with increasing $f$; it falls because the residual gas displaces fuel-air and because it warms the fuel-air, thereby reducing the charge density.