APPLIED THERMODYNAMICS

Internal Combustion Engines
(Module III)

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List of Topics

1. Internal Combustion Engine – Components, Nomenclature and Classifications
2. Basic Engine Cycle and Engine Kinematic Analysis
3. Engine Operating Characteristics
4. Thermodynamic Analysis of Air Standard Cycles
5. Valve Timing Diagram and Fuel – Air Cycle
6. Thermochemistry and Fuel Characteristics
7. Combustion Phenomena in Engines
8. Heat Transfer Analysis in Engines
9. Exergy Analysis and Engine Emission/Pollution

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Lecture 9

Exergy Analysis and Engine Emission/Pollution

- Evaluation of Exergy for Engine
- Engine Emissions and Pollution
  - Hydrocarbon
  - Carbon monoxide
  - Oxides of Nitrogen
  - Solid particulates
  - Emission index

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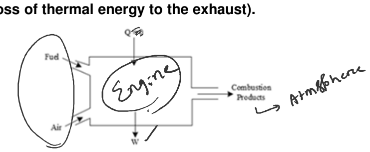
Evaluation of Exergy for Engines

- Estimation of available energy determines the maximum possible performance of a thermodynamic system. In addition, impact of process change in the system in terms of losses is also assessed.
- The exergy analysis provides the knowledge of how the available energy is lost or destroyed in the engine system. These findings help in reducing the exergy loss to improve the performance of an engine in terms of efficiency and power output.
- In an IC engine operation, exergy analysis reveals the capability of working medium to produce useful mechanical work in following two aspects:
  - Energy destroyed due to thermodynamic irreversibility (such as combustion, heat transfer, mixing, throttling, friction, etc)
  - Energy lost due to undesirable transfers (such as heat transfer to the cylinder walls and loss of thermal energy to the exhaust).



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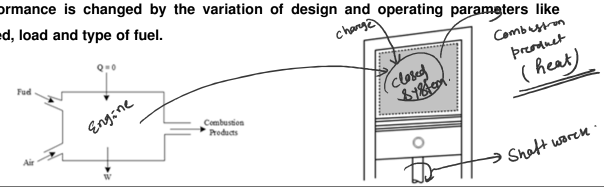
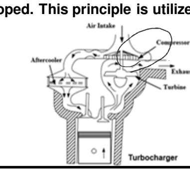
Evaluation of Exergy for Engines

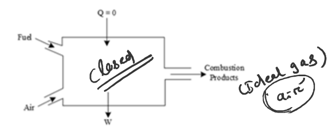
- The exergy analysis indicates various forms of energy that have different levels of ability to do useful mechanical work.
- In IC engines, the exergy input is contained as chemical exergy of the fuel converted into other forms:
  - ➢ Exergy transfer with shaft work output
  - ➢ Exergy transfer with cooling water
  - ➢ Exergy transfer with exhaust gas
  - ➢ Unaccounted exergy destructions (or irreversibility due to friction, radiation, heat transfer to surroundings, operating auxiliary equipment)
- These system loss data are used to develop an explanation of why engine performance is changed by the variation of design and operating parameters like speed, load and type of fuel.



Evaluation of Exergy for Engines

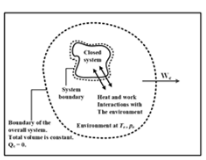
- "Exergy" is the maximum theoretical work obtainable from an overall system consisting of a system and the environment when the system comes to equilibrium with environment (as it passes to dead state).
- In IC engines, it is possible to quantify "exergy" from exhaust gases. The engineering model has the following assumptions:
  - ➢ The gaseous combustion products are a closed system.
  - ➢ The combustion products are modelled as air behaving as an ideal gas.
  - ➢ The effects of motion and gravity can be ignored.
  - ➢ The dead state of environment is fixed at atmospheric (300 K and 1.013 bar).
- If the gases are discharged directly to the surroundings, the potential for developing work (exergy), is wasted. By venting the gases through a turbine, some work could be developed. This principle is utilized by "turbocharger" added to IC engines.





Evaluation of Exergy for Engines

- The closed system plus the environment is referred as overall system.
- The boundary of the overall system is located so that there is no energy transfer as heat. Further, the boundary of overall system is so located that the total volume remains constant, even though the volumes of system and environment can vary.
- The exergy of a system (E) at a specified state can be written mathematically. Here, U, KE, PE, V and S denote, internal energy, kinetic energy, potential energy, volume and entropy at a specified state. The subscripts represent the system at dead state.
- When the system is at dead state, it is at rest relative to the environment and the values of kinetic and potential energies are zero ($KE_0=PE_0=0$).
- The unit of exergy is same as that of energy and it is an extensive property. Often it is convenient to use per unit mass, known as, 'specific exergy'.

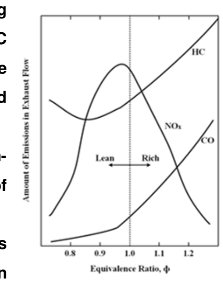


$$E=(U-U_0)+p_0(V-V_0)-T_0(S-S_0)+KE+PE$$

$$e=(u-u_0)+p_0(v-v_0)-T_0(s-s_0)+\frac{c^2}{2}+gz$$

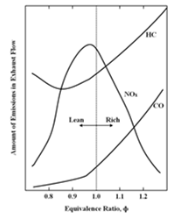
Engine Emissions and Air Pollution

- The undesirable emissions generated during combustion process of automobiles and IC engines pollute the environment and contribute to global warming, acid rain, smog, odors and respiratory/health issues.
- Major causes of the emissions are non-stoichiometric combustion, dissociation of nitrogen and impurities in fuel and air.
- The emissions of concern are, hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), Sulphur and solid particulates.



Engine Emissions and Air Pollution

- Emissions from an SI engine is a function of equivalence ratio.
- A fuel rich air-fuel ratio does not have enough oxygen to react with all the carbon and hydrogen, and both HC and CO emissions increase.
- HC emissions also increase at very lean mixtures due to poor combustion and misfires.
- The generation of Nitrogen oxide emissions is a function of the combustion temperature. It is greatest near stoichiometric conditions when temperatures are the highest.
- Peak NOx emissions occur at slightly lean conditions, where the combustion temperature is high and there is an excess of oxygen to react with the nitrogen.



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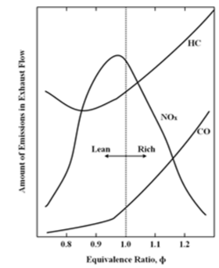
Engine Emissions and Pollution

Hydrocarbons (HC)

- The exhaust gases leaving the combustion chamber of SI engine contains about 6000ppm of HC components equivalent to 1-1.5% of fuel.
- About 40% of them are unburnt gasoline components and rest are partially reacted components (small non-equilibrium molecules formed when large molecules break due to thermal cracking during combustion).
- CI engines operate with overall fuel-lean equivalence ratio for which they have only one-fifth of HC emissions of SI engines.
- HC emissions into atmosphere, act as irritants, odorants and react with atmospheric gases to form photochemical smog.



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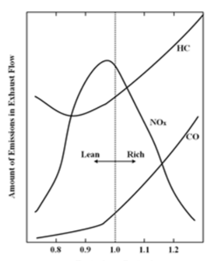
Engine Emissions and Pollution

Hydrocarbons (HC)

- The possible causes of HC emissions are as follows:
  - Non-stoichiometric air-fuel ratio
  - Incomplete combustion
  - Crevice volume (space around piston rings)
  - Leak past the exhaust valve
  - Valve overlap
  - Deposits on combustion chamber wall
  - Oil on combustion chamber wall



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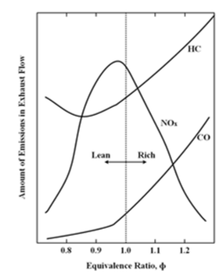
Engine Emissions and Pollution

Carbon monoxide (CO)

- CO is a colorless, odorless, but poisonous gas, generated from an engine when operated at fuel-rich equivalence ration, during starting and acceleration phase.
- When there is not enough oxygen to convert all carbon to CO_2, some fuel does not get burnt while some carbon ends of with CO.
- CO can be combusted to supply additional thermal energy.

  $[CO + (1/2)O_2 \rightarrow CO_2 + \text{heat}]$
- Typically, exhaust of an SI engine will have 0.2-5% CO while CI engines operate in overall lean manner with very less CO emissions.



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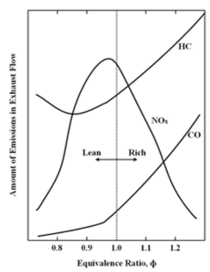
Engine Emissions and Pollution

Oxides of nitrogen (NOx)

- Exhaust gases of an engine can have up to 2000 ppm of oxides of nitrogen. Most of them are nitrogen oxide (NO) with small quantities of nitrogen dioxide (NO_2).
- In addition to air-fuel ratio, combustion time in the cylinder, instantaneous chemical reaction, the formation of NOx is highly dependent on temperature (2500-3000K) at which dissociation of nitrogen and oxygen could occur. There are many possible reactions that are possible cause for formation of NOx.



$O + N_2 \rightarrow NO + N$; $O_2 + N \rightarrow NO + O$; $N_2 \rightarrow 2N$;
$O_2 \rightarrow 2O$; $H_2O \rightarrow OH + (1/2)\ H_2$; $N + OH \rightarrow NO + H$;
$NO + O_2 \rightarrow NO_2 + O$; $NO + H_2O \rightarrow NO_2 + H_2$

2000 K
3000 K

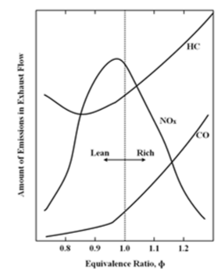
Engine Emissions and Pollution

Oxides of nitrogen (NOx)

- The maximum NOx is formed at a slightly lean equivalence ratio (0.95) at which the flame temperature is very high. The excess oxygen can combine nitrogen to form NOx.
- NOx released from exhaust react with atmospheric gases and becomes major cause for formation of petrochemical smog.

NO_2 + energy from sunlight $\rightarrow NO + O +$ smog;
$O + O_2 \rightarrow O_3$

- Monatomic oxygen is highly reactive and initiates many reaction. One of them is the ozone formation in the ground level which is harmful to lungs and biological tissues.



Engine Emissions and Pollution

Solid particulates

- The exhaust of CI engines contains solid carbon 'soot' particles that are generated in the fuel-rich zones within the cylinder during combustion.
- They are seen as heavy exhaust smoke emitted from truck, locomotives during acceleration uphill of from a stop.
- About 25% of carbon in the soot comes from lubricating oil components that vaporize and then react during combustion. The rest comes from fuel amounting 0.2-0.5% of fuel.
- Maximum density of particulates are seen when the engine is at wide-open-throttle (WOT).
- Soot particles are clusters of solid carbon spheres having diameters from 10 nm to 80 nm. A single soot particle can contain up to 4000 carbon spheres.

Engine Emissions and Pollution

Solid particulates

- Carbon spheres are generated in the combustion chamber in fuel-rich zones where there is not enough oxygen to convert all carbon to CO_2.
- As turbulence and mass motion continue to mix the components in the combustion chamber, most of these particles find sufficient oxygen to react for CO_2 formation.

$$C_xH_y + z\ O_2 \rightarrow a\ CO_2 + b\ H_2O + c\ CO + d\ C(s) \qquad C(s) + O_2 \rightarrow CO_2$$

$$C_x H_y + z\ O_2 + z\ (3.76)\ N_2 \rightarrow b\ CO_2 + c\ CO + d\ C(s) + e\ H_2O + z\ (3.76)\ N_2$$

$$x = b + c + d \qquad y = 2e \qquad z = b + 0.5\ c + 0.5\ e$$

- Particulate generation can be reduced by engine design and control of operating condition. Quite often, it creates other adverse result such as increase in NOx and HC.
- Engine management system are generally designed to minimize NOx, HC, CO and particulate by controlling ignition timing, injection pressure, injection timing and/or valve timing.

Engine Emissions and Pollution

Emission Index

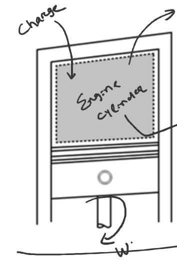
- There are four main exhaust emissions from the engine that should be controlled, namely, oxides of nitrogen (NOx), carbon monoxide (CO), hydrocarbons (HC) and solid particulates.
- The standard emissions norms have drive cycles that includes periods of acceleration, deceleration, steady state cruising and idling. The exhaust gases are continuously analyzed.
- The common methods for quantification of these emissions are, specific emissions [SE–(gm/kW-hr)] and emission index [EI–(gm/s)/(kg/s)].

$$(SE)_{NO_x} = \frac{\dot{m}_{NO_x}}{BP};\ (SE)_{CO} = \frac{\dot{m}_{CO}}{BP};\ (SE)_{HC} = \frac{\dot{m}_{HC}}{BP};\ (SE)_{part} = \frac{\dot{m}_{part}}{BP}$$

$$(EI)_{NO_x} = \frac{\dot{m}_{NO_x}}{\dot{m}_f};\ (EI)_{CO} = \frac{\dot{m}_{CO}}{\dot{m}_f};\ (EI)_{HC} = \frac{\dot{m}_{HC}}{\dot{m}_f};\ (EI)_{part} = \frac{\dot{m}_{part}}{\dot{m}_f}$$

Numerical Problems

Q1. The cylinder of an IC engine contains gaseous combustion products at 7 bar and 847°C just before the opening of exhaust valve. Determine the specific exergy of the gas.



Soln

→ Closed system
→ Comb. products behave as ideal gas (air)
→ No change in KE & PE
→ Dead state. (p_0 = 1.013 bar, T_0 = 300 K)

p = 7 bar
T = 847°C = 1120°C

Specific exergy,

$$e = (u-u_0) + p_0(v-v_0) - T_0(s-s_0) + \cancel{KE}^{\,0} + \cancel{PE}^{\,0}$$

$u - u_0$ = 648.8 kJ/kg.

$p(v-v_0)$

$= \frac{\bar{R}}{M}\left(\frac{p_0 T}{p} - T_0\right)$ $\quad v = \left(\frac{\bar{R}}{M}\right)\frac{T}{p}$ $\quad v_0 = \frac{\bar{R}}{M}\left(T_0/p_0\right)$

$\Rightarrow p(v-v_0) = -39.6$ kJ/kg.

$(s-s_0) = \left[s(T) - s(T_0) - \frac{\bar{R}}{M}\ln(p/p_0)\right]$

$(s-s_0) = 0.84$ kJ/kg.K.

Data table

T(K)	u(kJ/kg.K)	s(kJ/kg.K)
300	214	1.7
1120K	862.8	3.09

$\bar{R}$ = 8.314 kJ/kg.K

M = 28.97.

$e = 648.8 - 39.6 - (300)(0.84)$

e = 357.2 kJ/kg

Numerical Problems

Q2. A twelve-cylinder, two-stroke CI engine operates at 550rpm to produce brake power 2450kW by using stoichiometric light diesel fuel. The engine has a bore of 240mm and stroke of 320mm with volumetric and combustion efficiency of 98%. Calculate, (i) mass flow rate fuel into the engine; (ii) specific emission of hydrocarbons due to unburnt fuel; (iii) emission index of hydrocarbons due to unburnt fuel.

B = 240 mm = 0.24 m
S = 320 mm. = 0.32 m.
K = 12
η_v = 0.98. N = 550 rpm.
n = 2

Soln

$\dot{m}_a = \frac{\eta_v \rho_a V_d N}{n}$.

$V_d = (K)(\frac{\pi}{4} B^2 S)$

$\Rightarrow V_d = 0.1737\ m^3$.

ρ_a = 1.18 kg/m³.

$\Rightarrow \dot{m}_a$ = 0.92 kg/s.

$\dot{m}_f = \frac{0.92}{AF} = \frac{0.92}{14.6}$

(i) $\Rightarrow \dot{m}_f$ = 0.0634 kg/s.

(ii) $\dot{m}_{unburnt} = (1-\eta_c)\dot{m}_f = (1-0.98) \times 0.0634 = 1.27$ gm/s.

$(SE)_{HC} = \frac{\dot{m}_{unburnt}}{W_b} = \frac{1.27 \frac{gm}{s}\ 3600\left(\frac{s}{hr}\right)}{2450} = 1.86$ gm/kW Hr

(iii) $(EI)_{HC} = \frac{\dot{m}_{unburnt}}{\dot{m}_f} = \frac{1.27\ (gm/s)}{0.0634\ (kg/s)} = 20\ \frac{gm/s}{kg/s}$.

THANK YOU