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

Lecture 8

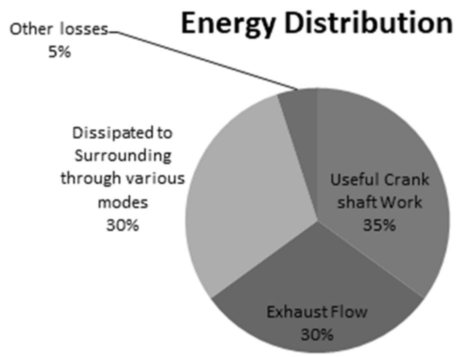
Heat Transfer Analysis on Engines

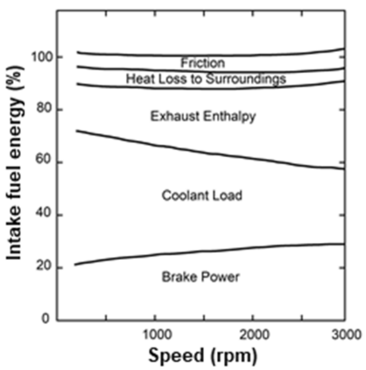
- **Energy Distribution and Engine Temperatures**
- **Hear Transfer in Intake System**
- **Heat Transfer in Combustion Chambers**
- **Heat Transfer in Exhaust System**
- **Effects of Engine Operating Variables on Heat Transfer**
- **Adiabatic Engine**

Energy Distribution and Engine Temperatures

Energy distribution in engines

- **The heat transfer process is a very important topic for efficient operations in IC engines.**
- **As an estimate, about 35% of total chemical energy that enters the engine through fuel is converted to useful crankshaft work. Next, 30% of fuel energy is carried away from the engine in exhaust flow in the form of enthalpy and chemical energy. The remaining 30% of fuel energy is dissipated to surroundings in different modes of heat transfer.**
- **Hence, additional cooling mechanisms becomes a necessity.**





Energy Distribution and Engine Temperatures

Energy distribution in engines

- **The fuel flow rate is limited by the mass flow air needed to react with the fuel.**
- **The shaft power of CI engines is on higher side as compared to SI engine.**
- **A greater percentage of energy is lost in the exhaust of SI engines because of their higher exhaust temperature.**
- **Loss of exhaust energy has two parts: enthalpy (heat) and chemical energy. At full load, the engine runs with fuel-rich, thus chemical energy loss is about half of exhaust loss.**
- **At high load, the energy lost to coolant can amount to half of brake power output, the energy lost is about twice the brake power output at low load.**

Power avaialble for use in engine : $\dot{W} = \dot{m}_f Q_{hv}$; $\dot{m}_f$:fuel flow rate to engine, Q_{hv} :heating value of fuel

Brake Thermal Efficiency : $\eta_{BTE} = \dot{W}_b \big/ \left(\dot{m}_f Q_{hv}\, \eta_c\right)$; $\dot{W}_b$:brake power, η_c : combustion efficiency

For any engine, power generated : $P = \left(\dot{W}_{shaft} + \dot{W}_{acc} + \dot{W}_{friction}\right) + \dot{Q}_{exhaust} + \dot{Q}_{loss}$

$\dot{W}_{shaft}$:brake output power of the crankshaft $(\approx 25-40\%)$; $\dot{W}_{acc}$:power requirement for engine accessories $(\approx 10\%)$

$\dot{W}_{friction}$:friction power losses in engines $(\approx 10\%)$; $\dot{Q}_{exhaust}$:energy lost in exhaust flow $(\approx 20-45\%)$

$\dot{Q}_{loss}$:energy lost to surroundings by heat transfer $(\approx 10-35\%)$; $\dot{Q}_{loss} = \dot{Q}_{coolant} + \dot{Q}_{oil} + \dot{Q}_{ambient}$

$\dot{Q}_{coolant} \approx 10-30\%$; $\dot{Q}_{oil} \approx 5-15\%$; $\dot{Q}_{ambient} \approx 2-10\%$

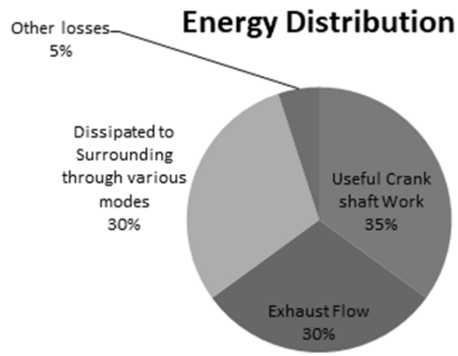
Energy Audit

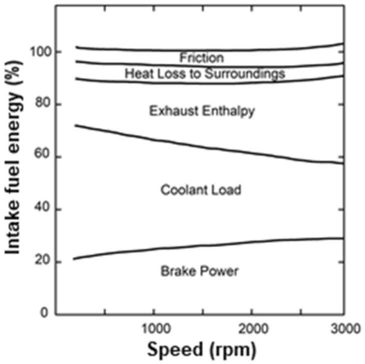
Energy Balance eqn.

Energy Distribution and Engine Temperatures

Energy distribution in engines

- **In order to reduce thermal endurance of engine materials subjected to high temperature, the heat must be continuously removed (specifically from combustion chamber) by employing suitable cooling system. On the other hand, the engine must operate as 'hot' as possible to maximize thermal efficiency.**
- **There are two general methods employed for this purposes: engine block is surrounded by water jackets with water as cooling fluid and typically known as "water cooled engine" (high CR diesel engine). The other category is air-cooled engine that has finned outer surface on the block over which flow of air is directed (mainly used in low CR petrol engines).**

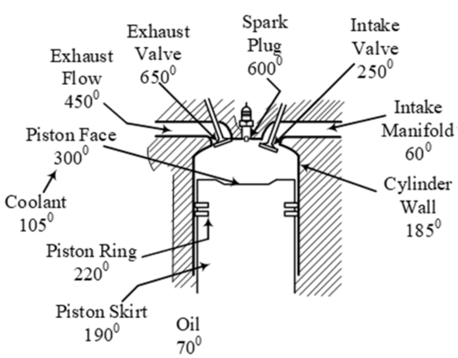


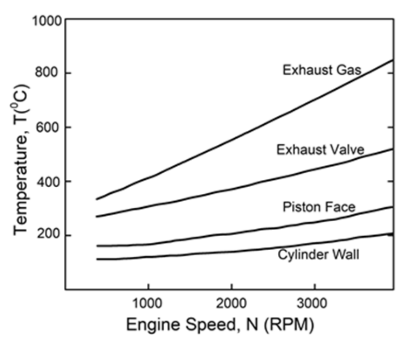


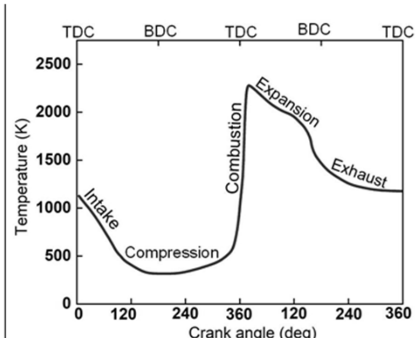
Energy Distribution and Engine Temperatures

Engine temperatures

- There are three hot-spot locations (spark plug, exhaust valve and port, face of the piston) in an engine.
- These places are exposed to high temperature combustion gases and they are difficult location to provide cooling arrangements.
- At normal steady-state operation, the typical temperature values are noted and they are function of engine speed.
- The gas temperature in the engine cylinder is almost lowest at the end of suction stroke and there is a steep rise in temperature at the end of combustion process. The peak temperature in the engine could be as high as 2500K.







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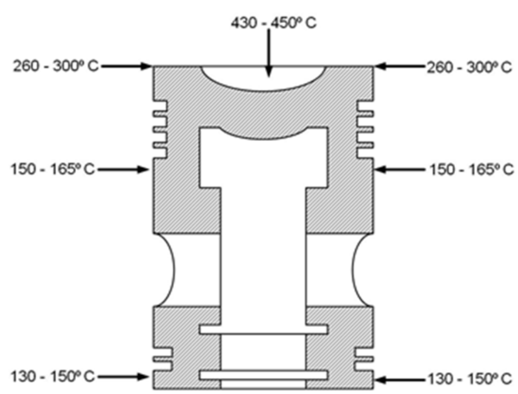
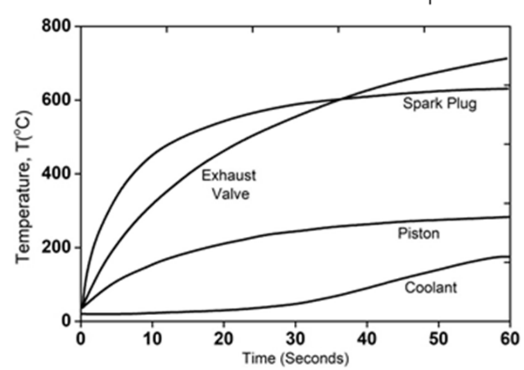
Energy Distribution and Engine Temperatures

Engine temperatures

- **The crown of the piston is exposed to a very high temperature with maximum temperature at center of the crown. The temperature decreases with increase in distance from the center with lowest value at bottom of the skirt.**
- **Thermal cracking could occur during over load operation due to excessive temperature difference between the piston crown and its outer edge.**
- **It is necessary to increase the thickness of the crown from center to the outer edge so as to have adequate cross-section available for increasing heat quantity.**



Piston temperatures



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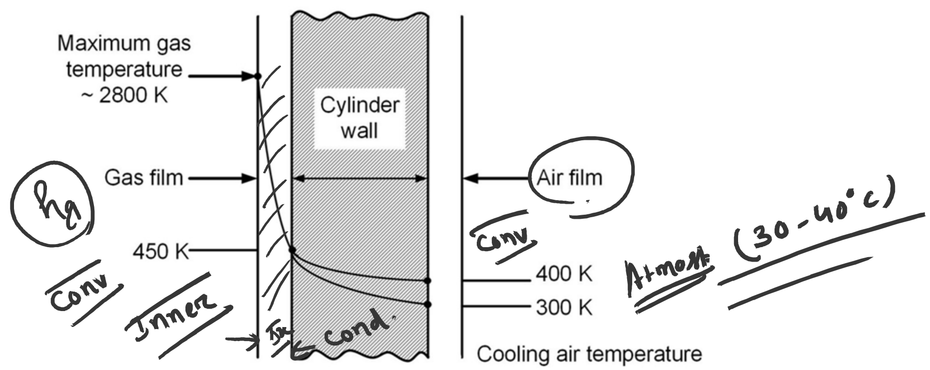
Energy Distribution and Engine Temperatures

Engine temperatures

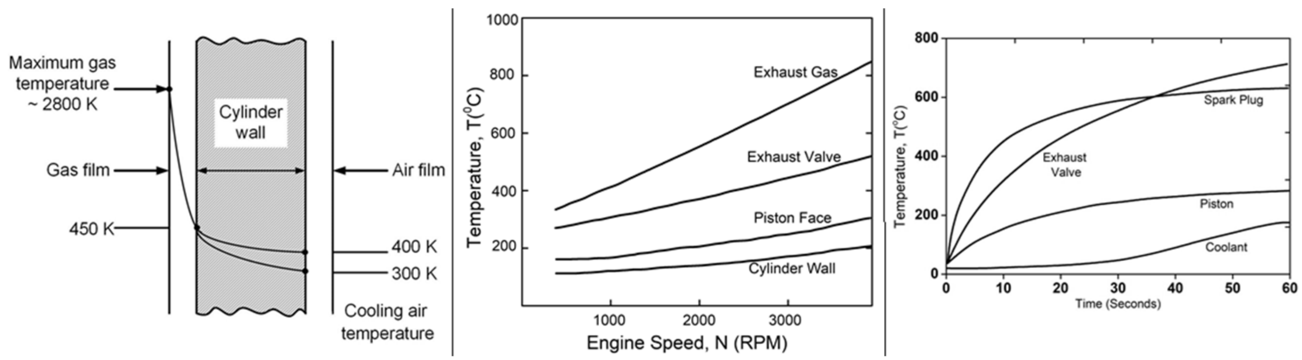
- **The moving gas in contact with cylinder wall forms a layer of stagnant gas layer, that acts as thermal insulator. The resistance of this layer to heat flow is very high.**
- **Heat transfer from the cylinder wall gases takes place through this layer followed by cylinder wall thickness and then to the cooling medium.**
- **The large temperature drop takes place within the gas film from peak temperature of 2800 K to about 450K.**
- **Heat is transferred from gases to the cylinder walls when the gas temperature is higher than the wall temperature.**



Energy Distribution and Engine Temperatures

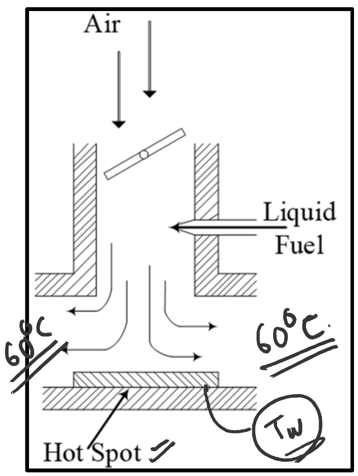
Engine temperatures

- **If no cooling is provided, there would be no heat flow so that cylinder temperature would reach to average temperature of the cylinder gas. With adequate cooling, the cylinder temperature can be maintained at optimum level.**
- **When a cold engine heats up to steady-state temperature, there will be thermal expansion in all components. The magnitude of the expansion is different for each engine component, depending on its temperature and materials. At operating temperatures, very high resulting forces between piston rings, skirt and engine walls, could cause high viscous heating of oil film.**



Heat Transfer in Intake Systems

- **The air-fuel mixture (SI engine) or only air (CI engine) enters the intake system and its temperature has to increase of the order of 60°C. Hence, the walls of intake manifold are hotter than flowing gases (heat transfer by convection).**
- **The hot spots in intake manifold (localized wall surface) accelerates fuel evaporation. They can be heated by conduction from exhaust manifold or by electrical heating.**
- **It is desired that engines should operate as 'hot as possible. So, the heated sections are placed close to fuel addition where high convection occurs. system**



$$\dot{Q} = h\,A\left(T_{wall} - T_{gas}\right);\quad T:\text{Temperature}$$

A : Inside surface area of intake manifold

h : Convection heat transfer coefficient

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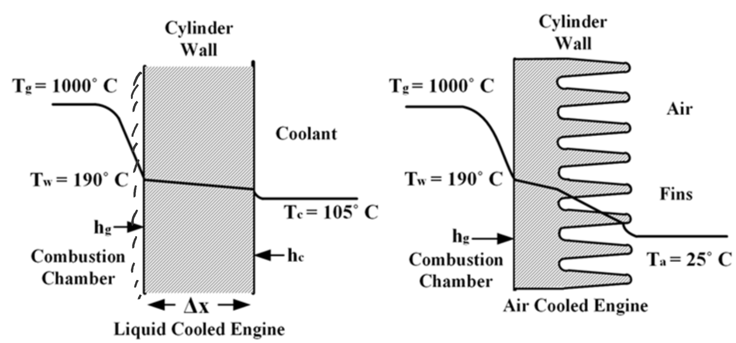
Heat Transfer in Intake Systems

- Typically, carbureted engines and throttle body injection introduce fuel early in the flow process in the intake heated manifold to assist early evaporation of fuel. Hence, there are localized hot surfaces (hot-spot region) in intake system.
- The convective heating in intake manifold allows early fuel vaporization with longer mixing with air for homogeneous mixture for SI engines.
- The preheating of air allows minimum temperature at the beginning of compression stroke in CI engine.
- Both effects avoid potential problem of engine knock because higher temperature at start of compression, eventually increases temperature in the rest of the cycle.
- The side-effect of intake heating, reduces volumetric efficiency of the engine because higher temperature reduces air density and vaporized fuel displaces some of the air. Thus, mass of air reaching the engine cylinder reduces.
- If an engine is supercharged or turbocharged, the temperature of inlet air is also affected by the compression heating. So, many of these systems are equipped with “after-cooling”.

Heat Transfer in Combustion Chambers

- **All three primary modes of heat transfer plays key role when the air-fuel mixture is in the engine cylinder for smooth steady-state operation.**
- **The temperature within the cylinders is affected by phase change i.e. evaporation of remaining liquid fuel.**
- **The air-fuel mixture entering the cylinder during intake stroke may be hotter/cooler than the cylinder wall resulting heat transfer in either direction.**
- **In compression stroke, there is "convective heat transfer" to cylinder wall, followed by combustion where peak temperature is of the order of 3000 K.**



Heat transfer through the combustion chamber cylinder wall of an IC engine

hot gas ↓ Coolant gas ↑

Convection Inner/Outer wall.

Conduction. (within wall & Fin)

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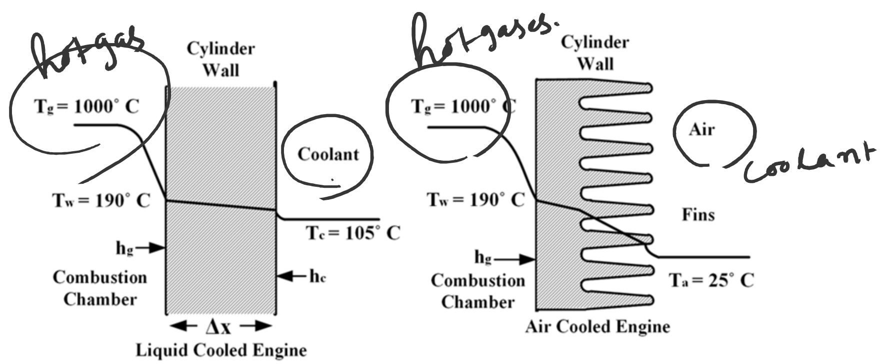
Heat Transfer in Combustion Chambers

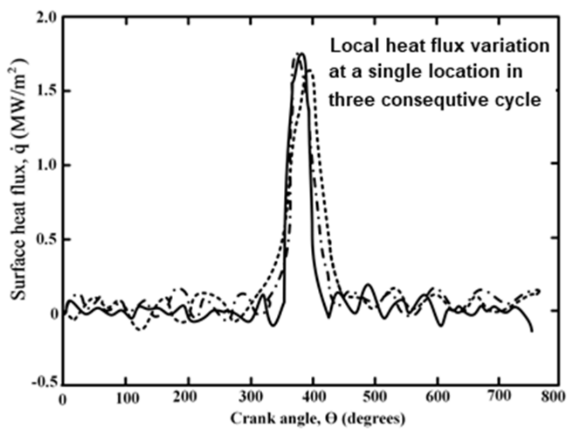
- "Convection and conduction" are dominant modes to extract heat from the combustion chamber for protecting cylinder walls from melting.
- The cylinder gas temperature and convection heat transfer coefficient varies largely over an engine cycle ranging from maximum value during combustion to minimum value during intake.
- The cylinder gas temperature and convection heat transfer coefficient vary over a large ranges of each engine cycle while the coolant temperature and heat transfer coefficient of coolant side is fairly constant. As a result, the heat conduction is cyclic for a small depth into cylinder wall on the combustion chamber side.

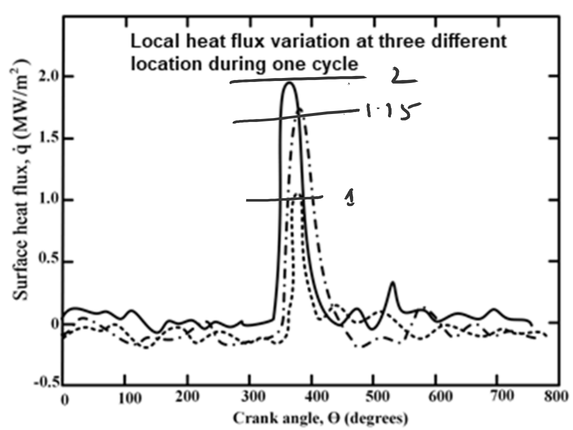


Heat transfer through the combustion chamber cylinder wall of an IC engine

Heat Transfer in Combustion Chambers

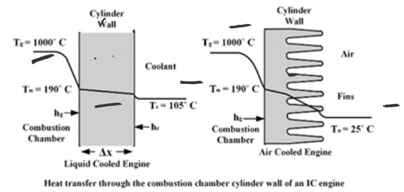
- The convection heat transfer coefficient on the cylinder gas side of the wall has large spatial variation and significant changes during an engine cycle due to gas motion, turbulence and swirl. The convection heat transfer coefficient on the coolant side of the wall is fairly constant.
- The thermal conductivity of the cylinder wall is a function of wall temperature and it is fairly constant within the working ranges.
- The coolant temperature is fairly constant over a longer cycle times.





Heact Transfer in Combustion Chambers

Heat transfer modelling: There are number of routes to identify Reynolds number for comparing flow characteristics and heat transfer in engines of different sizes, speeds and geometries. The Reynolds number and Nusselt number relation is one of the simple approach of forced convection heat transfer.



Heat transfer per unit surface area through the cylinder wall: $\dot{q} = \left(\frac{\dot{Q}}{A}\right) = \frac{\left(T_g - T_c\right)}{\left(1/h_g\right) + \left(\Delta x/k\right) + \left(1/h_c\right)}$

T_g :gas temperature in the combustion chamber; T_c :coolant temperature

h_g & h_c :convection heat transfer coefficient on gas side and coolant side

Δx : thickness of combustion chamber wall; k : thermal conductivity of cylinder wall

Convection heat transfer per unit surface area on the inside surface of cylinder wall: $\dot{q} = \left(\frac{\dot{Q}}{A}\right) = h_g\left(T_g - T_c\right)$

Conduction
Convection
Radiation.

Reynolds number : $\mathrm{Re} = \frac{\left(\dot{m}_a + \dot{m}_f\right)B}{A_p\,\mu_g}$; Nusselt number : $Nu = \frac{h_g B}{k_g} = C_1\left(\mathrm{Re}\right)^{c_2}$; C_1 & C_2 are constants

B : bore of the cylinder; A_p : area of piston face; μ_g :dynamic viscosity of the gas in the cylinder

$\dot{m}_a$ & $\dot{m}_f$:mass flow rate into the cylinder for air and fuel

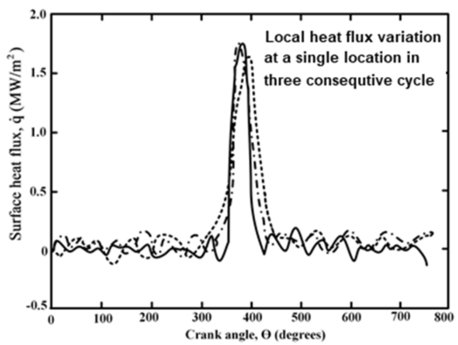
Radiation heat transfer per unit surface area between cylinder gas and combustion chamber wall:

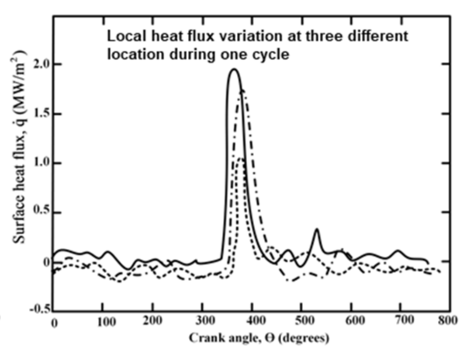
$$\dot{q} = \left(\frac{\dot{Q}}{A}\right) = \frac{\sigma\left(T_g^4 - T_w^4\right)}{\left(\frac{1-\varepsilon_g}{\varepsilon_g}\right) + \frac{1}{F_{1-2}} + \left(\frac{1-\varepsilon_w}{\varepsilon_w}\right)};$$ T_g & T_w : gas and wall tempartaure

σ : Stefan-Boltzmann constant; F_{1-2} : view factor between gas and wall; ε_g & ε_w :emissivity of gas and wall

Heat Transfer in Combustion Chambers

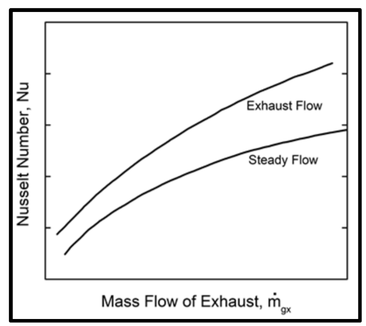
- **In SI engines, even through gas temperature is very high, the radiation to the walls amounts only about 10% of total heat transfer. It is mainly due to poor emissivity properties of gases that emit at specific wavelengths.**
- **For CI engines, radiation mode contributes about 20-35% of total heat transfer because the combustion products (mainly solid carbon soot particles) are good radiators at all wavelengths.**
- **A large percentage of radiation heat transfer to the walls occurs early in the power stroke. Instantaneous heat fluxes could be in the range of 2 MW/m² for SI engine and 10 MW/m² for CI engines.**





Heat Transfer in Exhaust System

- The heat losses in the exhaust system affect emissions and turbocharging.
- The flow in the exhaust pipe resembles pulsating cyclic flow. The Nusselt number is higher (about 1.5 to 2 times) the value which is predicted for same mass flow in the same pipe at steady flow conditions.
- The cyclic pulsing that occurs in exhaust increases the Nusselt number and convection heat transfer in exhaust pipe by a factor 1.5 over steady flow values.
- Pseudo-steady-state exhaust temperatures in SI engines are generally in the range of 400-600°C and can go as high as 300-900°C. For CI engines, it is lower (200-500°C) due to greater expansion ratio.
- Automobile engines and large stationary engines have exhaust valves with hollow stems containing sodium and they act as heat pipes for effective removal of heat from hot face area of valve through conduction.



Effect of Engine Operating Variables on Heat Transfer

The heat transfer within engines depends on many different variables. Hence, it is difficult to correlate one engine to another. Some are listed here:

- **Engine size**	- **Engine speed**	- **Engine load**
- **Spark timing**	- **Equivalence ratio**	- **Evaporative cooling**
- **Inlet air temperature**	- **Coolant temperature**	- **Engine material**
- **Compression ratio**	- **Knock**	- **Swirl and squish**

Engine size

- **When two geometrically similar engines of different sizes (displacements) run at same speed (with all other variables kept as close to same as possible), the larger engine will have greater absolute heat loss but more thermally efficient.**
- **The energy generated is proportional to cube of the length while heat losses goes up with square of length. Hence, a combustion chamber with high volume-to-surface area ratio is always desirable for good thermal efficiency. Due to this reason, modern overhead valve engine is more efficient than valve-in-block L-head engines.**

Effect of Engine Operating Variables on Heat Transfer

Engine speed

- **At higher engine speed, the gas velocity into/out of the engine increases, resulting rise in turbulence and convection heat transfer coefficient. Hence, the heat transfer occurring during intake, exhaust and early part of compression increases.**
- **During combustion and power stroke, the gas velocities within the cylinder is fairly independent of engine speed because they are mostly controlled by swirl, squish and combustion motion. Therefore, convection heat transfer coefficient is fairly independent of engine speed. Radiation which is important only during this portion of the cycle is also independent of speed.**
- **At higher engine speeds, there is less time per cycle. Combustion occurs at same engine rotation (burn angle) at all speeds. So, the time of combustion is less at higher speeds, i.e. less time for self-ignition and knock. Since, there is less time for heat transfer per cycle, the engine runs hotter. So, a hotter engine is a greater risk of knock.**
- **A part of exhaust blowdown process, will have sonic velocity through exhaust valve and the flow rate is choked. This process becomes independent of engine speed. But, when the engine speed is higher, blowdown process lasts over a larger engine rotation angle, resulting in hotter exhaust valves and ports. Hence, the gases in exhaust system are hotter at higher engine speeds.**

Effect of Engine Operating Variables on Heat Transfer

Engine load

- **The SI engines, when the load increases, the throttle must be opened fully to keep engine speed constant. Mass flow rate of air and fuel goes up with load at a given engine speed. The heat transfer within the engine goes up as a function of Reynolds number (that varies with mass flow rate).**
- **The engine knock mostly occurs at higher loads. The result of knock is the localized increase in temperature and heat transfer. Moreover, the engine temperature increases with increase in load.**
- **CI engines are run un-throttled for which mass flow is almost independent of load. Hence, convection heat transfer coefficient within the engine is fairly independent of engine load.**

Spark timing

- **More power and higher temperatures are generated when the spark setting is set to give maximum pressure and temperature at about 5-10° aTDC. Higher peak temperature creates higher momentary heat loss but over shorter time.**
- **With spark timing too early/late, the combustion efficiency and average temperature will be lower. It leads to less peak heat loss but spreads for a longer length of time.**

Effect of Engine Operating Variables on Heat Transfer

Fuel equivalence ratio

- **Theoretically, maximum power from an engine is obtained at stoichiometric condition (ϕ = 1). At this point, the engine requires highest fuel octane number and greatest heat loss occurs.**
- **Under fuel rich or lean condition, there will be lower heat losses.**

Evaporative cooling

- **As the fuel is vaporized during intake/start of compression, the evaporative cooling lowers the intake temperature and raises latent heat.**
- **Fuels with high latent heat (e.g. alcohols) have greater evaporative cooling and generally make for cooler running engines.**
- **At fuel-rich engine operation, evaporation of excess fuel lowers the cycle temperature.**

Inlet air temperature and Coolant temperature

- **The increase in inlet air temperature results in higher temperatures over entire cycle with increase in heat loss. Many a times, it increases the chances of engine knock.**
- **The rise of inlet temperature of 100°C will cause about 10-15% increase in heat losses.**
- **Increase of coolant temperature of the engine results in higher temperatures of all cooled components. Although, indicated thermal efficiency is higher, there is greater knock problem for hotter engine.**

Effect of Engine Operating Variables on Heat Transfer

Engine materials

- The materials used for manufacture of cylinder and piston components, result is different operating temperatures. For example, pistons made out of aluminum operate 30-80°C cooler than equivalent cast-iron.
- Ceramic faced piston have poor thermal conductivity, resulting very high thermal endurance. So, modern engines have ceramic exhaust valves with lower mass inertia and high temperature tolerance.

Compression ratio

- Increase in CR (from 7 to 10), decreases heat transfer slightly (within 10%). It is mainly due to change in combustion characteristics (such as, flame speed, gas motion etc.)
- CI engines operate at higher CR (12 to 24) and have less exhaust temperatures.

Knock

- The temperature and pressure at localized spots increases within combustion chamber, Many times, surface damage to piston and valves can occur in extreme cases.

Swirl and Squish

- Higher swirl and squish velocity results in higher convection heat transfer coefficient within the cylinder resulting better heat transfer to the walls.

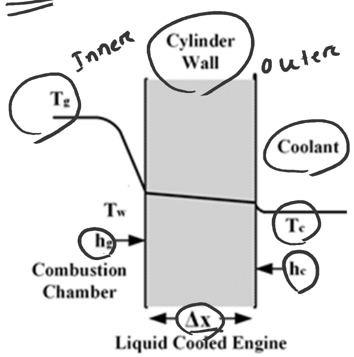
Adiabatic Engine

- The 'thermal endurance' of engine materials subjected to high temperature requires suitable cooling system. On the other hand, the engine must operate as 'hot' as possible to maximize thermal efficiency.
- About 30% of available energy is converted to useful work during expansion stroke while heat losses occurs over entire cycle. Therefore, only one-fourth of saved energy is available when the work is generated and 30% of this energy is utilized.
- A decrease in 10% heat loss (low grade energy) accomplished over a cycle could appear as a gain in crankshaft power (high grade energy) by about 1% which is a major accomplishment.
- Most reduced heat loss energy ends up increase in enthalpy at exhaust and higher steady state temperature of engine components.
- "Adiabatic engines" assumes no heat losses but do have greatly reduced heat losses from the combustion chambers. These engines do not have any cooling mechanism (water jackets/finned surfaces). The heat losses are only due to natural convection of exterior surface. Thus, engine runs with hotter components with some gain in brake power. For this purpose, advance material technology allow engine components to operate at much higher temperatures without mechanical/thermal failure. Adiabatic engines are all compression ignition and in the recent development in automobile sector.

Numerical Problems

Q1. A 3-litre, 5-cylinder, 4-stroke SI engine operates at 3000 rpm with volumetric efficiency of 80%. The stroke of the engine is 1.1 times the bore. The engine uses gasoline fuel with equivalence ratio of 0.9. At certain point in the engine cycle, the gas temperature in the combustion chamber is 2000°C while the cylinder wall temperature is 180°C. Estimate the convection heat transfer to the engine cylinder at this instant.

Inner Outer



Soln

$q = h_g (T_g - T_w)$

$T_g = 2000^\circ C = 2273\ K$

$T_c = 180^\circ C = 453\ K.$

$Nu = \frac{h_g B}{k_g} = C_1 (R_e)^{C_2}.$

$C_1 = 0.035$ $\quad$ $k_g = 0.09\ W/m.K.$

$C_2 = 0.8.$ $\quad$ $\mu_g = 5.2 \times 10^{-5}\ kg/m.s$

$R_e = \frac{(\dot{m}_a + \dot{m}_f) B}{A_p \mu_g}$

$A_p = \frac{\pi}{4} B^2 = 0.006235\ m^2$

$V_d = \frac{\pi}{4} B^2 S = \frac{3000}{5} = 600\ cm^3.$

$S = 1.1 B$

$\Rightarrow B = 8.84\ cm$

$= 0.0884\ m.$

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

$\dot{m}_a = 0.0145\ kg/s.$

$\eta_v = 0.8$

$\rho_a = 1.18\ kg/m^3$

$V_d = \frac{3000}{5} = 600\ cm^3$

$N = 3000\ rpm$ $\quad$ $n = 2$

Numerical Problems

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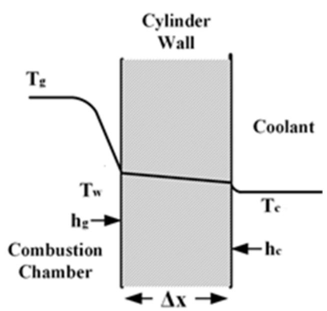

Liquid Cooled Engine

$$\dot{m}_f = \frac{\dot{m}_a}{\phi\,(AF)_{stoi}} = \frac{0.0145}{0.9\,(14.6)} = 0.0011 \text{ kg/s.}$$

$$R_e = 4253$$

$$h_g = 0.035\,(4253)^{0.8}\left(\frac{0.09}{0.0884}\right) = 28.5 \text{ W/m}^2\text{K.}$$

$$q = \underset{h_g\,(T_g - T_c)}{\underline{28.5\,(2273 - 453)}} = 51.87 \text{ kW/m}^2$$

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THANK YOU