2.61 Internal Combustion Engines
Spring 2008

Engine Heat Transfer

1. Impact of heat transfer on engine operation
2. Heat transfer environment
3. Energy flow in an engine
4. Engine heat transfer
    - Fundamentals
    - Spark-ignition engine heat transfer
    - Diesel engine heat transfer
5. Component temperature and heat flow

Engine Heat Transfer

- Heat transfer is a parasitic process that contributes to a loss in fuel conversion efficiency

- The process is a “surface” effect

- Relative importance reduces with:
  - Larger engine displacement
  - Higher load

Engine Heat Transfer: Impact

- **Efficiency and Power:** Heat transfer in the inlet decrease volumetric efficiency. In the cylinder, heat losses to the wall is a loss of availability.

- **Exhaust temperature**: Heat losses to exhaust influence the turbocharger performance. In- cylinder and exhaust system heat transfer has impact on catalyst light up.

- **Friction**: Heat transfer governs liner, piston/ ring, and oil temperatures. It also affects piston and bore distortion. All of these effects influence friction. Thermal loading determined fan, oil and water cooler capacities and pumping power.

- **Component design**: The operating temperatures of critical engine components affects their durability; e.g. via mechanical stress, lubricant behavior

Engine Heat Transfer: Impact

- **Mixture preparation in SI engines:** Heat transfer to the fuel significantly affect fuel evaporation and cold start calibration

- **Cold start of diesel engines:** The compression ratio of diesel engines are often governed by cold start requirement

- **SI engine octane requirement:** Heat transfer influences inlet mixture temperature, chamber, cylinder head, liner, piston and valve temperatures, and therefore end-gas temperatures, which affect knock. Heat transfer also affects build up of in-cylinder deposit which affects knock.

Engine heat transfer environment

- Gas temperature: ~300 – 3000^{o}K
- Heat flux to wall: $\dot{Q}$ /A <0 (during intake) to 10 MW/m^2
- Materials limit:
  - Cast iron ~ 400^{o}C
  - Aluminum ~ 300^{o}C
  - Liner (oil film) ~200^{o}C
- Hottest components
  - Spark plug > Exhaust valve > Piston crown > Head
  - Liner is relatively cool because of limited exposure to burned gas
- Source
  - Hot burned gas
  - Radiation from particles in diesel engines

Energy flow diagram for an IC engine

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Energy flow distribution for SI and Diesel

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Energy distribution in SI engine

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Heat transfer process in engines

- **Areas where heat transfer is important**
  - Intake system: manifold, port, valves
  - In-cylinder: cylinder head, piston, valves, liner
  - Exhaust system: valves, port, manifold, exhaust pipe
  - Coolant system: head, block, radiator
  - Oil system: head, piston, crank, oil cooler, sump
- **Information of interest**
  - Heat transfer per unit time (rate)
  - Heat transfer per cycle (often normalized by fuel heating value)
  - Variation with time and location of heat flux (heat transfer rate per unit area)

Schematic of temperature distribution and heat flow across the combustion chamber wall (Fig. 12-1)

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Combustion Chamber Heat Transfer

Turbulent convection: hot gas to wall

$$\dot{Q} = Ah_g(\overline{T}_g - T_{wg})$$

Conduction through wall

$$\dot{Q} = A\frac{\kappa}{t_w}(T_{wg} - T_{wc})$$

Turbulent convection: wall to coolant

$$\dot{Q} = Ah_c(T_{wc} - \overline{T}_c)$$

Overall heat transfer

$$\dot{Q} = Ah(\overline{T}_g - \overline{T}_c)$$

Overall thermal resistance: three resistance in series

$$\frac{1}{h} = \frac{1}{h_g} + \frac{t_w}{\kappa} + \frac{1}{h_c}$$

(κ_{alum} ~180 W/m-k

$\kappa_{cast\ iron}$ ~ 60 W/m-k

$\kappa_{stainless\ steel}$ ~18 W/m-k)

Turbulent Convective Heat Transfer Correlation

Approach: Use Nusselt- Reynolds number correlations similar to those for turbulent pipe or flat plate flows.

e.g. In-cylinder:

$$Nu = \frac{hL}{\kappa} = a(Re)^{0.8}$$

h = Heat transfer coefficient

L = Characteristic length (e.g. bore)

Re = Reynolds number, $\rho UL/\mu$

U = Characteristic gas velocity

κ = Gas thermal conductivity

μ = Gas viscosity

ρ = Gas density

a = Turbulent pipe flow correlation coefficient

Radiative Heat Transfer

- Important in diesels due to presence of hot radiating particles (particulate matters) in the flame
- Radiation from hot gas relatively small

$$\dot{Q}_{rad} = \varepsilon \cdot \sigma \cdot T_{particle}^4$$

σ = Stefan Boltzman Constant (5.67×10^{-8} W/m^2-K^4)

ε = Emissivity

where

$$T_{cyl.\ ave} < T_{particle} < T_{max\ burned\ gas}$$

- Radiation spectrum peaks at λ_{max}

λ_{max} T = constant (λ_{max} = 3 μm at 1000K)

Typically, in diesels: $\overline{Q}_{rad} \approx 0.2\overline{Q}_{total}$ **(cycle cum)**

$\dot{Q}_{rad,max} \approx 0.4\dot{Q}_{total,max}$ **(peak value)**

IC Engine heat transfer

- Heat transfer mostly from hot burned gas
  - That from unburned gas is relatively small
  - Flame geometry and charge motion/turbulence level affects heat transfer rate
- Order of Magnitude
  - SI engine peak heat flux ~ 1-3 MW/m^2
  - Diesel engine peak heat flux ~ 10 MW/m^2
- For SI engine at part load, a reduction in heat losses by 10% results in an improvement in fuel consumption by 3%
  - Effect substantially less at high load

SI Engine Heat Transfer

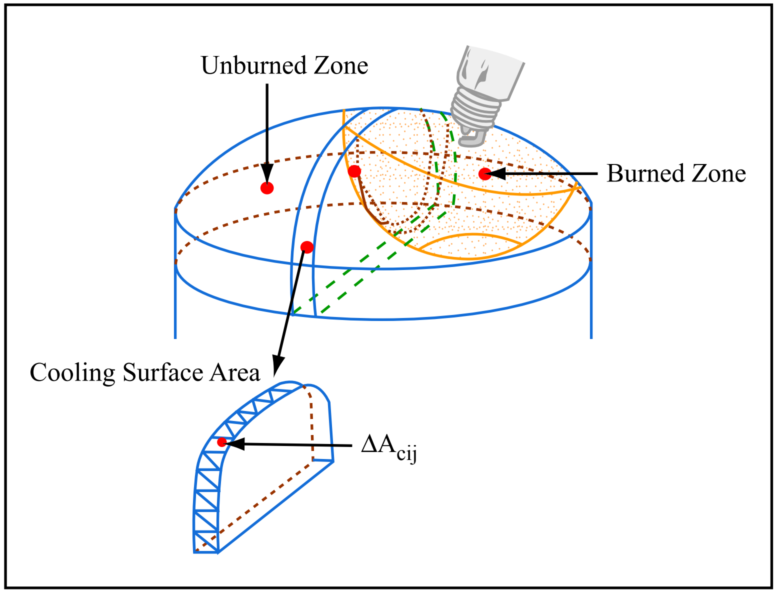

Figure by MIT OpenCourseWare.

- Heat transfer dominated by that from the hot burned gas
- Burned gas wetted area determine by cylinder/ flame geometry
- Gas motion (swirl/ tumble) affects heat transfer coefficient

Heat transfer

Burned zone: sum over area "wetted" by burned gas

$$\dot{Q}_b = \sum_i A_{ci,b} h_b (T_b - T_{w,i})$$

Unburned zone: sum over area "wetted" by unburned gas

$$\dot{Q}_u = \sum_i A_{ci,u} h_u (T_u - T_{w,i})$$

Note: Burned zone heat flux >> unburned zone heat flux

SI engine heat transfer environment

Fig. 14-9 5.7 L displacement, 8 cylinder engine at WOT, 2500 rpm; fuel equivalence ratio 1.1; GIMEP 918 kPa; specific fuel consumption 24 g/kW-hr.

SI engine heat flux

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Heat transfer scaling

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Nu correlation: heat transfer rate $\propto \rho^{0.8}N^{0.8}$
Time available (per cycle) $\propto 1/N$
Fuel energy $\propto \rho$
BMEP $\propto \rho$

Thus Heat Transfer/Fuel energy $\propto \mathrm{BMEP}^{-0.2}N^{-0.2}$

Diesel engine heat transfer

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Fig. 12-13 Measured surface heat fluxes at different locations in cylinder head and liner of naturally aspirated 4-stroke DI diesel engine. Bore=stroke=114mm; 2000 rpm; overall fuel equivalence ratio = 0.45.

Diesel engine radiative heat transfer

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Fig. 12-15

Radiant heat flux as fraction of total heat flux over the load range of several different diesel engines

Heat transfer effect on component temperatures
Temperature distribution in head

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Fig. 12-20 Variation of cylinder head temperature with measurement location n SI engine operating at 2000 rpm, WOT, with coolant water at 95°C and 2 atmosphere.

Heat transfer paths from piston

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Fig. 12-24 Heat outflow form various zones of piston as percentage of heat flow in from combustion chamber. High-speed DI diesel engine, 125 mm bore, 110 mm stroke, CR=17

Piston Temperature Distribution

Figure 12-19

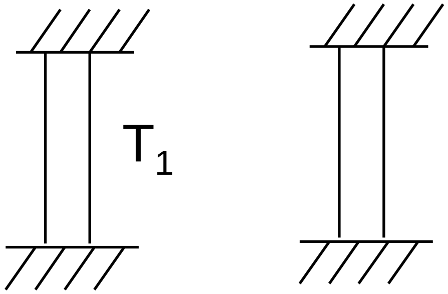
Isothermal contours (solid lines) and heat flow paths (dashed lines) determined from measured temperature distribution in piston of high speed DI diesel engine. Bore 125 mm, stroke 110 mm, r_c=17, 3000 rev/min, and full load

Thermal stress

Simple 1D example : column constrained at ends

Stress-strain relationship

$$\varepsilon_x=[\sigma_x-\nu(\sigma_y+\sigma_z)]/E + \alpha(T_2-T_1)$$



$T_2>T_1$ induces compression stress

REAL APPLICATION - FINITE ELEMENT ANALYSIS

- Complicated 3D geometry
- Solution to heat flow to get temperature distribution
- Compatibility condition for each element

Example of Thermal Stress Analysis:Piston Design

Heat Transfer Analysis

Images removed due to copyright restrictions. Please see Castleman, Jeffrey L. "Power Cylinder Design Variables and Their Effects on Piston Combustion Bowl Edge Stresses." *SAE Journal of Engines* 102 (September 1993): 932491.

Thermal-Stress-Only Loading Structural Analysis

Power Cylinder Design Variables and Their Effects on Piston Combustion Bowl Edge Stresses

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Heat Transfer Summary

1. Magnitude of heat transfer from the burned gas much greater than in any phase of cycle
2. Heat transfer is a significant performance loss and affects engine operation
   - ➢ Loss of available energy
   - ➢ Volumetric efficiency loss
   - ➢ Effect on knock in SI engine
   - ➢ Effect on mixture preparation in SI engine cold start
   - ➢ Effect on diesel engine cold start
3. Convective heat transfer depends on gas temperature, heat transfer coefficient, which depends on charge motion, and transfer area, which depends on flame/combustion chamber geometry
4. Radiative heat transfer is smaller than convective one, and it is only significant in diesel engines