Solutions Manual

Engineering Fundamentals of the Internal Combustion Engine

Second Edition

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PEARSON
Prentice Hall

Pearson Education, Inc.
Upper Saddle River, New Jersey 07458

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Pearson Prentice Hall
Pearson Education, Inc.
Upper Saddle River, NJ 07458

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

ISBN 0-13-141035-0

Pearson Education Ltd., *London*
Pearson Education Australia Pty. Ltd., *Sydney*
Pearson Education Singapore, Pte. Ltd.
Pearson Education North Asia Ltd., *Hong Kong*
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Contents

CHAPTER 1

(1-1)

SI engines use spark plugs.
CI engines use self-ignition.

SI engines intake an air-fuel mixture.
CI engines intake air only.

SI engines have combustion at about constant volume.
CI engines have some combustion at about constant pressure.

SI engines use gasoline fuel.
CI engines use diesel oil fuel.

SI engines use carburetors or fuel injectors in the intake system.
CI engines have fuel injectors in the combustion chamber.

(1-2)

Two stroke cycle engines have no exhaust stroke. Excess exhaust must be pushed out of cylinder (scavenged) by the intake air-fuel mixture (or intake air in CI engines). This requires that the intake mixture be at a higher pressure than the exhaust residual.

(1-3)

Advantages of two stroke cycle:

Smoother cycle with a power stroke from every cylinder on every revolution.
Do not need mechanical valves.
More power from same weight engine.

Advantages of four stroke cycle:

Can operate without an intake pressure boost.
Cleaner operation with less exhaust pollution.
Can use crankcase for oil reservoir.

(1-4)

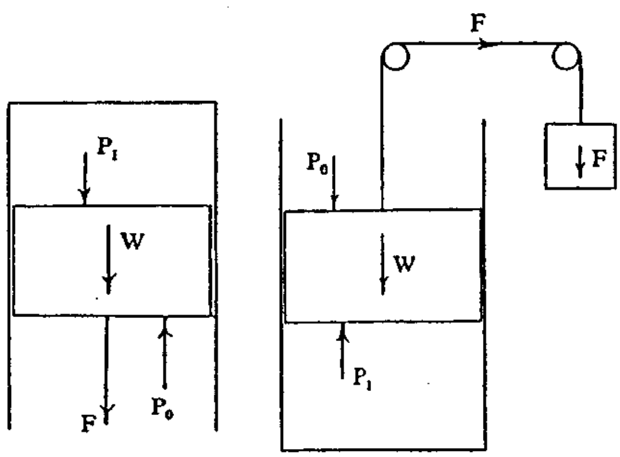
(a) They do not need mechanical valves. Valve mechanism for a very small engine would need to be high precision and costly. With no valves engines can be made cheaper and lighter which is very desirable for small engines.

(b) Very large engines operate at a very low RPM. Because of this they need a power stroke from every cylinder during every revolution to have a smooth operating cycle.

(c) Because of large valve overlap there is too much pollution in the exhaust of a two stroke cycle engine. They cannot pass automobile emission standards required by law.

(d) More power can be obtained from the same weight engine.

(1-5)



(a) weight of piston

$W = mg/g_c = [(2700 \text{ kg})(9.81 \text{ m/sec}^2)]/[(1 \text{ kg-m/N-sec}^2)(1000 \text{ N/kN})] = 26.487 \text{ kN}$

forces down = forces up

P_1(piston face area) + weight + F = P_0(piston face area)

$(22 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2] + (26.487 \text{ kN}) + F = (98 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2]$

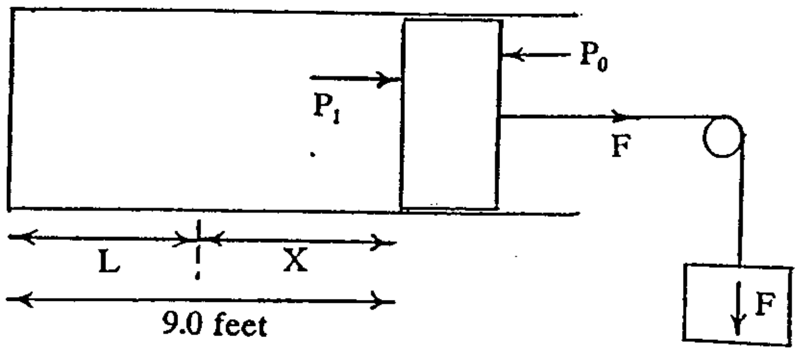
$F = 59.5 \text{ kN} = mg/g_c = m(9.81)/(1)(1000)$ $\underline{m = 6062 \text{ kg}}$

(b) P_0(piston face area) + weight = F + P_1(piston face area)

$(98 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2] + (26.487 \text{ kN}) = F + (22 \text{ kPa})[(\pi/4)(1.2 \text{ m})^2]$

$F = 112.441 \text{ kN} = mg/g_c = m(9.81)/(1)(1000)$ $\underline{m = 11{,}462 \text{ kg}}$

(1-6)



(a) after combustion air in cylinder cools at constant volume pressure in cylinder P_1 when piston is first unlocked

$P_1 = P_0(T_0/T_{comb}) = (14.7 \text{ psia})(530/1000) = 7.8 \text{ psia}$

balance of forces on piston
P_1(piston face area) + F = P_0(piston face area)

$[(7.8)(144)\ \text{lbf/ft}^2][(\pi/4)(3.2\ \text{ft})^2] + F = [(14.7)(144)\ \text{lbf/ft}^2][(\pi/4)(3.2\ \text{ft})^2]$

$\underline{F = 7991 \text{ lbf}}$

(b) cylinder volume before cooling
$V_1 = (\pi/4)B^2S = (\pi/4)(3.2\ \text{ft})^2(9\ \text{ft}) = 72.38\ \text{ft}^3$

with no load piston will move at constant temperature until cylinder pressure $P_2 = P_0 = 14.7$ psia
$V_2 = V_1(P_1/P_2) = (72.38\ \text{ft}^3)(7.8/14.7) = 38.41\ \text{ft}^3$

after piston movement
$V_2 = (\pi/4)(3.2\ \text{ft})^2L = 38.41\ \text{ft}^3$ $\qquad$ L = 4.78 ft

distance piston moves X = effective power stroke
X = 9 - 4.78 $\underline{= 4.22 \text{ ft}}$

(c) cylinder volume at end of power stroke
$\underline{V_2 = 38.41\ \text{ft}^3}$ from above

(1-7)

(a) Shorter engine length allows for shorter engine compartment.

Shorter crankshaft will have less bending stress.

(b) Smaller diameter cylinders will have shorter flame travel distance.

Smoother engine cycle with more power strokes per revolution.

(c) Less mechanical friction in engine.

Larger cylinder volume/surface area ratio giving less heat loss per cycle.

(d) Lower engine height.

Shorter engine length.

Shorter engine crankshaft.

(e) Smoother engine cycle with more power strokes per revolution.

Smaller diameter cylinders will have shorter flame travel distance.

(1-8)

(a) as a radial engine rotates every other cylinder fires
giving 4.5 ignitions and power strokes per revolution

(360°/rev)/(4.5 ignitions/rev) = <u>80°/ignition</u>

(b) <u>4.5 power strokes/rev</u>

(c) (4.5 power strokes/rev)(900/60 rev/sec) = <u>67.5 power strokes/sec</u>

(1-9)

(a) standard automobile

m_f = (16,000 miles)/(31 miles/gal) <u>= 516.1 gal</u>

hybrid automobile

m_f = (16,000 miles)/(82 miles/gal) <u>= 195.1 gal</u>

(b) (516.1) - (195.1) = (321.0 gal/year)($1.65) <u>= $529.65/year</u>

(c) difference in cost

($32,000) - ($18,000) = $14,000

t = ($14,000)/($529.65/year) <u>= 26.4 years = 317 months</u>

CHAPTER 2

(2-1)

(a) [(171,000 miles)(60 min/hr)(1700 rev/min)]/(40 miles/hr) $\underline{= 4.36 \times 10^8 \text{ rev}}$

(b) $(4.36 \times 10^8$ rev)(4 firings/rev) $\underline{= 1.744 \times 10^9 \text{ firings}}$

(c) there are same number of intake strokes as spark plug firings

$(1.744 \times 10^9$ intake strokes/engine)/(8 cyl/engine) $\underline{= 2.18 \times 10^8 \text{ strokes/cyl}}$

(2-2)

(a) Eq. (2-9)
$V_d = N_c(\pi/4)B^2S = (4 \text{ cyl})(\pi/4)(10.9 \text{ cm})^2(12.6 \text{ cm}) \underline{= 4703 \text{ cm}^3 = 4.703 \text{ L}}$

(b) Eq. (2-2)
$\overline{U}_p = 2SN = (2 \text{ strokes/rev})(0.126 \text{ m/stroke})(2000/60 \text{ rev/sec}) = 8.40 \text{ m/sec}$

Eq. (2-15)
$A_p = (\pi/4)B^2N_c = (\pi/4)(0.109 \text{ m})^2(4 \text{ cyl}) = 0.0373 \text{ m}^2$

Eq. (2-46)
$W_b = (\text{bmep})A_p\overline{U}_p/2$
$88 \text{ kW} = (\text{bmep})(0.0373 \text{ m}^2)(8.40 \text{ m/sec})/2$ $\underline{\text{bmep} = 561 \text{ kPa}}$

or using Eq.(2-88)
$\text{bmep} = (1000)(88)(1)/(4.703)(2000/60) \underline{= 561 \text{ kPa}}$

(c) Eq. (2-40)
$\tau = (\text{bmep})V_d/2\pi = (561 \text{ kPa})(0.004703 \text{ m}^3)/2\pi = 0.420 \text{ kN-m} \underline{= 420 \text{ N-m}}$

or using Eq.(2-76)
$\tau = (159.2)(88)/(2000/60) \underline{= 420 \text{ N-m}}$

(d) for one cylinder
$V_d = (4703 \text{ cm}^3)/4 = 1176 \text{ cm}^3$

Eq. (2-12)
$r_c = (V_d + V_c)/V_c = 18 = (1176 + V_c)/V_c$ $\underline{V_c = 69.2 \text{ cm}^3}$

(2-3)

(a)

for one cylinder

$V_d = (2.4\ L)/4 = 0.6\ L = 600\ cm^3$

Eq. (2-12)

$r_c = (V_d + V_c)/V_c = 9.4 = (600 + V_c)/V_c$

$\underline{V_c = 71.43\ cm^3 = 0.07143\ L = 4.36\ in.^3}$

(b)

Eq. (2-8)

$V_d = 600\ cm^3 = (\pi/4)B^2S = (\pi/4)B^2(1.06\ B)$

$\underline{B = 8.97\ cm = 3.53\ in.}$

$S = 1.06\ B = (1.06)(8.97\ cm)\ \underline{= 9.50\ cm = 3.74\ in.}$

(c)

Eq. (2-2)

$\overline{U}_p = 2SN = (2\ strokes/rev)(0.0950\ m/stroke)(3200/60\ rev/sec)$

$\underline{= 10.13\ m/sec = 33.2\ ft/sec}$

(2-4)

Advantages of over square engine:

For the same cylinder displacement volume an over square engine will have a shorter stroke length. This will result in a lower average piston speed and lower friction losses.

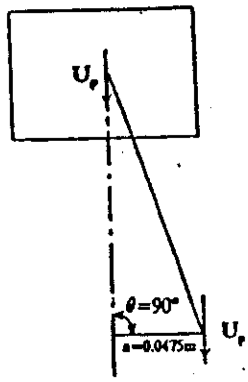
Cylinder lengths will be slightly shorter.

Advantages of under square engine:

An under square engine will have smaller diameter cylinders, resulting in a shorter flame travel distance.

Combustion chamber surface area will be smaller resulting in less heat loss per cycle.

(2-5)



(a) from Problem (2-3) $\quad\quad \underline{\bar{U}_p = 10.13 \text{ m/sec}}$

(b) approximate piston speed is as shown
crankshaft offset equals half of stroke length
$a = S/2 = (0.095 \text{ m})/2 = 0.0475 \text{ m}$

$U_p = \omega r = [(3200/60)(2\pi) \text{ radians/sec}](0.0475 \text{ m}) \underline{= 15.9 \text{ m/sec}}$

(2-6)
for one cylinder $\quad V_d = (3.5 \text{ L})/5 = 0.7 \text{ L} = 0.0007 \text{ m}^3$

(a) Eq. (2-29)
$\text{imep} = W/V_d = (1000 \text{ J})/[(0.0007 \text{ m}^3)(1000 \text{ J/kJ})] \underline{= 1429 \text{ kPa}}$

(b) Eq. (2-37c)
$\text{bmep} = \eta_m \text{imep} = (0.62)(1429 \text{ kPa}) \underline{= 886 \text{ kPa}}$

(c) Eq. (2-37d)
$\text{fmep} = \text{imep} - \text{bmep} = (1429 \text{ kPa}) - (886 \text{ kPa}) \underline{= 543 \text{ kPa}}$

(d) indicated power using Eq. (2-42)
$\dot{W}_i = WN/n$
$=[(1\text{kJ/cyl-cycle})(2500/60\text{rev/sec})(5\text{cyl})]/(2\text{rev/cycle})=104.2\text{kW}$

Eq. (2-47)
$\dot{W}_b = \eta_m \dot{W}_i = (0.62)(104.2 \text{ kW}) \underline{= 64.6 \text{ kW} = 86.6 \text{ hp}}$

or using Eq.(2-81)
$\dot{W}_b = [(886)(3.5)(2500/60)]/[(1000)(2)] \underline{= 64.6 \text{ kW}}$

(e) Eq. (2-41)
$\tau = (\text{bmep})V_d/4\pi = (886 \text{ kN/m}^2)(0.0035 \text{ m}^3)/4\pi \underline{= 247 \text{ N-m}}$

or using Eq.(2-76)
$\tau = (159.2)(64.6)/(2500/60) \underline{= 247 \text{ N-m}}$

(2-7)

Eq. (2-8) for one cylinder
$V_d = 0.0007\ m^3 = (\pi/4)B^2S = (\pi/4)B^3$

$$B = S = 0.0962\ m = 9.62\ cm$$

(a)

Eq. (2-51)
$SP = \dot{W}_b/A_p = \dot{W}_b/[(\pi/4)B^2N_c] = (64.6\ kW)/[(\pi/4)(9.62\ cm)^2(5\ cyl)]$ $\underline{= 0.178\ kW/cm^2}$

(b)

Eq. (2-52)
$OPD = \dot{W}_b/V_d = (64.6\ kW)/(3500\ cm^3)$ $\underline{= 0.0185\ kW/cm^3}$

(c)

Eq. (2-53)
$SV = V_d/\dot{W}_b = (3500\ cm^3)/(64.6\ kW)$ $\underline{= 54.1\ cm^3/kW}$

(d)

Eq. (2-49)
$\dot{W}_f = \dot{W}_i - \dot{W}_b = (104.2\ kW) - (64.6\ kW)$ $\underline{= 39.6\ kW = 53.1\ hp}$

(2-8)

(a)

mass flow rate of fuel into engine
$\dot{m}_f = 0.0060\ kg/sec$ from Example Problem 2-4

mass flow of fuel not burned
$(\dot{m}_f)_{nb} = \dot{m}_f(1 - \eta_c) = (0.0060\ kg/sec)(1 - 0.97)(3600\ sec/hr)$ $\underline{= 0.648\ kg/hr}$

(b)

Eq. (2-73)
$(SE)_{HC} = \dot{m}_{HC}/\dot{W}_b = (648\ gm/hr)/(77.3\ kW)$ $\underline{= 8.38\ gm/kW\text{-}hr}$

(c)

mass flow of unburned fuel emissions
$\dot{m}_{HC} = [(0.648\ kg/hr)(1000\ gm/kg)]/(3600\ sec/hr) = 0.18\ gm/sec$

Eq. (2-74)
$(EI)_{HC} = \dot{m}_{HC}/\dot{m}_f = (0.18\ gm/sec)/(0.0060\ kg/sec)$ $\underline{= 30\ gm/kg}$

(2-9)

(a)

Eq. (2-9)
$V_d = N_c(\pi/4)B^2S = (8\text{ cyl})(\pi/4)(5.375\text{ in.})^2(8.0\text{ in.}) \underline{= 1452\text{ in.}^3}$

(b)

Eq. (2-15)
$A_p = (\pi/4)B^2N_c = (\pi/4)(5.375\text{ in.})^2(8\text{ cyl}) = 181.5\text{ in.}^2 = 1.260\text{ ft}^2$

Eq. (2-2)
$\overline{U}_p = 2SN = (2\text{ strokes/rev})(8/12\text{ ft/stroke})(1000/60\text{ rev/sec}) = 22.2\text{ ft/sec}$

Eq. (2-45)
$\dot{W}_b = (\text{bmep})A_p\overline{U}_p/4$
$(152\text{ hp})(550\text{ ft-lbf/sec/hp}) = (\text{bmep})(1.260\text{ ft}^2)(22.2\text{ ft/sec})/4$

$\text{bmep} = 11{,}955\text{ lbf/ft}^2 \underline{= 83.0\text{ psia}}$

or using Eq.(2-90)
$\text{bmep} = [(396{,}000)(152)(2)]/[(1452)(1000)] \underline{= 83.0\text{ psia}}$

(c)

Eq. (2-41)
$\tau = (\text{bmep})V_d/4\pi = (11{,}955\text{ lbf/ft}^2)[1452/(12)^3]\text{ft}^3/(4\pi) = \underline{799\text{ lbf-ft}}$

or using Eq.(2-77)
$\tau = (5252)(152)/1000 = \underline{799\text{ lbf-ft}}$

(d)

Eq. (2-47)
$\dot{W}_i = \dot{W}_b/\eta_m = (152\text{ hp})/0.60 = \underline{253\text{ hp}}$

(e)

Eq. (2-49)
$\dot{W}_f = \dot{W}_i - \dot{W}_b = (253\text{ hp}) - (152\text{ hp}) = \underline{101\text{ hp}}$

(2-10)

(a)

Eq. (2-71)

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.001500)(0.92)(3000/60)/(2) = \underline{0.0407\ \text{kg/sec}}$

(b)

rate of fuel into engine using Eq. (2-55)

$\dot{m}_f = \dot{m}_a/(AF) = (0.0407\ \text{kg/sec})/21 = 0.00194\ \text{kg/sec} = 6.985\ \text{kg/hr}$

Eq. (2-60)

$\text{bsfc} = \dot{m}_f/\dot{W}_b = (6.985\ \text{kg/hr})/(48\ \text{kW}) = 0.1455\ \text{kg/kW-hr} = \underline{145.5\ \text{gm/kW-hr}}$

(c)

mass flow of exhaust equals air plus fuel

$\dot{m}_{ex} = [(0.0407)(22/21)\ \text{kg/sec}](3600\ \text{sec/hr}) = \underline{153.5\ \text{kg/hr}}$

(d)

Eq. (2-52)

$\text{OPD} = \dot{W}_b/V_d = (48\ \text{kW})/(1.5\ \text{L}) = \underline{32\ \text{kW/L}}$

(2-11)

(a)

Eq. (2-8) for one cylinder

$V_d = (5\ \text{L})/6 = 0.8333\ \text{L} = 833.3\ \text{cm}^3 = (\pi/4)B^2S = (\pi/4)(0.92)B^3$

$B = 10.49\ \text{cm} \qquad S = 0.92\ B = (0.92)(10.49\ \text{cm}) = \underline{9.65\ \text{cm}}$

(b)

Eq. (2-2)

$\bar{U}_p = 2SN = (2\ \text{strokes/rev})(0.0965\ \text{m/stroke})(2400/60\ \text{rev/sec}) = \underline{7.72\ \text{m/sec}}$

(c)

Eq. (2-12)

$r_c = (V_d + V_c)/V_c = 10.2 = (833.3 + V_c)/V_c$

$\underline{V_c = 90.6\ \text{cm}^3}$

(d)

Eq. (2-71)

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.005)(0.91)(2400/60)/(2) = \underline{0.107\ \text{kg/sec}}$

(2-12)

(a) (500 miles)/(18 gal) $= \underline{27.78\ \text{mpg}}$

(b) (3.785 L/gal)/[(27.78 miles/gal)(1.609 km/mile)]
$= 0.0847\ \text{L/km} = \underline{8.47\ \text{L/100 km}}$

(c) rate of fuel use during trip
$\dot{m}_f$=[(18gal)(3.785L/gal)(0.692kg/L)]/[(12.5hr)(3600 sec/hr)]
= 0.001048 kg/sec

mass of CO
(0.001048kg/sec)[(28gm/kg)](3600sec/hr)(12.5hr)/(1000gm/kg)
$= \underline{1.32\ \text{kg}}$

(2-13)

(a) displacement volume of one cylinder
$V_d = (0.0056\ m^3)/(10\ \text{cylinders}) = 0.00056\ m^3/\text{cylinder}$
eq (2-8)
$V_d = (\pi/4)B^2S = (0.00056\ m^3) = (\pi/4)B^2(1.12\ B)$
B = 0.0860 m   S - 1.12 B = (1.12)(0.0860 m) = 0.0963 m

eq (2-2)
$\bar{U}_p$=2SN=(2strokes/rev)(0.0963m/stroke)(3600/60rev/sec)
$= \underline{11.56\ \text{m/sec}}$

(b) eq (2-76)
$\tau = [(159.2)(162)]/(3600/60) = \underline{429.8\ \text{N-m}}$

(c) eq (2-87)
bmep = [(6.28)(2)(429.8)]/(5.6) $= \underline{964\ \text{kPa}}$

(2-14)

(a) displacement volume of one cylinder

$V_d = (4800\ cm^3)/(8) = 600\ cm^3/\text{cylinder}$

Eq.(2-8)

$V_d = (\pi/4)B^2S = 600\ cm^3 = (\pi/4)(1.06\ S)^2S$

$\underline{S = 8.79\ cm = 0.0879\ m}$

(b) Eq.(2-2)

$\overline{U}_p = 2SN = (2\ \text{strokes/rev})(0.0879\ \text{m/stroke})(2000/60\ \text{rev/sec})$

$\underline{= 5.86\ \text{m/sec}}$

(c) each spark plug fires once each cycle

(2000/2 cycles/min)(60 min/hr)(24 hr/day)(5 days)

$\underline{= 7.20 \times 10^6\ \text{cycles}}$

(d) Eq.(2-71)

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

$=(0.92)(1{,}181\text{kg/m}^3)(0.0048\text{m}^3/\text{cycle})(2000/60\text{rev/sec})/(2\text{rev/cycle})$

$\underline{= 0.0870\ \text{kg/sec}}$

(e) Eq.(2-55)

$\dot{m}_f = \dot{m}_a/AF = (0.0870\ \text{kg/sec})/(14.6)$ $\underline{= 0.00595\ \text{kg/sec}}$

(2-15)

(a)

Eq. (2-8) with B = S

$V_d = 6.28\ cm^3 = (\pi/4)B^2S = (\pi/4)B^3$

$B = 2.00\ cm = S$

Eq. (2-2)

$\overline{U}_p = 2SN = (2\ strokes/rev)(0.0200\ m/stroke)(8000/60\ rev/sec) = \underline{5.33\ m/sec}$

(b)

Eq. (2-71)

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.00000628)(0.85)(8000/60)/(1) = \underline{0.00084\ kg/sec}$

(c)

Eq. (2-56)

$\dot{m}_f = (FA)\dot{m}_a = (0.067)(0.00084\ kg/sec) = \underline{5.63 \times 10^{-5}\ kg/sec}$

(d)

$m_f = (5.63 \times 10^{-5}\ kg/sec)/[8000/60\ rev/sec)(1\ cycle/rev)] = \underline{4.22 \times 10^{-7}\ kg/cycle}$

(2-16)

(a)

brake power using Eq. (2-43)
$\dot{W}_b = 2\pi N\tau = (2\pi \text{ radians/rev})(800/60 \text{ rev/sec})(76 \text{ N-m})/(1000 \text{ W/kW}) = 6.365 \text{ kW}$

or using Eq. (2-80)
$\dot{W}_b = (800/60)(76)/159.2 = 6.365 \text{ kW}$

mass flow rate of fuel
$\dot{m}_f = (0.113/4 \text{ kg/min})(1000 \text{ gm/kg})(60 \text{ min/hr}) = 1695 \text{ gm/hr}$

Eq. (2-60)
$\text{bsfc} = \dot{m}_f/\dot{W}_b = (1695 \text{ gm/hr})/(6.365 \text{ kW}) = \underline{266.3 \text{ gm/kW-hr}}$

(b)

displacement volume using Eq. (2-9)
$V_d = N_c(\pi/4)B^2S = (1 \text{ cyl})(\pi/4)(12.9 \text{ cm})^2(18.0 \text{ cm})$
$= 2353 \text{ cm}^3 = 2.353 \text{ L} = 0.002353 \text{ m}^3$

Eq. (2-41)
$\text{bmep} = 4\pi\tau/V_d = (4\pi)(76 \text{ N-m})/(0.002353 \text{ m}^3) = 405{,}700 \text{ N/m}^2 \underline{= 405.7 \text{ kPa}}$

or using Eq. (2-87)
$\text{bmep} = (6.28)(2)(76)/(2.353) = \underline{405.7 \text{ kPa}}$

or using Eq. (2-88)
$\text{bmep} = (1000)(6.365)(2)/[(2.353)(800/60)] \underline{= 405.7 \text{ kPa}}$

(c)

from above $\underline{\dot{W}_b = 6.365 \text{ kW}}$

(d)

piston face area using Eq. (2-15)
$A_p = (\pi/4)B^2 = (\pi/4)(12.9 \text{ cm})^2 = 130.7 \text{ cm}^2$

Eq. (2-51)
$\text{SP} = \dot{W}_b/A_p = (6.365 \text{ kW})/(130.7 \text{ cm}^2) = \underline{0.0487 \text{ kW/cm}^2}$

(e)

Eq. (2-52) $\text{OPD} = \dot{W}_b/V_d = (6.365 \text{ kW})/(2.353 \text{ L}) = \underline{2.71 \text{ kW/L}}$

(f)

Eq. (2-53) $\text{SV} = V_d/\dot{W}_b = (2.353 \text{ L})/(6.365 \text{ kW}) = \underline{0.370 \text{ L/kW}}$

(2-17)

(a) $\dot{Q} = \dot{m}c_p\Delta T$

$[(72\ hp)(2545\ BTU/hr/hp)(0.93)]/(60\ min/hr)$

$= (30\ gal/min)(62.4\ lbm/ft^3)(0.1337\ ft^3/gal)(1\ BTU/lbm\text{-}°R)\Delta T$

$\Delta T = 11°\ F$ $\qquad T_{exit} = 46° + 11° = \underline{57°\ F}$

(b) Eq. (2-43)

$\dot{W}_b = 2\pi N\tau = (72\ hp)(550\ ft\text{-}lbf/sec/hp)(60\ sec/min) = (2\pi\ radians/rev)(4050\ rev/min)\tau$

$\underline{\tau = 93.4\ lbf\text{-}ft}$

or using Eq.(2-77)

$\tau = (5252)(72)/(4050) = \underline{93.4\ lbf\text{-}ft}$

(c) brake power $\dot{W}_b = (72\ hp)(550\ ft\text{-}lbf/sec/hp)(60\ sec/min) = 2.376 \times 10^6\ ft\text{-}lbf/min$

displacement $\qquad V_d = (302\ in.^3)/(12\ in./ft)^3 = 0.1748\ ft^3$

Eq.(2-86)

$bmep = n\dot{W}_b/V_dN = (2\ rev/cycle)(2.376 \times 10^6\ ft\text{-}lbf/min)/(0.1748\ ft^3)(4050\ rev/min)$

$= 6712.4\ lbf/ft^2 \underline{= 46.6\ psia}$

or using Eq.(2-90)

$bmep = [(396{,}000)(72)(2)]/[(302)(4050)] \underline{= 46.6\ psia}$

(2-18)

(a) power out of generator

$\dot{W}_g = (220\ volts)(54.2\ amps) = 11{,}924\ W = 11.924\ kW$

brake power from engine using Eq. (2-50)

$\dot{W}_b = \dot{W}_g/\eta_{gen} = (11.924\ kW)/0.87 \underline{= 13.7\ kW = 18.4\ hp}$

(b) Eq. (2-43)

$\dot{W}_b = 2\pi N\tau = 13.7\ kW = (2\pi\ radians/rev)(1200/60\ rev/sec)\tau$

$\tau = 0.109\ kN\text{-}m \underline{= 109\ N\text{-}m}$

or using Eq.(2-76)

$\tau = (159.2)(13.7)/(1200/60) \underline{= 109\ N\text{-}m}$

(c) Eq. (2-40)

$\tau = (bmep)V_d/2\pi = 109\ N\text{-}m = (bmep)(0.0031\ m^3/rev)/(2\pi\ radians/rev)$

$bmep = 221{,}000\ N/m^2 \underline{= 221\ kPa}$

or using Eq.(2-87)

$bmep = (6.28)(1)(109)/(3.1) \underline{= 221\ kPa}$

(2-19)

(a)

Eq. (2-55)

$\dot{m}_a = \dot{m}_f(AF) = (0.198\ kg/sec)(1.7) = 0.3366\ kg/sec$

Eq. (2-71)

$\eta_v = n\dot{m}_a/\rho_a V_d N = (2)(0.3366)/(1.181)(0.006)(6000/60) = 0.950 \underline{= 95.0\%}$

(b)

$\underline{\dot{m}_a = 0.3366\ kg/sec}$ from above

(c)

Eq. (2-64) heat in for engine per time

$\dot{Q}_{in} = \dot{m}_f Q_{HV}\eta_c = (0.198\ kg/sec)(10{,}920\ kJ/kg)(0.99) = 2140.5\ kJ/sec$

heat in for engine per cycle

$Q_{in} = (2140.5\ kJ/sec)(2\ rev/cycle)/(6000/60\ rev/sec) = 42.81\ kJ/cycle$

heat in per cycle per cylinder

$Q_{in} = (42.81\ kJ/cycle)/(8\ cylinder) \underline{= 5.35\ kJ/cyl\text{-}cycle}$

(d)

$\dot{Q}_{unburned} = \dot{m}_f Q_{HV}(1 - \eta_c) = (0.198\ kg/sec)(10{,}920\ kJ/kg)(1 - 0.99) \underline{= 21.6\ kW}$

(2-20)

assuming four-stroke cycle

(a) Eq.(2-71)

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

$=(0.51)(1.181\text{kg/m}^3)(0.0046\text{m}^3\text{/cycle})(1750/60\text{rev/sec})/(2\text{rev/cycle})$

$\underline{= 0.0404 \text{ kg/sec}}$

(b) Eq.(2-55)

$\dot{m}_f = \dot{m}_a/AF = (0.0404 \text{ kg/sec})/(14.5) \underline{= 0.00278 \text{ kg/sec})}$

(c) Eq.(2-60)

$bsfc=\dot{m}_f/\dot{W}_b=[(0.00278\text{kg/sec})(1000\text{gm/kg})(3600\text{sec/hr})]/(32.4\text{kW})$

$\underline{= 309 \text{ gm/kW-hr}}$

(d) with same indicated thermal efficiency and same combustion efficiency, fuel flow needed will be proportional to mechanical efficiency, fuel flow rate needed for V4:

$\dot{m}_f = (0.00278 \text{ kg/sec})[(75/87)] = 0.00240 \text{ kg/sec}$

Eq.(2-55) gives air flow needed

$\dot{m}_a = \dot{m}_f(AF) = (0.00240 \text{ kg/sec})(18.2) = 0.0437 \text{ kg/sec}$

use Eq.(2-71) to find needed engine speed

$\dot{m}_a = \eta_v \rho_a V_d N/n = (0.0437\text{kg/sec})$

$=(0.86)(1.181\text{kg/m}^3)(0.0023\text{m}^3\text{/cycle})(N/60\text{rev/sec})/(2\text{rev/cycle})$

$\underline{N = 2245 \text{ RPM}}$

(e) Eq.(2-60)

$bsfc=\dot{m}_f/\dot{W}_b=[(0.00240\text{kg/sec})(1000\text{gm/kg})(3600\text{sec/hr})]/(32.4\text{kW})$

$\underline{= 267 \text{ gm/kW-hr}}$

(2-21)

(a) $V_1 = (70 \text{ MPH})/(2.237 \text{ MPH/m/sec}) = 31.29 \text{ m/sec}$

$V_2 = (20)/(2.237) = 8.94 \text{ m/sec}$

$\Delta KE = (m/2g_c)[V_1^2 - V_2^2]$

$=(1900 \text{ kg})/[(2)(1\text{kg-m/N-sec}^2)][(31.29\text{m/sec})^2-(8.94)^2]=854{,}180\text{N-m}$

$= 854.18 \text{ kJ}$

51% of this is recovered in battery

$E = (854.18 \text{ kJ})(0.51) \underline{= 436 \text{ kJ}}$

(b) 24% of chemical energy recovered

$e = (26950 \text{ kJ/kg})(0.24) = 6468 \text{ kJ/kg}$

mass of fuel saved

$m = (436 \text{ kJ})/(6468 \text{ kJ/kg}) \underline{= 0.067 \text{ kg}}$

CHAPTER 3

(3-1)

(a)(b) using Fig. 3-2

$\underline{T_1 = 60° C}$ = 333 K given

$\underline{P_1 = 98 \text{ kPa}}$ given

Eqs. (3-4) and (3-5)

$T_2 = T_1(r_c)^{k-1} = (333\text{ K})(9.5)^{0.35} = 732\text{ K} \underline{= 459° C}$

$P_2 = P_1(r_c)^k = (98\text{ kPa})(9.5)^{1.35} \underline{= 2047\text{ kPa}}$

Eq. (3-11)

$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2)$

$(43{,}000\text{ kJ/kg})(0.96) = (15.5 + 1)(0.821\text{ kJ/kg-K})(T_3 - 732\text{ K})$

$T_3 = 3779\text{ K} \underline{= 3506° C}$

at constant volume

$P_3 = P_2(T_3/T_2) = (2047\text{ kPa})(3779/732) \underline{= 10{,}568\text{ kPa}}$

Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (3779\text{ K})(1/9.5)^{0.35} = 1719\text{ K} \underline{= 1446° C}$

$P_4 = P_3(1/r_c)^k = (10{,}568\text{ kPa})(1/9.5)^{1.35} \underline{= 506\text{ kPa}}$

(c)

Eq. (3-18)

$w_{3\text{-}4} = R(T_4 - T_3)/(1 - k) = (0.287\text{ kJ/kg-K})(1719 - 3779)\text{K}/(1 - 1.35) \underline{= 1689\text{ kJ/kg}}$

(d)

Eq. (3-12)

$q_{in} = c_v(T_3 - T_2) = (0.821\text{ kJ/kg-K})(3779 - 732)\text{K} \underline{= 2502\text{ kJ/kg}}$

(e)

Eq. (3-7)

$w_{1\text{-}2} = R(T_2 - T_1)/(1 - k) = (0.287\text{ kJ/kg-K})(732 - 333)\text{K}/(1 - 1.35) = -327\text{ kJ/kg}$

$w_{net} = w_{1\text{-}2} + w_{3\text{-}4} = (-327\text{ kJ/kg}) + (+1689\text{ kJ/kg}) \underline{= +1362\text{ kJ/kg}}$

(f)

$\eta_t = w_{net}/q_{in} = 1362/2502 = 0.545 \underline{= 54.5\%}$

or using Eqs. (3-29) or (3-31)

$\eta_t = 1 - (T_1/T_2) = 1 - (333/732) = 0.545$

$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/9.5)^{0.35} = 0.545 \underline{= 54.5\%}$

(3-2)

(a) using Fig. 3-2

for 1 cylinder $\quad V_d = (3\ L)/6 = 0.5\ L = 0.0005\ m^3$

Eq. (2-12)

$r_c = 9.5 = (V_d + V_c)/V_c = (0.0005 + V_c)/V_c \qquad V_c = 0.0000588\ m^3$

$V_1 = V_{BDC} = V_d + V_c = 0.0005 + 0.0000588 = 0.0005588\ m^3$

mass in cylinder at point 1

$m = PV/RT = (98\ kPa)(0.0005588\ m^3)/(0.287\ kJ/kg\text{-}K)(333\ K) = 0.000573\ kg$

work per cylinder per cycle $\quad W = mw_{net} = (0.000573\ kg)(1362\ kJ/kg) = 0.780\ kJ$

Eq. (2-42) $\quad \dot{W}_i = WN/n$

$= [(0.780 kJ/cycle)(2400/60 rev/sec)/(2 rev/cycle)](6 cyl) = 93.6 kW$

Eq. (2-47) $\quad \dot{W}_b = \eta_m \dot{W}_i = (0.84)(93.6\ kW) = \underline{78.6\ kW}$

(b) Eq. (2-43)

$\dot{W}_b = 2\pi N\tau = 78.6\ kJ/sec = (2\pi\ radians/rev)(2400/60\ rev/sec)\tau$

$\tau = 0.313\ kN\text{-}m = \underline{313\ N\text{-}m}$

(c) Eq. (2-41)

$\tau = (bmep)V_d/4\pi = 0.313\ kN\text{-}m = bmep(0.003\ m^3)/4\pi \qquad bmep = \underline{1311\ kPa}$

(d) Eq. (2-49)

$\dot{W}_f = \dot{W}_i - \dot{W}_b = (93.6\ kW) - (78.6\ kW) = \underline{15.0\ kW}$

(e) for 1 cylinder from (a) above

$m_m = 0.000573\ kg = m_a + m_f = m_a(1 + FA) = m_a[1 + (1/15.5)]$

$m_a = 0.000538\ kg \qquad m_f = 0.000035\ kg$

$\dot{m}_f = (0.000035\ kg/cycle\text{-}cyl)(6\ cyl)(2400/60\ rev/sec)/(2\ rev/cycle)$

$= 0.0042\ kg/sec = 4.2\ gm/sec = 15{,}120\ gm/hr$

Eq. (2-60)

$bsfc = \dot{m}_f/\dot{W}_b = (15{,}120\ gm/hr)/78.6\ kW = \underline{192.4\ gm/kW\text{-}hr}$

(f) Eq. (2-70)

$\eta_v = m_a/\rho_a V_d = [(0.000538\ kg)/(1.181\ kg/m^3)(0.0005\ m^3)](100) = \underline{91.1\%}$

(g) Eq. (2-52)

$OPD = \dot{W}_b/V_d = (78.6\ kW)/(3\ L) = \underline{26.2\ kW/L}$

(3-3)

(a)

using Fig. 3-6

Eq. (3-37)

$T_7 = T_{ex} = T_4(P_{ex}/P_4)^{(k-1)/k}$

$= (1719\ K)(100/506)^{(1.35-1)/1.35} = 1129\ K = \underline{856°\ C}$

(b)

Eq. (3-46)

$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9.5)(1719/1129)(100/506) = 0.032 = \underline{3.2\%}$

(c)

Eq. (3-50)

$(T_m)_1 = x_r T_{ex} + (1 - x_r)T_a$

$333\ K = (0.032)(1129) + (1 - 0.032)T_a$

$T_a = 307\ K = \underline{34°\ C}$

(3-4)

(a)

using Fig. 3-4

expansion cooling of exhaust residual when intake valve opens

$T_{ex} = (1129\ K)(75/100)^{(1.35-1)/1.35} = 1048\ K$

Eq. (3-50)

$T_1 = x_r T_{ex} + (1 - x_r)T_a$

$= (0.032)(1048\ K) + (1 - 0.032)(307\ K) = 331\ K = \underline{58°\ C}$

(b)

Eq. (3-4)

$T_2 = T_1(r_c)^{k-1} = (331\ K)(9.5)^{0.35} = 728\ K = \underline{455°\ C}$

(3-5)

(a)(b)

using Fig. 3-2

$\underline{T_1 = 100° F} = 560° R$ given

$\underline{P_1 = 14.7 \text{ psia}}$ given

Eqs. (3-4) and (3-5)

$T_2 = T_1(r_c)^{k-1} = (560° R)(10)^{1.4-1} = 1407° R \underline{= 947° F}$

$P_2 = P_1(r_c)^k = (14.7 \text{ psia})(10)^{1.4} \underline{= 369 \text{ psia}}$

Eq. (3-12)

$q_{in} = c_v(T_3 - T_2) = 800 \text{ BTU/lbm} = (0.216 \text{ BTU/lbm-°R})(T_3 - 1407° R)$

$T_3 = 5110° R \underline{= 4650° F}$

at constant volume

$P_3 = P_2(T_3/T_2) = (369 \text{ psia})(5110/1407) \underline{= 1340 \text{ psia}}$

Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (5110° R)(1/10)^{1.3-1} = 2561° R \underline{= 2101° F}$

$P_4 = P_3(1/r_c)^k = (1340 \text{ psia})(1/10)^{1.3} \underline{= 67.2 \text{ psia}}$

(c)

Eq. (3-7)

$w_{1-2} = R(T_2 - T_1)/(1 - k)$

$= [(0.069 \text{ BTU/lbm-°R})(1407 - 560)°R]/(1 - 1.4) = -146.1 \text{ BTU/lbm}$

Eq. (3-18)

$w_{3-4} = R(T_4 - T_3)/(1 - k)$

$= [(0.069 \text{ BTU/lbm-°R})(2561 - 5110)°R]/(1 - 1.3) = +586.3 \text{ BTU/lbm}$

$\eta_t = w_{net}/q_{in} = [(+586.3) + (-146.1)]/(800) = 0.550 = 55.0\%$

Eq. (3-31)

$\eta_t = 0.550 = 1 - (1/r_c)^{k-1} = 1 - (1/10)^{k-1}$

$\underline{k = 1.347}$

(3-6)

(a)(b)

using Fig. 3-8

$\underline{T_1 = 65^\circ\ C}$ = 338 K given

$\underline{P_1 = 130\ kPa}$ given

Eqs. (3-52) and (3-53)

$T_2 = T_1(r_c)^{k-1} = (338\ K)(19)^{0.35} = 947\ K \underline{= 674^\circ\ C}$

$P_2 = P_1(r_c)^k = (130\ kPa)(19)^{1.35} \underline{= 6922\ kPa}$

use Eq. (2-57) for actual air-fuel ratio

$AF = (AF)_{stoich}/\phi = (14.5)/(0.8) = 18.125$

Eq. (3-58)

$Q_{HV}\eta_c = (AF + 1)c_p(T_3 - T_2)$

$(42{,}500\ kJ/kg)(0.98) = (18.125 + 1)(1.108\ kJ/kg\text{-}K)(T_3 - 947)K$

$T_3 = 2913\ K \underline{= 2640^\circ\ C}$

$P_3 = P_2 \underline{= 6922\ kPa}$

$v_4 = v_1 = RT_1/P_1 = (0.287)(338)/(130) = 0.7462\ m^3/kg$

$v_3 = RT_3/P_3 = (0.287)(2913)/(6922) = 0.1208\ m^3/kg$

Eqs. (3-64) and (3-65)

$T_4 = T_3(v_3/v_4)^{k-1} = (2913\ K)(0.1208/0.7462)^{0.35} = 1540\ K \underline{= 1267^\circ\ C}$

$P_4 = P_3(v_3/v_4)^k = (6922\ kPa)(0.1208/0.7462)^{1.35} \underline{= 592\ kPa}$

(c)

Eq. (3-62)

$\beta = T_3/T_2 = 2913/947 \underline{= 3.08}$

(d)

Eq. (3-73)

$(\eta_t)_{DIESEL} = 1 - (1/r_c)^{k-1}[(\beta^k - 1)/\{k(\beta - 1)\}]$

$\eta_t = 1 - (1/19)^{0.35}[\{(3.08)^{1.35} - 1\}/\{(1.35)(3.08 - 1)\}] = 0.547 \underline{= 54.7\%}$

(e)

Eq. (3-59)

$q_{in} = c_p(T_3 - T_2) = (1.108\ kJ/kg\text{-}K)(2913 - 947)K = 2178\ kJ/kg$

$w_{net} = q_{in}\eta_t = (2178\ kJ/kg)(0.547) = 1191\ kJ/kg$

$q_{ex} = q_{out} = q_{in} - w_{net} = 2178 - 1191 \underline{= 987\ kJ/kg}$

(3-7) using Fig.3-11

$T_1 = 50° C = 323$ K given
$P_1 = 98$ kPa given

Eq. (3-52) and (3-53)
$T_2 = T_1(r_c)^{k-1} = (323 \text{ K})(18)^{0.35} = 888 \text{ K} = 615° \text{ C}$
$P_2 = P_1(r_c)^k = (98 \text{ kPa})(18)^{1.35} = 4851 \text{ kPa}$

$P_3 = P_{max} = 9000 \text{ kPa} = P_x$

(a) highest possible thermal efficiency will be when as much of combustion as possible is done at constant volume, i.e., as close to Otto cycle as possible

at constant volume $T_x = T_2(P_3/P_2) = (888 \text{ K})(9000/4851) = 1647 \text{ K}$

$(AF) = 1/(FA) = 1/0.054 = 18.52$

total heat in is found by combining Eqs. (3-76), (3-81), and (3-86)
$(Q_{in})_{total} = Q_{2-x} + Q_{x-3} = m_f Q_{HV} \eta_c = (m_a + m_f)c_v(T_x - T_2) + (m_a + m_f)c_p(T_3 - T_x)$
let $\eta_c = 1$ and divide by m_f
$Q_{HV} = (AF + 1)c_v(T_x - T_2) + (AF + 1)c_p(T_3 - T_x)$
$42{,}500 \text{ kJ/kg} = 19.52(0.821 \text{ kJ/kg-K})(1647 - 888)\text{K} + (19.52)(1.108 \text{ kJ/kg-K})(T_3 - 1647)\text{K}$
$T_3 = 3050 \text{ K}$

pressure ratio using Eq. (3-79) $\alpha = P_x/P_2 = 9000/4851 = 1.855$
cutoff ratio using Eq. (3-85) $\beta = T_3/T_x = 3050/1647 = 1.852$
thermal efficiency using Eq. (3-89)
$(\eta_t)_{DUAL} = 1 - (1/r_c)^{k-1}[\{\alpha\beta^k - 1\}/\{k\alpha(\beta - 1) + \alpha - 1\}]$
$= 1-(1/18)^{0.35}[\{1.855(1.852)^{1.35}-1\}/\{(1.35)(1.855)(1.852-1)+1.855-1\}] = 0.603 \underline{= 60.3\%}$

(b) $T_{peak} = T_3 = 3050 \text{ K} \underline{= 2777° \text{ C}}$ from above

(c) minimum thermal efficiency is when combustion is at constant pressure, i.e., operate as a Diesel cycle
Eq. (3-58)
$Q_{HV}\eta_c = (AF+1)c_p(T_3-T_2) = (42{,}500 \text{ kJ/kg})(1) = (18.52+1)(1.108 \text{ kJ/kg-K})(T_3-888 \text{ K})$
$T_3 = 2853 \text{ K}$

cutoff ratio using Eq. (3-62) $\beta = T_3/T_2 = 2853/888 = 3.213$
thermal efficiency using Eq. (3-73)
$(\eta_t)_{DIESEL} = 1 - (1/r_c)^{k-1}[(\beta^k - 1)/\{k(\beta - 1)\}]$
$= 1 - (1/18)^{0.35}[\{(3.213)^{1.35} - 1\}/\{1.35(3.213 - 1)\}] = 0.533 \underline{= 53.3\%}$

(d) $T_{peak} = T_3 = 2853 \text{ K} \underline{= 2580° \text{ C}}$ from above

(3-8)

(a)(b) using Fig.3-11

$T_1 = 60° C = \underline{333\ K}$ given

$\underline{P_1 = 101\ kPa}$ given

Eqs. (3-52) and (3-53)

$T_2 = T_1(r_c)^{k-1} = (333\ K)(14)^{0.35} \underline{= 839\ K} = 566°\ C$

$P_2 = P_1(r_c)^k = (101\ kPa)(14)^{1.35} \underline{= 3561\ kPa}$

Eq. (3-11) with half of heat in at constant volume

$Q_{HV}\eta_c = (AF + 1)c_v(T_x - T_2)$

$½(42{,}500\ kJ/kg)(1) = (20 + 1)(0.821\ kJ/kg\text{-}K)(T_x - 839\ K)$

$\underline{T_x = 2072\ K} = 1799°\ C$

Eq. (3-58) with half of heat in at constant pressure

$Q_{HV}\eta_c = (AF + 1)c_p(T_3 - T_x)$

$½(42{,}500\ kJ/kg)(1) = (20 + 1)(1.108\ kJ/kg\text{-}K)(T_3 - 2072\ K)$

$\underline{T_3 = 2985\ K} = 2712°\ C$

Eq. (3-78)

$P_x = P_2(T_x/T_2) = (3561\ kPa)(2072/839) \underline{= 8794\ kPa = P_3}$

$v_4 = v_1 = RT_1/P_1 = (0.287)(333)/(101) = 0.9462\ m^3/kg$

$v_3 = RT_3/P_3 = (0.287)(2985)/(8794) = 0.0974\ m^3/kg$

Eqs. (3-64) and (3-65)

$T_4 = T_3(v_3/v_4)^{k-1} = (2985\ K)(0.0974/0.9462)^{0.35} \underline{= 1347\ K} = 1074°\ C$

$P_4 = P_3(v_3/v_4)^k = (8794\ kPa)(0.0974/0.9462)^{1.35} \underline{= 408\ kPa}$

(c) Eq. (3-85)

$\beta = T_3/T_x = 2985/2072 \underline{= 1.441}$

(d) Eq. (3-79)

$\alpha = P_3/P_2 = 8794/3561 \underline{= 2.470}$

(e) Eq. (3-89)

$(\eta_t)_{DUAL} = 1 - (1/r_c)^{k-1}[\{\alpha\beta^k - 1\}/\{k\alpha(\beta - 1) + \alpha - 1\}]$

$\eta_t = 1\text{-}(1/14)^{0.35}\{[(2.470)(1.441)^{1.35}\text{-}1]/[(1.35)(2.470)(0.441)+2.470\text{-}1]\} = 0.589 \underline{= 58.9\%}$

(f) Eq. (3-87)

$q_{in} = c_v(T_x - T_2) + c_p(T_3 - T_x)$

$= (0.821\ kJ/kg\text{-}K)(2072 - 839)K + ((1.108\ kJ/kg\text{-}K)(2985 - 2072)K \underline{= 2024\ kJ/kg}$

(g) $w_{net} = \eta_t q_{in} = (0.589)(2024\ kJ/kg) \underline{= 1192\ kJ/kg}$

(3-9)

(a)

using Fig.3-11

Eq. (2-43)

$\dot{W} = 2\pi N\tau = 57$ kJ/sec $= (2\pi$ radians/rev$)(2000/60$ rev/sec$)\tau$

$\tau = 0.272$ kN-m $= \underline{272 \text{ N-m}}$

(b)

for 1 cylinder

$V_d = (0.0033\ m^3)/6 = 0.00055\ m^3$

Eq. (2-12) $\quad r_c = (V_d + V_c)/V_c = 14 = (0.00055 + V_c)/V_c$

$V_c = 0.000042\ m^3$

$V_1 = V_d + V_c = (0.00055\ m^3) + (0.000042\ m^3) = 0.000592\ m^3$

mass in 1 cylinder

$m_1 = P_1V_1/RT_1 = (101)(0.000592)/(0.287)(333) = 0.000626$ kg

using q_{in} and η_t values from Problem 3-8

$Q_{in} = mq_{in} = (0.000626$ kg$)(2024$ kJ/kg$)(6$ cyl$) = 7.602$ kJ/cycle

$(W_i)_{net} = \eta_t Q_{in} = (0.589)(7.602$ kJ/cycle$) = 4.48$ kJ/cycle

Eq. (2-42)

$\dot{W}_i = WN/n = (4.48$ kJ/cycle$)(2000/60$ rev/sec$)/(2$ rev/cycle$) = 74.7$ kW

Eq. (2-47) $\quad \eta_m = \dot{W}_b/\dot{W}_i = 57/74.7 = 0.763 = \underline{76.3\%}$

(c)

Eq. (2-41)

$\tau = (\text{bmep})V_d/4\pi = 272$ N-m $= \text{bmep}(0.0033\ m^3)/4\pi \qquad \underline{\text{bmep} = 1036 \text{ kPa}}$

(d)

with AF = 20, mass of fuel will be (1/21) of total mass

$m_f = (0.000626$ kg/cyl-cycle$)(1/21)(6$ cyl$) = 0.00018$ kg/cycle

$\dot{m}_f = (0.00018$ kg/cycle$)(2000/60$ rev/sec$)/(2$ rev/cycle$)$

$= 0.003$ kg/sec $= 10.8$ kg/hr $= 10{,}800$ gm/hr

Eq. (2-60)

$\text{bsfc} = \dot{m}_f/\dot{W}_b = (10{,}800$ gm/hr$)/(57$ kW$) = \underline{189 \text{ gm/kW-hr}}$

(3-10)

(a)

using Eq. (3-37) and Fig. 3-6

$T_{ex} = T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2800\ K)(100/9000)^{(1.35-1)/1.35}$

$= 872\ K \underline{= 599°\ C}$

(b)

Eq. (3-1h)

$T_4 = T_3(P_4/P_3)^{(k-1)/k} = (2800\ K)(460/9000)^{(1.35-1)/1.35} = 1295\ K$

Eq. (3-46)

$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9)(1295/872)(100/460) = 0.036 \underline{= 3.6\%}$

(c)

velocity will be sonic - choked flow

Eq. (3-1j)

$Vel = c = [kRT]^{½} = [(1.35)(287\ J/kg\text{-}K)(1295\ K)]^{½} \underline{= 708\ m/sec}$

(d)

as velocity is dissipated kinetic energy will be changed to an enthalpy increase

$V^2/2g_c = \Delta h = c_p\Delta T$

$(708\ m/sec)^2/[(2)(1\ kg\text{-}m/N\text{-}sec^2)] = (1.108\ kJ/kg\text{-}K)\Delta T$

$\Delta T = 226°\ K$

$T_{max} = T_7 + \Delta T = 872 + 226 = 1098\ K \underline{= 825°\ C}$

(3-11)

(a)(b)

using Fig. 3-5

$\underline{T_1 = 70° C}$ = 343 K given

$\underline{P_1 = 140 \text{ kPa}}$ given

Eqs. (3-4) and (3-5)

$T_2 = T_1(r_c)^{k-1} = (343 \text{ K})(8)^{0.35} = 710 \text{ K} \underline{= 437° \text{ C}}$

$P_2 = P_1(r_c)^k = (140 \text{ kPa})(8)^{1.35} \underline{= 2319 \text{ kPa}}$

Eq. (3-12)

$q_{in} = c_v(T_3 - T_2) = 1800 \text{ kJ/kg} = (0.821 \text{ kJ/kg-K})(T_3 - 710)\text{K}$

$T_3 = 2902 \text{ K} \underline{= 2629° \text{ C}}$

at constant volume

$P_3 = P_2(T_3/T_2) = (2319 \text{ kPa})(2902/710) \underline{= 9479 \text{ kPa}}$

Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (2902 \text{ K})(1/8)^{0.35} = 1402 \text{ K} \underline{= 1129° \text{ C}}$

$P_4 = P_3(1/r_c)^k = (9479 \text{ kPa})(1/8)^{1.35} \underline{= 572 \text{ kPa}}$

(c)

Eq. (3-18)

$w_{3-4} = R(T_4 - T_3)/(1 - k)$

$= [(0.287 \text{ kJ/kg-K})(1402 - 2902)\text{K}]/(1 - 1.35) \underline{= +1230 \text{ kJ/kg}}$

(d)

Eq. (3-7)

$w_{1-2} = R(T_2 - T_1)/(1 - k)$

$= [(0.287 \text{ kJ/kg-K})(710 - 343)\text{K}]/(1 - 1.35) \underline{= -301 \text{ kJ/kg}}$

(e)

$v_1 = RT_1/P_1 = (0.287)(343)/(140) = 0.7032 \text{ m}^3/\text{kg}$

$v_2 = RT_2/P_2 = (0.287)(710)/(2319) = 0.0879 \text{ m}^3/\text{kg}$

using Eq. (3-35) per unit mass

$w_{pump} = (P_i - P_{ex})(v_1 - v_2)$

$= [(140 - 100)\text{kPa}][(0.7032 - 0.0879)\text{m}^3/\text{kg}] \underline{= 24.6 \text{ kJ/kg}}$

(f)

$w_{net} = (-301) + (+1230) + (+24.6) = 953.6 \text{ kJ/kg}$

$\eta_t = w_{net}/q_{in} = 953.6/1800 = 0.530 \underline{= 53.0\%}$

(3-12)

(a)(b)

using Fig. 3-15

$\underline{T_7 = T_8 = 70^\circ\ C} = 343\ K$ given

$\underline{P_7 = P_8 = 140\ kPa}$ given

$T_2 = T_7(r_c)^{k-1} = (343\ K)(8)^{0.35} = 710\ K \underline{= 437^\circ\ C}$

$P_2 = P_7(r_c)^k = (140\ kPa)(8)^{1.35} \underline{= 2319\ kPa}$

$q_{in} = c_v(T_3 - T_2) = 1800\ kJ/kg = (0.821\ kJ/kg\text{-}K)(T_3 - 710)K$

$T_3 = 2902\ K \underline{= 2629^\circ\ C}$

at constant volume $P_3 = P_2(T_3/T_2) = (2319\ kPa)(2902/710) \underline{= 9479\ kPa}$

$T_4 = T_3(1/r_e)^{k-1} = (2902\ K)(1/10)^{0.35} = 1296\ K \underline{= 1023^\circ\ C}$

$P_4 = P_3(1/r_e)^k = (9479\ kPa)(1/10)^{1.35} \underline{= 423\ kPa}$

at constant volume $T_5 = T_4(P_5/P_4) = (1296\ K)(100/423) = 306\ K \underline{= 33^\circ\ C} = T_6$

$\underline{P_5 = P_6 = 100\ kPa}$ given

(c)

Eq. (3-1i)

$w_{3\text{-}4} = R(T_4 - T_3)/(1 - k) = (0.287\ kJ/kg\text{-}K)(1296 - 2902)K/(1 - 1.35) \underline{= +1317\ kJ/kg}$

(d)

Eq. (3-1i)

$w_{7\text{-}2} = (0.287\ kJ/kg\text{-}K)(710 - 343)K/(1 - 1.35) \underline{= -301\ kJ/kg}$

(e)

$v_5 = RT_5/P_5 = (0.287)(306)/(100) = 0.8790\ m^3/kg$

$v_7 = RT_7/P_7 = (0.287)(343)/(140) = 0.7032\ m^3/kg$

$v_6 = v_7/r_c = 0.7032/8 = 0.0879\ m^3/kg$

$w_{5\text{-}6} = P(v_6 - v_5) = (100)(0.0879 - 0.8790) = -79.1\ kJ/kg$

$w_{6\text{-}7} = P(v_7 - v_6) = (140)(0.7032 - 0.0879) = +86.1\ kJ/kg$

$w_{7\text{-}8}$ cancels $w_{8\text{-}7}$

$w_{pump} = (+86.1) + (-79.1) \underline{= +7.0\ kJ/kg}$

(f)

$w_{net} = (+1317) + (-301) + (+7.0) = +1023\ kJ/kg$

$\eta_t = w_{net}/q_{in} = 1023/1800 = 0.568 \underline{= 56.8\%}$

(3-13)

(a)(b)

using Fig.3-16

$\underline{T_7 = 70^\circ\ C} = 343\ K$ $\qquad \underline{P_7 = 140\ kPa}$ given

$T_2 = T_7(r_c)^{k-1} = (343\ K)(8)^{0.35} = 710\ K \underline{= 437^\circ\ C}$

$P_2 = P_7(r_c)^k = (140\ kPa)(8)^{1.35} \underline{= 2319\ kPa}$

$q_{in} = c_v(T_3 - T_2) = 1800\ kJ/kg = (0.821\ kJ/kg\text{-}K)(T_3 - 710)K$

$T_3 = 2902\ K \underline{= 2629^\circ\ C}$

at constant volume $\qquad P_3 = P_2(T_3/T_2) = (2319\ kPa)(2902/710) \underline{= 9479\ kPa}$

$T_4 = T_3(1/r_c)^{k-1} = (2902\ K)(1/10)^{0.35} = 1296\ K \underline{= 1023^\circ\ C}$

$P_4 = P_3(1/r_c)^k = (9479\ kPa)(1/10)^{1.35} \underline{= 423\ kPa}$

$\underline{P_5 = 100\ kPa = P_6}$ given

at constant volume $\qquad T_5 = T_4(P_5/P_4) = (1296\ K)(100/423) = 306\ K \underline{= 33^\circ\ C} = T_6$

$v_1 = v_5 = v_4 = RT_5/P_5 = (0.287\ kJ/kg\text{-}K)(306\ K)/(100\ kPa) = 0.8790\ kg/m^3$

$v_6 = v_3 = v_2 = v_5/r_c = (0.8790\ m^3/kg)/10 = 0.0879\ m^3/kg$

$v_7 = RT_7/P_7 = (0.287)(343)/(140) = 0.7032\ m^3/kg$

$P_1 = P_7(v_7/v_1)^k = (140\ kPa)(0.7032/0.8790)^{1.35} \underline{= 104\ kPa}$

$T_1 = P_1v_1/R = (104\ kPa)(0.8790\ m^3/kg)/(0.287\ kJ/kg\text{-}K) = 318\ K \underline{= 45^\circ\ C}$

(c)

Eq. (3-1i)

$w_{3\text{-}4} = R(T_4 - T_3)/(1 - k) = (0.287\ kJ/kg\text{-}K)(1296 - 2902)K/(1 - 1.35) \underline{= +1317\ kJ/kg}$

(d)

Eq. (3-1i) $\qquad w_{7\text{-}2} = (0.287\ kJ/kg\text{-}K)(710 - 343)K/(1 - 1.35) \underline{= -301\ kJ/kg}$

(e)

$w_{6\text{-}7} = P(v_7 - v_6) = (140)(0.7032 - 0.0879) = +86.1\ kJ/kg$

$w_{5\text{-}6} = P(v_6 - v_5) = (100)(0.0879 - 0.8790) = -79.1\ kJ/kg$

$w_{7\text{-}1}$ cancels $w_{1\text{-}7}$

$w_{pump} = (+86.1) + (-79.1) \underline{= +7.0\ kJ/kg}$

(f)

$w_{net} = (+1317) + (-301) + (+7.0) = +1023\ kJ/kg$

$\eta_t = w_{net}/q_{in} = 1023/1800 = 0.568 \underline{= 56.8\%}$

(3-14)

(a) Eq.(3-4)

$T_2 = T_1(r_c)^{k-1} = (570\ °R)(10.5)^{1.35-1}$ $\underline{= 1298°R = 838°F}$

(b) $R = r/a = (6.64\ in.)/(1.66\ in.) = 4.0$

Eq.(2-14) gives chamber volume when intake valve closes

$V_1/V_c = 1 + ½(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$

$=(1)+(½)(10.5-1)[(4.0)+(1)-\cos(200°)-\sqrt{(4.0)^2-\sin^2(200°)}]=10.283$

Eq.(2-14) for volume when spark plug fires

$V_2/V_c=(1)+(½)(10.5-1)[(4.0)+(1)-\cos(245°)-\sqrt{(4.0)^2-\sin^2(245°)}]$

$= 1.202$

$V_1/V_2 = (V_1/V_c)/(V_2/V_c) = (10.283)/(1.202) = 8.556$

$T_2 = T_1(V_1/V_2)^{k-1} = (570\ °R)(8.556)^{1.35-1}$ $\underline{= 1208°R = 748°F}$

(3-15)

(a) $P_2 = P_7(r_c)^k = (100\ kPa)(8.2)^{1.35} = 1713\ kPa$

$P_{min} = P_1(1/r_e)^k = (1713\ kPa)(1/10.2)^{1.35}$ $\underline{= 74.5\ kPa}$

(b) Miller cycle has no pump work $\underline{W_{pump} = 0}$

(c) $P_{EVO} = P_4 = P_3(1/r_e)^k = (9197\ kPa)(1/10.2)^{1.35}$ $\underline{= 400\ kPa}$

(3-16)

(a) $R = r/a = (9.5\ in.)/(2.5\ in.) = 3.8$

Eq.(2-14)

$V_2/V_1 = V_2/V_c = 1 + ½(r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$

$=(1)+(½)(10.5-1)[(3.8)+(1)-\cos(110°)-\sqrt{(3.8)^2-\sin^2(110°)}]=7.935$

$T_2 = T_1(V_1/V_2)^{k-1} = (4660°R)(1/7.935)^{1.35-1}$ $\underline{= 2257°R = 1797°F}$

(b) $\underline{(r_c)_{eff} = 7.935}$

(c) $P_7 = P_6[(r_c)_{eff}]^k = (17.8\ psia)(7.935)^{1.35} = 292\ psia$

at constant volume

$T_7 = T_1(P_7/P_1) = (4660°R)(292/1137)$ $\underline{= 1197°R = 737°F}$

(3-17)

(a)

Eq. (2-43)

$\dot{W}_b = 2\pi N\tau = 3600$ kJ/sec $= (2\pi$ radians/rev$)(210/60$ rev/sec$)\tau$

$\underline{\tau = 164 \text{ kN-m} = 164{,}000 \text{ N-m}}$

(b)

Eq. (2-9)

$V_d = N_c(\pi/4)B^2S = (6 \text{ cyl})(\pi/4)(0.35 \text{ m})^2(1.05 \text{ m}) = 0.606 \text{ m}^3 \underline{= 606 \text{ L}}$

(c)

Eq. (2-40)

$\tau = (\text{bmep})V_d/2\pi = 164 \text{ kN-m} = \text{bmep}(0.606 \text{ m}^3)/2\pi$

$\underline{\text{bmep} = 1700 \text{ kPa}}$

(d)

Eq. (2-2)

$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(1.05 \text{ m/stroke})(210/60 \text{ rev/sec}) \underline{= 7.35 \text{ m/sec}}$

(3-18)

(a)

Eq. (2-60)

$\text{bsfc} = \dot{m}_f/\dot{W}_b = (31.7 \text{ gm/min})(60 \text{ min/hr})/(1.42 \text{ kW}) \underline{= 1339 \text{ gm/kW-hr}}$

(b)

Eq. (2-9) with S = B

$V_d = N_c(\pi/4)B^2S = (1 \text{ cyl})(\pi/4)B^2S = (1)(\pi/4)B^3 = 7.54 \text{ cm}^3$

$B = S = 2.13 \text{ cm} = 0.0213 \text{ m}$

Eq. (2-2)

$\bar{U}_p = 2SN = (2 \text{ strokes/rev})(0.0213 \text{ m/stroke})(23{,}000/60 \text{ rev/sec}) \underline{= 16.33 \text{ m/sec}}$

(c)

65% gets trapped, so 35% gets exhausted
in addition only 94% of trapped fuel gets burned

$\dot{m}_{ex} = (0.35)(31.7 \text{ gm/min}) + (1 - 0.94)(0.65)(31.7 \text{ gm/min}) \underline{= 12.3 \text{ gm/min}}$

(d)

Eq. (2-43)

$\dot{W}_b = 2\pi N\tau = 1.42$ kJ/sec $= (2\pi$ radians/rev$)(23{,}000/60$ rev/sec$)\tau$

$\tau = 0.00059 \text{ kN-m} \underline{= 0.59 \text{ N-m}}$

(3-19)

(a)(b)

using Fig.3-21

$\underline{T_1 = T_2 = 70° F} = 530° R$ given

$\underline{P_1 = P_2 = P_0 = 14.7 \text{ psia}}$ given

$V_2 = (\pi/4)B^2(S/2) = (\pi/4)(1 \text{ ft})^2(3 \text{ ft}/2) = 1.178 \text{ ft}^3$

mass of air-fuel in cylinder

$m_2 = P_2V_2/RT_2 = [(14.7)(144) \text{ lbf/ft}^2](1.178 \text{ ft}^3)/[(53.33 \text{ ft-lbf/lbm-°R})(530° R)]$
$= 0.0882 \text{ lbm}$

with AF = 18, then mass of fuel will be

$m_f = (0.0882 \text{ lbm})(1/19) = 0.00464 \text{ lbm}$

Eq. (3-11) assuming combustion efficiency = 100%

$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2)$

$(12{,}000 \text{ BTU/lbm})(1) = (18 + 1)(0.196 \text{ BTU/lbm-°R})(T_3 - 530)°R$

$T_3 = 3752° R \underline{= 3292° F}$

at constant volume

$P_3 = P_2(T_3/T_2) = (14.7 \text{ psia})(3752/530) \underline{= 104 \text{ psia}}$

Eqs.(3-124)and(3-125)with $v_4 = 2v_3$

$T_4 = T_3(v_3/v_4)^{k-1} = (3752° R)(1/2)^{0.35} = 2944° R \underline{= 2484° F}$

$P_4 = P_3(v_3/v_4)^k = (104 \text{ psia})(1/2)^{1.35} \underline{= 40.8 \text{ psia}}$

$\underline{P_5 = 14.7 \text{ psia}}$

at constant volume

$T_5 = T_4(P_5/P_4) = (2944° R)(14.7/40.8) = 1061° R \underline{= 601° F}$

(c)

Eq.(3-133)

$\eta_t = 1 - [(T_4 - T_5) + k(T_5 - T_2)]/(T_3 - T_2)$
$= 1 - [(2944 - 1061)°R + 1.35(1061 - 530)°R]/(3752 - 530)°R$
$= 0.193 \underline{= 19.3\%}$

(d)

for one cycle for 1 side of piston

Eq. (3-126)

$W_{3\text{-}4} = mc_v(T_3 - T_4) = (0.0882\ \text{lbm})(0.196\ \text{BTU/lbm-°R})(3752 - 2944)°\text{R} = 13.97\ \text{BTU}$

Eq. (3-131)

$W_{5\text{-}2} = P_0(V_2 - V_5) = [(14.7)(144)\ \text{lbf/ft}^2][(\pi/4)(1\ \text{ft})^2(-1.5\ \text{ft})]/(778\ \text{ft-lbf/BTU})$
$= -3.21\ \text{BTU}$

$W_{1\text{-}2}$ cancels $W_{2\text{-}1}$

$W_{net} = (13.97\ \text{BTU}) + (-3.21\ \text{BTU}) = 10.76\ \text{BTU}$

indicated power at 140 RPM using Eq. (2-42)

$\dot{W}_i = WN/n = [(10.76\ \text{BTU/cycle})(140/60\ \text{rev/sec})/(1\ \text{rev/cycle})](3600\ \text{sec/hr})$
$= 90{,}384\ \text{BTU/hr} = (90{,}384\ \text{BTU/hr})/(2545\ \text{BTU/hr/hp}) = 35.51\ \text{hp}$

Eq. (2-47) $\dot{W}_b = \dot{W}_i\eta_m = (35.51\ \text{hp})(0.05) = 1.78\ \text{hp}$

using both sides of piston $\dot{W}_b = (2)(1.78\ \text{hp}) = \underline{3.56\ \text{hp}}$

(e)

Eq. (2-2)

$\bar{U}_p = 2SN = (2\ \text{strokes/rev})(3\ \text{ft/stroke})(140/60\ \text{rev/sec}) = \underline{14\ \text{ft/sec}}$

(3-20)

(a)

using Fig. 3-2

$\underline{T_1 = 27°\ C} = 300\ K$ $\underline{P_1 = 100\ \text{kPa}}$ given

Eqs. (3-4) and (3-5)

$T_2 = T_1(r_c)^{k-1} = (300\ k)(8)^{0.35} = 621\ K = \underline{348°\ C}$

$P_2 = P_1(r_c)^k = (100\ \text{kPa})(8)^{1.35} = \underline{1656\ \text{kPa}}$

Eq. (3-12)

$q_{in} = c_v(T_3 - T_2) = 2000\ \text{kJ/kg} = (0.821\ \text{kJ/kg-K})(T_3 - 621)K$
$T_3 = 3057\ K = \underline{2784°\ C}$

at constant volume $P_3 = P_2(T_3/T_2) = (1656\ \text{kPa})(3057/621) = \underline{8152\ \text{kPa}}$

Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (3057\ K)(1/8)^{0.35} = 1476\ K = \underline{1203°\ C}$

$P_4 = P_3(1/r_c)^k = (8152\ \text{kPa})(1/8)^{1.35} = \underline{492\ \text{kPa}}$

(b)

Eq. (3-31)

$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/8)^{0.35} = 0.517 \underline{= 51.7\%}$

(c)

using air tables from Ref. [73]

$\underline{T_1 = 27^\circ\ C} = 300$ K $\underline{P_1 = 100\ kPa}$ given

$v_1 = v_4 = RT_1/P_1 = (0.287$ kJ/kg-K)(300 K)/(100 kPa) $= 0.861$ m^3/kg

Eq. (2-12)

$v_2 = v_1/r_c = (0.861$ m^3/kg)/8 $= 0.1076$ m^3/kg $= v_3$

for isentropic compression using relative specific volumes

$(v_2/v_1) = (v_{r2}/v_{r1}) = (1/8) = v_{r2}/62.393$ $v_{r2} = 7.799$

$T_2 = 673$ K $\underline{= 400^\circ\ C}$ from tables

$P_2 = RT_2/v_2 = (0.287)(673)/(0.1076) \underline{= 1795\ kPa}$

$u_2 = 491.41$ kJ/kg from tables

$q = (u_3 - u_2) = 2000$ kJ/kg $= (u_3 - 491.41$ kJ/kg)

$u_3 = 2491.41$ kJ/kg $T_3 = 2829$ K $\underline{= 2556^\circ\ C}$ from tables

at constant volume

$P_3 = P_2(T_3/T_2) = (1795$ kPa)(2829/673) $\underline{= 7545\ kPa}$

for isentropic expansion using relative specific volumes

$v_{r4} = v_{r3}(v_4/v_3) = (0.08548)(8) = 0.68384$

$T_4 = 1524$ K $\underline{= 1251^\circ\ C}$ from tables

$P_4 = RT_4/v_4 = (0.287)(1524)/(0.861) \underline{= 508\ kPa}$

(d)

Eq. (3-7) using internal energy values from tables

$w_{1-2} = (u_1 - u_2) = 214.32 - 491.41 = -277.09$ kJ/kg

Eq. (3-18)

$w_{3-4} = (u_3 - u_4) = 2491.41 - 1227.32 = 1264.09$ kJ/kg

$w_{net} = (1264.09$ kJ/kg) + (-277.09 kJ/kg) = +987.00 kJ/kg

thermal efficiency

$\eta_t = w_{net}/q_{in} = 987.00/2000 = 0.494 \underline{= 49.4\%}$

CHAPTER 4

(4-1) an unknown amount of fuel burned with an unknown amount of air with z = amount of water removed before analysis

$$x\, C_4H_8 + y\, O_2 + y(3.76)\, N_2 \longrightarrow 14.95\, CO_2 + 0.75\, C_4H_8 + 84.3\, N_2 + z\, H_2O$$

conservation of N	$y(3.76) = 84.3$	$y = 22.42$
conservation of O	$2(22.42) = 2(14.95) + z$	$z = 14.94$
conservation of H	$8x = 8(0.75) + 2(14.94)$	$x = 4.485$

put these into reaction equation

$$4.485\, C_4H_8 + 22.42\, O_2 + 22.42(3.76)\, N_2 \longrightarrow 14.95\, CO_2 + 0.75\, C_4H_8 + 84.3\, N_2 + 14.94\, H_2O$$

divide by 4.485

$$C_4H_8 + 5\, O_2 + 5(3.76)\, N_2 \longrightarrow 3.33\, CO_2 + 0.167\, C_4H_8 + 18.80\, N_2 + 3.33\, H_2O$$

(a) Eqs. (2-55) and (4-1)
$AF = m_a/m_f = N_aM_a/N_fM_f = [5(4.76)(29)]/[(1)(56)] \underline{= 12.325}$

(b) stoichiometric reaction equation

$$C_4H_8 + 6\, O_2 + 6(3.76)\, N_2 \longrightarrow 4\, CO_2 + 4\, H_2O + 6(3.76)\, N_2$$

stoichiometric air-fuel ratio $\quad (AF)_{stoich} = [6(4.76)(29)]/[(1)(56)] = 14.79$

Eq. (4-2) $\quad \phi = (AF)_{stoich}/(AF)_{act} = 14.79/12.325 \underline{= 1.20}$

(c) Eq. (4-6)
$Q_{LHV} = Q_{HHV} - \Delta h_{vap}$ (evaporation of water in products)
for 1 kgmole of fuel in stoichiometric reaction there are 4 kgmoles of water

for 1 mole of fuel (h_{fg} value at 25° C from Ref. [90])
$\Delta h_{vap} = (4\text{ kgmoles})(18\text{ kg/kgmole})(2442.3\text{ kJ/kg}) = 175.85\text{ MJ}$

for 1 kg of fuel $\quad \Delta h_{vap} = (175.85\text{ MJ})/56 = 3.1\text{ MJ}$

$Q_{LHV} = Q_{HHV} - \Delta h_{vap} = (46.9\text{ MJ/kg}) - (3.1\text{ MJ/kg}) \underline{= 43.8\text{ MJ/kg}}$

(d) Eq. (2-63)
$Q_{in} = m_fQ_{LHV}\eta_c = (1\text{ kg})(43.8\text{ MJ/kg})(0.98) \underline{= 42.9\text{ MJ}}$

(4-2)

```
    H  C2H5 C2H5  H
    |   |    |    |
H - C - C -- C -- C - H
    |   |    |    |
    H  CH3   H    H
```

<u>Paraffin Family</u>

stoichiometric chemical reaction

$$C_9H_{20} + 14\ O_2 + 14(3.76)\ N_2 \longrightarrow 9\ CO_2 + 10\ H_2O + 14(3.76)\ N_2$$

reaction with equivalence ratio $\phi = 0.7$

$$C_9H_{20} + (14/0.7)\ O_2 + (14/0.7)(3.76)\ N_2 \longrightarrow 9\ CO_2 + 10\ H_2O + (14/0.7)(3.76)\ N_2 + 6\ O_2$$

this reduces to

$$C_9H_{20} + 20\ O_2 + 20(3.76)\ N_2 \longrightarrow 9\ CO_2 + 10\ H_2O + 20(3.76)\ N_2 + 6\ O_2$$

Eqs. (2-55) and (4-1)
$AF = m_a/m_f = N_aM_a/N_fM_f = [(14)(4.76)(29)]/[(1)(128)]$ $\underline{= 15.10}$

(4-3)

(a)

```
    H    H   CH3  CH3   H    H
    |    |    |    |    |    |
H - C -- C -- C -- C -- C -- C - H
    |    |    |    |    |    |
    H    H    H    H    H    H
```

C_8H_{18}

<u>isomer of octane</u>

(b)

```
    H   C2H5  H   C2H5  H
    |    |    |    |    |
H - C -- C -- C -- C -- C - H
    |    |    |    |    |
    H    H    H    H    H
```

C_9H_{20}

<u>isomer of nonane</u>

(c)

```
    H    H   CH3   H    H
    |    |    |    |    |
H - C -- C -- C -- C -- C - H
    |    |    |    |    |
    H    H   C2H5  H    H
```

C_8H_{18}

<u>isomer of octane</u>

(4-4)

chemical reaction equation

$$H_2 + \tfrac{1}{2} O_2 \longrightarrow H_2O$$

(a) Eqs. (2-56) and (4-1)
$FA = m_f/m_a = N_fM_f/N_aM_a = [(1)(2)]/[(0.5)(32)]$ $\underline{= 0.125}$

(b) stoichiometric $\underline{\phi = 1}$

(c) (using enthalpy values for water from Introduction to Thermodynamics, by Sonntag and Van Wylen, 3rd ed., John Wiley and Sons, 1991)

Eqs. (4-5) and (4-8)
$\Sigma_{PROD}N_i(h_f^o + \Delta h)_i = \Sigma_{REACT}N_i(h_f^o + \Delta h)_i$
$(1)[(-241,826) + \Delta h]_{H_2O} = (1)[0 + 0)]_{H_2} + (\tfrac{1}{2})[0 + 0]_{O_2}$
$\Delta h_{H_2O} = 241,826$ kJ/kgmole $\quad$ $\underline{T_{max} = 4991\ K}$

(d) exhaust is all H_2O with $P_{H_2O} = P_{ex} = 101$ kPa $\quad$ $\underline{T_{DP} = 100° C}$

(4-5)

stoichiometric combustion equation

$$C_8H_{18} + 12.5\ O_2 + 12.5(3.76)\ N_2 \longrightarrow 8\ CO_2 + 9\ H_2O + 12.5(3.76)\ N_2$$

at equivalence ratio $\phi = 0.833$

$$C_8H_{18} + (12.5/0.833)O_2 + (12.5/0.833)N_2 \longrightarrow 8\ CO_2 + 9\ H_2O + (12.5/.833)(3.76)N_2 + 2.5\ O_2$$

this reduces to

$$C_8H_{18} + 15\ O_2 + 15(3.76)\ N_2 \longrightarrow 8\ CO_2 + 9\ H_2O + 15(3.76)\ N_2 + 2.5\ O_2$$

(a) Eqs. (2-55) and (4-1)
$AF = m_a/m_f = N_aM_a/N_fM_f = [(15)(4.76)(29)]/[(1)(114)]$ $\underline{= 18.16}$

(b) amount of air relative to stoichiometric
% air = [(15)(4.76)]/[(12.5)(4.76)] = 1.20 = 120% air $\underline{= \text{20\% excess air}}$

(c) Eq. (4-9) and values from Table A-2
AKI = (MON + RON)/2 = (100 + 100)/2 $\underline{= 100}$

Eq. (4-10) and values from Table A-2 $\quad$ FS = RON - MON = 100 - 100 $\underline{= 0}$

(4-6)

stoichiometric combustion

$CH_3NO_2+0.75O_2+(0.75)(3.76)N_2 \rightarrow CO_2+1,5H_2O+[(0.75(3.76)+½]N_2$

at equivalence ratio $\phi = 1.25$

$CH_3NO_2 + (0.75/1.25)\ O_2 + (0.75/1.25)(3.76)\ N_2$
$\rightarrow 0.8\ CO_2 + 1.2\ H_2O + [0.75(3.76)+½]/(1.25)\ N_2 + 0.2\ CH_3NO_2$

this reduces to

$CH_3NO_2+0.6\ O_2+0.6(3.76)\ N_2 \rightarrow 0.8\ CO_2+1.2\ H_2O+2.656\ N_2+0.2\ CH_3NO_2$

(a)

% air = [(0.6)(4.76)]/[(0.75)(4.76)] = 0.80 = 80% stoichiometric air

(b)

Eqs. (2-55) and (4-1)
$AF = m_a/m_f = N_aM_a/N_fM_f$ = [(0.6)(4.76)(29)]/[(1)(61)] = 1.36

(4-7)

stoichiometric combustion reaction

$$CH_3OH + 1.5\ O_2 + 1.5(3.76)\ N_2 \longrightarrow CO_2 + 2\ H_2O + 1.5(3.76)\ N_2$$

at equivalence ratio $\phi = 0.75$

$$CH_3OH + (1.5/0.75)\ O_2 + (1.5/0.75)\ N_2 \longrightarrow CO_2 + 2\ H_2O + (1.5/0.75)(3.76)\ N_2 + 0.5\ O_2$$

this reduces to

$$CH_3OH + 2\ O_2 + 2(3.76)\ N_2 \longrightarrow CO_2 + 2\ H_2O + 2(3.76)\ N_2 + 0.5\ O_2$$

(a) Eqs. (2-55) and (4-1)
$AF = m_a/m_f = N_aM_a/N_fM_f = [2(4.76)(29)]/[(1)(32)]$ $\underline{= 8.63}$

(b) mole fraction of water $\quad x = N_{water}/N_{total} = 2/[1 + 2 + 2(3.76) + 0.5] = 0.1815$

vapor pressure of water $\quad P_v = xP_{total} = (0.1815)(101\ kPa) = 18.33\ kPa$

using steam tables from Ref. [90] $\quad \underline{T_{DP} = 58°\ C}$

(c) using psychrometric equations and steam tables from Ref. [90]
$P_v = (rh)P_g = (0.40)(3.169\ kPa) = 1.268\ kPa$

specific humidity
$\omega = 0.622[P_v/(P_{total} - P_v)] = (0.622)[1.268/(101 - 1.268)] = 0.0079\ kg_v/kg_a$

convert this to molar units using Eq. (4-1)
$\omega = (0.0079)(29/18) = 0.0127\ moles_v/moles_a$

adding this amount of water vapor to the inlet reactants

$$CH_3OH + 2\ O_2 + 2(3.76)N_2 + 2(4.76)(.0127)H_2O \longrightarrow CO_2 + 2.12\ H_2O + 2(3.76)N_2 + .5\ O_2$$

mole fraction of water $\quad x = 2.12/[1 + 2.12 + 2(3.76) + 0.5] = 0.190$

vapor pressure of water $\quad P_v = (0.190)(101\ kPa) = 19.22\ kPa$

from steam tables $\quad \underline{T_{DP} = 59°\ C}$

(d) Eq. (4-9)
$AKI = (MON + RON)/2 = (92 + 106)/2$ $\underline{= 99}$

(4-8) thermal efficiency using Eq. (3-31)

$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/8.5)^{0.35} = 0.527$

for 1 cylinder $\qquad V_d = (3\text{ L})/4 = 0.75\text{ L} = 0.00075\text{ m}^3$

Eq. (2-12)

$r_c = (V_d + V_c)/V_c = 8.5 = (0.00075 + V_c)/V_c \qquad V_c = 0.0001\text{ m}^3$

Eq. (2-11) $\quad V_{BDC} = V_d + V_c = (0.00075\text{ m}^3) + (0.0001\text{ m}^3) = 0.00085\text{ m}^3$

mass in cylinder evaluated at BDC after intake

$m = PV/RT = (100\text{ kPa})((.00085\text{ m}^3)/(.287\text{ kJ/kg-K})(333\text{ K}) = .00089\text{ kg} = m_a + m_f$

for 1 cycle using gasoline with AF = 14.6 $\qquad m_f = (0.00089\text{ kg})/15.6 = 0.000057\text{ kg}$

Eq. (2-63)

$Q_{in} = m_f Q_{HV} \eta_c = (0.000057\text{ kg})(43{,}000\text{ kJ/kg})(0.98) = 2.402\text{ kJ/cyl-cycle}$

rate of heat in

$\dot{Q}_{in} = (2.402\text{ kJ/cyl-cycle})(4800/60\text{ rev/sec})(4\text{ cyl})/(2\text{ rev/cycle}) = 384.3\text{ kW}$

Eq. (2-65) $\qquad \dot{W}_i = \dot{Q}_{in}\eta_t = (384.3\text{ kW})(0.527) \underline{= 203\text{ kW}}$ using gasoline

for 1 cycle using methanol with AF = 6.5 $\qquad m_f = (0.00089\text{ kg})/7.5 = 0.000119\text{ kg}$

$Q_{in} = (0.000119\text{ kg})(20{,}050\text{ kJ/kg})(0.98) = 2.338\text{ kJ/cyl-cycle}$

rate of heat in

$\dot{Q}_{in} = (2.338\text{ kJ/cyl-cycle})(4800/60\text{ rev/sec})(4\text{ cyl})/(2\text{ rev/cycle}) = 374.1\text{ kW}$

$\dot{W}_i = (374.1\text{ kW})(0.527) \underline{= 197\text{ kW}}$ using methanol

fuel rate in for gasoline

$\dot{m}_f = (0.000057\text{ kg/cyl-cycle})(4800/60\text{ rev/sec})(4\text{ cyl})/(2\text{ rev/cycle})$

$\qquad = 0.00912\text{ kg/sec} = 9.12\text{ gm/sec} = 32{,}832\text{ gm/hr}$

Eq. (2-61)

$\text{isfc} = \dot{m}_f/\dot{W}_i = (32{,}832\text{ gm/hr})/(203\text{ kW}) \underline{= 161.7\text{ gm/kW-hr}}$ with gasoline

fuel rate in for methanol

$\dot{m}_f = (0.000119\text{ kg/cyl-cycle})(4800/60\text{ rev/sec})(4\text{ cyl})/(2\text{ rev/cycle})$

$\qquad = 0.01904\text{ kg/sec} = 19.04\text{ gm/sec} = 68{,}544\text{ gm/hr}$

$\text{isfc} = (68{,}544\text{ gm/hr})/(197\text{ kW}) \underline{= 347.9\text{ gm/kW-hr}}$ with methanol

(4-9)

stoichiometric combustion equation

$$C_2H_5OH + 3\ O_2 + 3(3.76)\ N_2 \longrightarrow 2\ CO_2 + 3\ H_2O + 3(3.76)\ N_2$$

(a) Eq. (2-57) and stoichiometric value from Table A-2
$(AF)_{act} = (AF)_{stoich}/\phi = 9.0/1.10 \underline{= 8.18}$

(b) using Fig. 3-2 and Eqs. (3-4) and (3-5) for conditions at end of compression
$T_2 = T_1(r_c)^{k-1} = (333\ K)(10)^{0.35} = 745\ K$
$P_2 = P_1(r_c)^{k} = (101\ kPa)(10)^{1.35} = 2261\ kPa$

Eq. (3-11)
$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2)$
$(26{,}950\ KJ/kg)(0.97) = (8.18 + 1)(0.821\ kJ/kg\text{-}K)(T_3 - 745\ K)$
$T_3 = T_{peak} = 4214\ K \underline{= 3941°\ C}$

(c) at constant volume
$P_3 = P_{peak} = P_2(T_3/T_2) = (2261\ kPa)(4214/745) \underline{= 12{,}789\ kPa}$

(4-10)

(a) at stoichiometric $\underline{\phi = 1}$

(b) actual AF will be stoichiometric value for isooctane from Table A-2
$(AF)_{act} = 15.1$

stoichiometric AF for ethanol $(AF)_{stoich} = 9.0$

Eq. (2-57) $\phi = (AF)_{stoich}/(AF)_{act} = 9.0/15.1 \underline{= 0.596}$

(c) Eqs. (2-62), (2-64) and (2-65)
$\dot{Q}_{in} = \dot{m}_f Q_{HV}\eta_c \qquad \dot{W}_i = \eta_t\dot{Q}_{in} \qquad \dot{W}_b = \eta_m\dot{W}_i$

if the air flow rate is the same and the fuel injectors are not readjusted, then the fuel flow rate will be the same

for same η_t, η_c, η_m, $\dot{m}_a$, and $\dot{m}_f$

$(\dot{W}_b)_{ethanol}/(\dot{W}_b)_{isooctane} = (\dot{m}_f Q_{HV}\eta_c\eta_t\eta_m)_{ethanol}/(\dot{m}_f Q_{HV}\eta_c\eta_t\eta_m)_{isooctane}$
$= (Q_{HV})_{ethanol}/(Q_{HV})_{isooctane} = (26{,}950\ kJ/kg)/(44{,}300\ kJ/kg) = 0.608$

<u>there will be a 39.2% decrease in brake power with ethanol</u>

(4-11)

for same thermal efficiency $\dot{W}_{out} \propto \dot{Q}_{in}$

(Eqs.(2-56) and (2-63)

$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (FA)_{stoich} \dot{m}_a Q_{HV} \eta_c$

using values from Table A-2

$\dot{W}_{nitro}/\dot{W}_{gasoline} = [(FA)_s \dot{m}_a Q_{HV} \eta_c]_{nitro}/[(FA)_s \dot{m}_a Q_{HV} \eta_c]_{gasoline}$

$= [(FA)_s Q_{HV}]_{nitro}/[(FA)_s Q_{HV}]_{gasoline}$

$= [(0.588)(10{,}920)]/[(0.068)(43{,}000)] = 2.20 = 220\%$

<u>120% increase in power with nitromethane</u>

(4-12)

for same thermal efficiency $\dot{W}_{out} \propto \dot{Q}_{in}$

Eqs.(2-56) and (2-64)

$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (FA)_{stoich} \dot{m}_a Q_{HV} \eta_c$

using values from Table A-2

$\dot{W}_{methanol}/\dot{W}_{gasoline} = [(FA)_s \dot{m}_a Q_{HV} \eta_c]_{methanol}/[(FA)_s \dot{m}_a Q_{HV} \eta_c]_{gasoline}$

$= [(FA)_s Q_{HV}]_{methanol}/[(FA)_s Q_{HV}]_{gasoline}$

$= [(0.155)(20{,}050)]/(0.068)(43{,}000)] = \underline{1.06}$

$\dot{W}_{nitro}/\dot{W}_{gasoline} = [(FA)_s \dot{m}_a Q_{HV} \eta_c]_{nitro}/[(FA)_s \dot{m}_a Q_{HV} \eta_c]_{gasoline}$

$= [(FA)_s Q_{HV}]_{nitro}/[(FA)_s Q_{HV}]_{gasoline}$

$= [(0.588)(10{,}920)]/[(0.068)(43{,}000)] = \underline{2.20}$

(4-13)

using values from Table A-2

(a)

Eq. (4-9)

$AKI = (MON + RON)/2 = (92 + 113)/2 = \underline{102.5}$

(b)

using Fig. 4-7, 0.2 gm/L raises ON about 4

$MON = 92 + 4 = \underline{96}$

(c) mass of isodecane

$m = (10 \text{ gal})(3.785 \text{ L/gal})(0.001 \text{ m}^3/\text{L})(768 \text{ kg/m}^3) = 29.07 \text{ kg}$

Eq.(2-11) with x = mass of butene-1 needed

$(x + 29.07)(87) = x(80) + (29.07)(92)$ $\quad x = 20.764 \text{ kg}$

gallons of butene-1 needed

$(20.764 \text{ kg})/[(595 \text{ kg/m}^3)(0.001 \text{ m}^3/\text{L})(3.785 \text{ L/gal}) = \underline{9.22 \text{ gal}}$

(4-14)

(a)

use Eq. (2-55) to find mass flow rate of air into engine

$\dot{m}_a = (AF)\dot{m}_f = (1.7)(0.198\ kg/sec) = 0.3366\ kg/sec$

Eq.(2-71)

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

$(2)(0.3366)/(1.181)(0.006)(6000/60) = 0.950$ $\underline{= 95.0\%}$

(b)

$\underline{\dot{m}_a = 0.3366\ kg/sec}$ from above

(c)

fuel into 1 cylinder per cycle

$m_f = [(0.198\ kg/sec)(2\ rev/cycle)]/[(6000/60\ rev/sec)(8\ cyl)]$

$= 0.000495\ kg/cyl\text{-}cycle$

using Eq.(2-63) and heating value from Table A-2

$Q_{in} = m_f Q_{HV} \eta_c = (0.000495\ kg)(10{,}920\ kJ/kg)(0.99)$ $\underline{= 5.35\ kJ}$

(d)

unburned fuel

$\dot{m}_f = (0.198\ kg/sec)(1 - \eta_c) = (0.198)(0.01) = 0.00198\ kg/sec$

$\dot{Q}_{exhaust} = (0.00198\ kg/sec)(10{,}920\ kJ/kg)$ $\underline{= 21.6\ kW}$

(4-15)

(a)

Good alternate fuel:

can be obtained from many sources
decrease in some emissions
high octane number
high h_{fg} which results in cooler engine cycle

(b)

Poor alternate fuel:

low energy content - about twice as much fuel needed
high aldehyde emissions
corrosive to many materials
poor starting characteristics

(4-16)

(a)

using Table A-3 and method from Ref. [90]

$\log_{10} K_e = -0.913$ $\underline{K_e = 0.1222}$

(b)

stoichiometric reaction equation

$\frac{1}{2} O_2 + \frac{1}{2} N_2 \longrightarrow NO$

because N and O combine 1 to 1 there will be equal amounts of N_2 and O_2 at equilibrium and the actual reaction will be:

$\frac{1}{2} O_2 + \frac{1}{2} N_2 \longrightarrow x\,NO + y\,O_2 + y\,N_2$

Eq. (4-4)

$K_e = [(N_C^{\nu_C} N_D^{\nu_D})/(N_A^{\nu_A} N_B^{\nu_B})](P/N_{total})^{\Delta\nu} = 0.1222 = [x/y^{1/2}y^{1/2})][50/(x+2y)]^{1-1/2-1/2} = x/y$

conservation of nitrogen $1 = x + 2y$ $x = 1 - 2y$

$0.1222 = (1 - 2y)/y$ $y = 0.4712$ $x = 1 - 2y = 0.0576$

moles of NO at equilibrium $\underline{N_{NO} = 0.0576}$

(c)

moles of O_2 at equilibrium $\underline{N_{O_2} = 0.4712}$

(d)

equilibrium is independent of pressure because pressure term in equilibrium equation is equal to 1

moles of NO at equilibrium $\underline{N_{NO} = 0.0576}$

(e)

actual reaction equation

$\frac{1}{2} O_2 + \frac{1}{2} N_2 + Ar \longrightarrow x\,NO + y\,O_2 + y\,N_2 + Ar$

$K_e = 0.1222 = [x(1)/y^{1/2}y^{1/2}(1)][50/(x+2y+1)]^{1+1-1/2-1/2-1} = x/y$

the argon coefficients cancel and because the pressure term equals 1, neither the presence of argon nor the high pressure affect final equilibrium

moles of NO at equilibrium $\underline{N_{NO} = 0.0576}$

(4-17)

(a) stoichiometric combustion equation

$H_2 + ½\, O_2 + ½(3.76)\, N_2 \rightarrow H_2O + ½(3.76)\, N_2$

$(AF)_{stoich} = [(½)(4.76)(29)]/[(1)(2)] = 34.51$

Eq.(2-57)

$\phi = (AF)_{stoich}/(AF)_{act} = (34.51)/(30)$ $\underline{= 1.15}$

(b) Eq.(2-58)

$\lambda = 1/\phi = (1)/(1.15)$ $\underline{= 0.869}$

(c) at AF = 30

$H_2 + x\, O_2 + x(3.76)\, N_2 \rightarrow$ products

$AF = [x(4.76)(29)]/[(1)(2)] = 30 \qquad x = 0.4347$

actual reaction equation

$H_2 + 0.4347O_2 + (0.4347)(3.76)N_2 \rightarrow 0.8694H_2O + (0.4347)(3.76)N_2 + 0.1306H_2$

Eq.(4-5) with enthalpy values from reference [90]

$Q = \Sigma_{PROD} N_i h_i - \Sigma_{REACT} N_i h_i$

$= (0.8694)[(-241,826)-(0)] + (0.4347)(3.76)[(0)+(0)]$
$+ (0.1306)[(0)+(0)] - (1)[(0)+(0)] - (0.4347)[(0)+(0)]$
$- (0.4347)(3.76)[(0)+(0)]$ $\underline{= 210,244\ kJ}$

(4-18)

(a) stoichiometric reaction for one mole of fuel

$½CH_3OH + ½C_4H_8 + (15/4)O_2 + (15/4)(3.76)N_2 \rightarrow (5/2)CO_2 + 3H_2O + (15/4)(3.76)N_2$

$AF = [(15/4)(4.76)(29)]/[(½)(32)+(½)(56)]$ $\underline{= 11.76}$

(b) find mass percents

methanol $m = (½)(32) = 16kg$ mass % $(16/44) = 0.364$

butene-1 $m = (½)(56) = \underline{28kg}$ $(28/44) = 0.636$

44kg

Eq.(4-11)

$ON = (\%\ of\ A)(ON_A) + (\%\ of\ B)(ON_B)$

$RON = (0.364)(106) + (0.636)(99) = 101.55$

$MON = (0.364)(92) + (0.636)(80) = 84.37$

Eq.(4-9)

$AKI = (MON+RON)/2 = [(101.55) + (84.37)]/(2)$ $\underline{= 93.0}$

(4-19)

(a) actual reaction

$H_2 \rightarrow x\, H + 2x\, H_2$

conservation of H

$2 = x + 2x$ $\qquad \underline{x = 0.40}$

(b) Eq.(4-4) with $A = H_2$ and $C = H$ $\qquad B = D = 0$

$K_e = [(x^2)/(2x)][1/(x + 2x)]^{2-1} = 1/6$ $\underline{= 0.1667}$

(c) $\log_{10}K_e = -0.7781$

by interpolation in Table A-3 for reaction (A) $\underline{T = 3362\ K}$

(4-20)

stoichiometric combustion equation using Table A-2

$$0.20\ C_8H_{18} + 0.2\ C_7H_{16} + 0.2\ C_{10}H_{22} + 0.4\ C_7H_8 + 11.4\ O_2 + 11.4(3.76)\ N_2 \longrightarrow 7.8\ CO_2 + 7.2\ H_2O + 11.4(3.76)\ N_2$$

(a)

Eqs. (2-55) and (4-1)

$$AF = m_a/m_f = N_aM_a/N_fM_f$$
$$= [(11.4)(4.76)(29)]/[(0.2)(114)+(0.2)(100)+(0.2)(142)+(0.4)(92)] \underline{= 14.57}$$

(b)

for 1 mole of fuel

	moles (N)	molecular weight(M)	mass m=NM	mass fraction
C_8H_{18}	0.2	114	22.8	0.211
C_7H_{16}	0.2	100	20.0	0.185
$C_{10}H_{22}$	0.2	142	28.4	0.263
C_7H_8	0.4	92	36.8	0.341
			108.0	1.000

108 = molecular weight of gas mixture

Eq. (4-11)

$$RON = (0.211)(100)+(0.185)(112)+(0.263)(113)+(0.341)(120) \underline{= 112}$$

(c)

for 1 mole of fuel

$$Q_{LHV} = (22.8)(44{,}300)+(20.0)(44{,}440)+(28.4)(44{,}220)+(36.8)(40{,}600)$$
$$= 4{,}648{,}768\ \text{kJ/kgmole}$$

$$Q_{LHV} = (4{,}648{,}768\ \text{kJ/kgmole})/(108\ \text{kg/kgmole}) \underline{= 43{,}044\ \text{kJ/kg}}$$

(4-21)

using values from Table A-2

	mass (m)	molecular weight(M)	moles N=m/M	mole fraction
C_8H_{18}	1	114	0.00877	0.142
CH_3OH	1	32	0.03125	0.506
C_2H_5OH	1	46	0.02174	0.352
			0.06176	1.000

stoichiometric combustion equation for one mole of fuel

$$0.142\ C_8H_{18} + 0.506\ CH_3OH + 0.352\ C_2H_5OH + 3.59\ O_2 + 3.59(3.76)\ N_2 \longrightarrow 2.346\ CO_2 + 3.346\ H_2O + 3.59(3.76)\ N_2$$

(a)

Eqs. (2-55) and (4-1)

$AF = m_a/m_f = N_aM_a/N_fM_f$

$= [(3.59)(4.76)(29)]/[(0.142)(114)+(0.506)(32)+(0.352)(46)]$ $\underline{= 10.20}$

(b)

Eqs. (4-11), (4-10) and (4-9)

MON = ⅓(100) + ⅓(92) + ⅓(89) $\underline{= 93.7}$

RON = ⅓(100) + ⅓(106) + ⅓(107) $\underline{= 104.3}$

FS = RON - MON = 104.3 - 93.7 $\underline{= 10.6}$

AKI = (MON + RON)/2 = (93.7 + 104.3)/2 $\underline{= 99}$

(4-22)

(a)

Eq. (4-12) CN = (23) + (0.15)(77) $\underline{= 34.6}$

(b)

specific gravity $s_g = \rho/\rho_{water} = 860/997 = 0.863$

Eq. (4-13)

$G = (141.5/0.863) - 131.5 = 32.46$

$T_{mp} = 229°\ C = 444°\ F$

$$CI = -420.34 + 0.016\ G^2 + 0.192\ G(\log_{10}T_{mp}) + 65.01(\log_{10}T_{mp})^2 - 0.0001809\ T_{mp}^2$$

$$= -420.34+(0.016)(32.46)^2+(0.192)(32.46)(\log_{10}[444])+(65.01)(\log_{10}[444])^2-(0.0001809)(444)^2$$

$= 32.9$

% error = [(32.9 - 34.6)/34.6](100) $\underline{= -4.91\%}$

(4-23)

$N = (2400/60 \text{ rev/sec})(360 \text{ deg/rev}) = 14{,}400 \text{ deg/sec}$

$ID = (15°)/(14{,}400 \text{ deg/sec}) \underline{= 0.0010 \text{ sec}}$

(4-24)

(a) stoichiometric combustion equation

$C_6H_{14}+(19/2)O_2+(19/2)(3.76)N_2 \rightarrow 6CO_2+7H_2O+(19/2)(3,76)N_2$

$(AF)_{stoic} = [(19/2)(4.76)(29)]/[(1)(86)] = 15.25$

Eq.(2-57)

$\phi = (AF)_{stoich}/(AF)_{act} = (15.25)/(25) \underline{= 0.610}$

(b) Eq.(2-58)

$\lambda = 1/\phi = (1)/(0.610) \underline{= 1.64}$

(c) Eq.(4-13)

$T_{mp} = 69°C = 156°F$

$G = (141.5/S_g)-(131.5) = [(141.5)/(0.659)]-(131.5) = 83.2$

$CI=-420.34+0.016G^2+0.192G(\log_{10}T_{mp})+65.01(\log_{10}T_{mp})^2-0.0001809T_{mp}^2$

$= (-420.34)+(0.016)(83.2)^2+(0.192)(83.2)[\log_{10}(156)]$

$+(65.01)[\log_{10}(156)]^2- (0.0001809)(156)^2 \underline{= 33.7}$

(4-25)

(a) Eq.(4-14) gives ignition delay in crank angle degrees

$E_A = (618,840)/(CN + 25) = (618,840)/(51 + 25) = 8143$

$ID=(.36+.22U_p)\exp\{E_A[(1/R_uT_ir_c^{k-1})-(1/17190)][(21.2)/(P_ir_c^{k}-12.4)]^{0.63}\}$

$=[0.36+(0.22)(9.50)]\exp(8143[(1/((8.314)(320)(16)^{1.35-1})-(1/17,190)][21.2/((1.1)(16)^{1.35})-12.4)]^{0.63})$

$= 4.08°$

start of injection

$x + (4.08°) = 12° \text{ bTDC}$ $\underline{x = 16.08° \text{ bTDC}}$

(b) Eq.(4-15)

$ID(ms) = ID(ca)/(0.006\ N) = (4.08)/[(0.006)(1295)]$

$\underline{= 0.525 \text{ ms}}$

(4-26)

specific gravity

$s_g = \rho/\rho_{water} = 720/997 = 0.722$

Eq. (4-13)

$G = (141.5/0.722) - 131.5 = 64.48$

$T_{mp} = 91° C = 195.2° F$

$CI = -420.34 + 0.016\ G^2 + 0.192\ G(\log_{10}T_{mp}) + 65.01(\log_{10}T_{mp})^2 - 0.0001809\ T_{mp}^2$

$= -420.34 + (0.016)(64.48)^2 + (0.192)(64.48)(\log_{10}[195.2])$
$+ (65.01)(\log_{10}[195.2])^2 - (0.0001809)(195.2)^2 \underline{= 8.7}$

(4-27)

$[CO + \frac{1}{2}(3.76)N_2]$ equals 2.88 moles of fuel

mass of fuel in 2.88 kgmoles using Eq. (4-1)

$m_f = (1)(28) + (\frac{1}{2})(3.76)(28) = 80.64\ kg$

mass of fuel in 1 kgmole = molecular weight

$M = m/N = (80.64\ kg)/(2.88\ kgmoles) = 28\ kg/kgmole$

(a) higher heating value in 2.88 kgmoles of fuel

$= [(28kg)(10,100kJ/kg)]_{CO} + [(\frac{1}{2})(3.76)(28)kg(0kJ/kg)]_{N2} = 282,800kJ$

higher heating value in 1 kgmole of fuel

$= (282,800\ kJ)/(2.88\ kgmoles) = 98,194\ kJ/kgmole$

higher heating value in mass units

$Q_{HHV} = (98,194\ kJ/kgmole)/(28\ kg/kgmole) \underline{= 3507\ kJ/kg}$

because there is no water vapor $\quad Q_{LHV} = Q_{HHV} \underline{= 3507\ kJ/kg}$

(b) stoichiometric combustion equation

$CO + \frac{1}{2}(3.76)\ N_2 + \frac{1}{2}\ O_2 + \frac{1}{2}(3.76)\ N_3 \longrightarrow CO_2 + (3.76)\ N_2$

Eqs. (2-55) and (4-1)

$AF = m_a/m_f = N_aM_a/N_fM_f = [\frac{1}{2}(4.76)(29)]/[(2.88)(28)] \underline{= 0.856}$

(c) <u>no dew point</u> as there is no water vapor

CHAPTER 5

(5-1)

(a) Eqs. (3-4) and (3-5)

$T_2 = T_1(r_c)^{k-1} = (336\ K)(11)^{0.35} \underline{= 778\ K} = 505°\ C$

$P_2 = P_1(r_c)^k = (92\ kPa)(11)^{1.35} \underline{= 2342\ kPa}$

(b) crankshaft offset = a = S/2 = 5.72/2 = 2.86 cm

R = r/a = 11.0/2.86 = 3.85

crank angle when intake valve closes and actual compression starts

$\theta = 180° + 41° = 221°$

crank angle when ignition occurs $\theta = 345°$

using Eq. (2-14) for combustion chamber volume when intake valve closes

$V_{IVC}/V_c = 1 + \frac{1}{2}(r_c - 1)[R + 1 - \cos\theta - (R^2 - \sin^2\theta)^{1/2}]$

$V_{IVC}/V_c = 1 + \frac{1}{2}(11 - 1)\{(3.85) + (1) - \cos(221°) - [(3.85)^2 - \sin^2(221°)]^{1/2}\} = 10.05$

combustion chamber volume when ignition occurs

$V_{ig}/V_c = 1 + \frac{1}{2}(11 - 1)\{(3.85) + (1) - \cos(345°) - [(3.85)^2 - \sin^2(345°)]^{1/2}\} = 1.214$

effective compression ratio

$V_{IVC}/V_{ig} = (V_{IVC}/V_c)/(V_{ig}/V_c) = (10.05)/(1.214) = 8.28$

(c) $T_2 = (336\ K)(8.28)^{1.35-1} \underline{= 704\ K = 431°C}$

$P_2 = (92\ kPa)(8.28)^{1.35} \underline{= 1596\ kPa}$

(5-2)

(a) using Fig. 3-5 and Eq. (3-4)

$T_2 = T_1(r_c)^{k-1} = (333\ K)(10.5)^{0.35} = 758\ K \underline{= 485°\ C}$

(b) Eq. (3-4) $758\ K = (353\ K)(r_c)^{0.35}$ $\underline{r_c = 8.88}$

(c) using Fig.5-19 and Eq.(5-15) with k = 1.4

$T_{2s} = T_1(P_2/P_1)^{(k-1)/k} = (333\ K)(130/96)^{(1.4-1)/1.4} = 363\ K$

Eq. (5-14) $(\eta_s)_{sc} = (T_{2s} - T_1)/(T_{2A} - T_1)$

$0.82 = (363 - 333)/(T_{2A} - 333)$ $T_{2A} = 370\ K = 97°\ C$

$\Delta T = T_{2A} - T_{inlet} = 97° - 80° \underline{= 17°\ C}$

(5-3)

(a)

use Eq. (2-57) for actual air-fuel ratio

$(AF)_{act} = (AF)_s/\phi = 14.6/0.95 = 15.37$

using low temperature value of c_p

$Q_{evap} = m_f h_{fg} = m_m c_p \Delta T = (m_a + m_f)c_p \Delta T$

$h_{fg} = [(m_a + m_f)/m_f]c_p \Delta T = (AF + 1)c_p \Delta T$

$(307\ kJ/kg)[0.4299\ (BTU/lbm)/(kJ/kg)] = (16.37)(0.240\ BTU/lbm\text{-}°R)\Delta T$

$$\Delta T = 34°\ F$$

$$T_2 = T_1 - \Delta T = 74° - 34° \underline{= 40°\ F} = 500°\ R$$

(b)

stoichiometric combustion reaction

$$C_8H_{15} + 11.75\ O_2 + 11.75(3.76)\ N_2 \longrightarrow 8\ CO_2 + 7.5\ H_2O + 11.75(3.76)\ N_2$$

combustion reaction with equivalence ratio $\phi = 0.95$

$$C_8H_{15}+(11.75/.95)O_2+(11.75/0.95)(3.76)N_2 \longrightarrow 8\ CO_2+7.5\ H_2O+(11.75/.95)(3.76)N_2+0.62O_2$$

this reduces to

$$C_8H_{15} + 12.37\ O_2 + 12.37(3.76)\ N_2 \longrightarrow 8\ CO_2 + 7.5\ H_2O + 12.37(3.76)\ N_2 + 0.62\ O_2$$

volume flow of air is reduced by volume of fuel vapor

in molar quantities volume flow of air with evaporation

$(\dot{Vol}_a)_{with} = (\dot{Vol}_a)_1(N_{without}/N_{with}) = [(12.37)(4.76)]/[(12.37)(4.76) + 1]$

$= 0.983\ (\dot{Vol}_a)_1$

this volume flow rate is now increased by reduction in temperature

$$(\dot{Vol}_a)_{final} = [0.983(\dot{Vol}_a)_1][(534°\ R)/(500°\ R)] = 1.050\ (\dot{Vol}_a)_1$$

<u>5.0% increase in η_v</u>

(c)

Eq. (3-50)

$T_1 = x_r T_{ex} + (1 - x_r)T_a = (0.05)(900°\ R) + (1 - 0.05)(500°\ R) = 520°\ R \underline{= 60°\ F}$

(5-4)

(a) cooling with water evaporation

$Q_{evap} = m_w h_{fg} = m_m c_p \Delta T = (m_a + m_f + m_w) c_p \Delta T$

$h_{fg} = \{[m_a+m_f+m_w]/m_w\} c_p \Delta T = \{[m_a+m_f+(m_f/30)]/(m_f/30)\} c_p \Delta T = [30(AF)+31] c_p \Delta T$

$1052\ \text{BTU/lbm} = [30(15.37) + 31](0.240\ \text{BTU/lbm-°R})\Delta T$

$\Delta T = 9°\ \text{F} \qquad T = T_2 - \Delta T = 40° - 9° = \underline{31°F = 491°R}$

(b) volume flow of air is reduced by volume of water vapor

moles of water for 1 mole of fuel using Eq. (4-1)

$m_f/m_w = 30 = N_f M_f / N_w M_w = (1)(111)/N_w(18) \qquad N_w = 0.206$

for every mole of fuel there are 0.206 moles of water vapor

original volume flow of air is reduced by both fuel vapor and water vapor

in molar quantities volume flow of air with evaporation

$(Vol_a)_{with} = (Vol_a)_1 (N_{without}/N_{with})$

$= (Vol_a)_1 [(12.37)(4.76)]/[(12.37)(4.76) + 1.206] = 0.980\ (Vol_a)_1$

this volume flow rate is now increased by reduction in temperature

$(Vol_a)_{final} = (Vol_a)_1 [(534°\ R)/(495°\ R)] = 1.057\ (Vol_a)_1$

<u>5.7% increase in η_v</u>

(5-5)

(a) When a turbocharger is used cylinder inlet air temperature is usually higher due to compressive heating, depending on amount of aftercooling. The compression ratio is often then reduced to lower the additional compressive heating that occurs during the compression stroke. If this were not done there would be a chance of combustion temperature becoming too high with resulting self-ignition and knock problems.

(b) Brake power could be increased or decreased depending on amount of pressure increase, aftercooling, compression ratio change, and exhaust pressure increase due to turbine of turbocharger.

(c) By air-standard Otto cycle analysis reducing the compression ratio will lower the indicated thermal efficiency [Eq. (3-31)]. However, greater indicated power generated in the cylinders along with basically the same mechanical efficiency will increase real brake thermal efficiency.

(d) Engine knock is not a problem in CI engines.

(5-6)

for 1 cylinder

$V_d = (2.4 \text{ L})/4 = 0.6 \text{ L} = 0.0006 \text{ m}^3$

(a)

using Eq.(2-71) for air flow rate into one cylinder at WOT

$\dot{m}_a = \rho_a V_d N \eta_v / n = (1.181)(0.0006)(5800/60)(0.95)/2 = 0.03254 \text{ kg/sec}$

Eq. (2-55) gives fuel flow rate into 1 cylinder which is the flow rate through an injector

$\dot{m}_f = \dot{m}_a/AF = (0.03254 \text{ kg/sec})/14.6 \underline{= 0.00223 \text{ kg/sec}}$

(b)

using Eq.(2-71) for air flow rate into one cylinder at WOT

Eq.(2-71) for air flow rate into one cylinder at idle

$m_a = [(1.181)(30/101)(0.0006)(600/60)]/(2) = 0.001052 \text{ kg/sec}$

Eq.(2-55) gives fuel flow into one cylinder

$m_f = (0.001052 \text{ kg/sec})/(14.6) = 0.0000721 \text{ kg/sec}$

fuel flow into one cylinder for one cycle at idle

$m_f=(.0000721\text{kg/sec})(2\text{rev/cycle})/(600/60\text{rev/sec})=0.0000144\text{kg/cycle}$

time of injection

$t = (0.0000144 \text{ kg})/(0.00223 \text{ kg/sec}) \underline{= 0.0065 \text{ sec}}$

(c)

rotational speed at idle

$(600/60 \text{ rev/sec})(360°/\text{rev}) = 3600°/\text{sec}$

time of injection = $(3600°/\text{sec})(0.0065 \text{ sec}) \underline{= 23.4°}$

(5-7)

use Eq. (2-57) to get actual AF ratio

$(AF)_{act} = (AF)_{stoich}/\phi = 9.0/1.06 = 8.49$

for 1 cylinder $\quad V_d = (2.4\ L)/6 = 0.4\ L = 0.0004\ m^3$

(a)

Eq.(2-70) gives mass of air into one cylinder for one cycle

$m_a = \rho_a V_d \eta_v = (1.181\ kg/m^3)(0.0004\ m^3)(0.87) = 0.000411\ kg$

Eq. (2-55) gives mass of fuel into 1 cylinder for 1 cycle

$m_f = m_a/(AF)_a = (0.000411\ kg)/8.49 = 0.0000484\ kg$

time of injection = (0.0000484 kg)/(0.02 kg/sec) $\underline{= 0.00242\ sec}$

(b)

actual AF from above $\quad \underline{(AF)_a = 8.49}$

(c)

when auxiliary injector is used at 3000 RPM

time of 1 cycle

$t = (2\ rev/cycle)/(3000/60\ rev/sec) = 0.04\ sec/cycle$

mass of fuel from port injector for 1 cylinder for 1 cycle

$m_f = 0.0000484\ kg$

mass of fuel from auxiliary injector for 1 cyl for 1 cycle

$m_f = (0.003\ kg/sec)(0.04\ sec)/(6\ cylinders) = 0.000020\ kg$

Eq. (2-55) for 1 cylinder for 1 cycle

$AF = m_a/m_f = 0.000411/(0.0000484 + 0.000020) \underline{= 6.01}$

(5-8)

Temperature of the air-fuel mixture at intake manifold exit could either increase or decrease as engine speed is increased. The mixture will pass through the manifold quicker allowing less time for heating from the hotter walls. However, a higher flow rate will increase the convection heat transfer rate. Also at higher speed engine components, including intake manifold, will be hotter. The amount of fuel that vaporizes in the manifold will change, changing the amount of evaporative cooling. Exit temperature will depend on many parameters including engine speed increase, engine geometry, type of fuel, air-fuel ratio, etc.

(5-9)

use Eq. (2-70) to get air flow rate needed at max speed
$\dot{m}_a = \rho_a V_d N \eta_v / n = (1.181)(0.0062)(6500/60)(0.88)/2 = 0.349$ kg/sec

for each of 4 barrels
$\dot{m}_a = (0.349 \text{ kg/sec})/4 = 0.0873$ kg/sec

(a)

use Eq. (5-12) for throat area of 1 barrel
$(\dot{m}_a)_{max} = 236.5\ C_{Dt}[A_t] = 0.0873 = (236.5)(0.95)[A_t]$

$$A_t = 0.0003886 \text{ m}^2 = 3.886 \text{ cm}^2 = (\pi/4)d_t^2$$

$\underline{d_t\ 2.224 \text{ cm}}$

(b)

Eq. (2-55) gives fuel flow rate needed for 1 barrel
$\dot{m}_f = \dot{m}_a/(AF) = (0.0873 \text{ kg/sec})/15 = 0.00582$ kg/sec

Eq. (5-10) gives pressure in carburetor throat
$P_t = (0.5283)P_0 = (0.5283)(101 \text{ kPa}) = 53.4$ kPa

Eqs. (5-6) and (5-7) give pressure differential in fuel capillary
$\Delta P_f = \Delta P_a = P_0 - P_t = 101 - 53.4 = 47.6$ kPa

use Eq. (5-8) for fuel capillary tube flow area
$\dot{m}_f = C_{Dc}A_c[2\rho_f \Delta P_f]^{1/2}$
$0.00582 \text{ kg/sec} = (0.85)A_c[(2)(750 \text{ kg/m}^3)(47.6 \text{ kN/m}^2)(1 \text{ kg-m/N-sec}^2)]^{1/2}$

$$A_c = 0.00000081 \text{ m}^2 = 0.81 \text{ mm}^2 = (\pi/4)d_c^2$$

$\underline{d_c = 1.016 \text{ mm}}$

(5-10)

(a) The choke is first closed by stepping the accelerator pedal fully down. The closed choke creates a high vacuum downstream through the carburetor. This causes a high fuel flow rate through both the fuel capillary tube and the idle valve. With a low air flow rate the resulting air-fuel mixture is very fuel-rich. Because only a very small percent of the fuel evaporates in the cold engine intake, the rich mixture is needed to assure a combustible air-fuel vapor mixture.

(b) When an automobile is accelerated the throttle valve is quickly opened to increase air intake rate. The gaseous air inflow rate increases quickly but the increase rate of the liquid fuel droplets and wall film is slower due to the higher mass inertia of the liquid. This would result in a fuel-lean mixture and poor acceleration. An accelerator pump adds addition fuel at this time to avoid the fuel deficiency that would occur. The result is a fuel-rich mixture which is desirable during acceleration.

(c) When the carburetor throttle is closed to decelerate an automobile which is traveling at high speed a large vacuum is created in the intake system. The engine is turning at high speed but there is very little air flow into the engine. Exhaust gases back flow into the intake manifold due to the low pressure there. This results in a high exhaust residual remaining in the cylinders for the next cycle. The low pressure after the throttle valve in the carburetor causes a fuel flow through the idle valve. This fuel mixes with the low air flow giving a fuel-rich mixture into the engine. This rich mixture is needed to give acceptable combustion because of the large exhaust residual.

(5-11)

(a)

Eq. (5-3) with 1 intake valve

$(A_i)_1 = \pi d_v l = \pi(3.4\ cm)[(0.22)(3.4\ cm)] = 7.99\ cm^2$

with two intake valves

$(A_i)_2 = (2\ valves)\pi(2.7\ cm)[(0.22)(2.7\ cm)] = 10.08\ cm^2$

increase in flow area

$\Delta A = (10.08\ cm^2) - (7.99\ cm^2) \underline{= 2.09\ cm^2}$

(b)

Advantages:

Greater intake valve flow area which improves volumetric efficiency.

Greater exhaust valve flow area which allows for a shorter exhaust blowdown process.

Greater flexibility in intake be allowing variation in valve timing and lift between the two valves.

Disadvantages:

Need for greater number and/or more complex camshafts.

Higher cost in manufacturing.

Difficulty of fitting valves into combustion chamber surface.

(5-12)

(a)

Eq.(5-27) gives mass flow rate through injector

$\dot{m}_f = C_D A_n[2\rho_f \Delta P]^{1/2}$

$= (0.72)[(\pi/4)(0.073\ mm)^2][2(860\ kg/m^3)(50 - 5\ MPa)(1\ kg\text{-}m/N\text{-}sec^2)]^{1/2} = 0.000838\ kg/sec$

$\dot{m}_f = 0.000838\ kg/sec = \rho_f(Vel)A = (860\ kg/m^3)(Vel)[(\pi/4)(0.073\ mm)^2]$

$\underline{Vel = 233\ m/sec}$

(b)

distance to travel $x = B/2 = (8.2\ cm)/2 = 4.1\ cm = 0.041\ m$

time $= (0.041\ m)/(233\ m/sec) \underline{= 0.00018\ sec}$

(5-13) for 1 cylinder using Eq. (2-8)

$V_d = 3.6/6 = 0.6\ L = 0.0006\ m^3 = (\pi/4)B^2S = (\pi/4)(1.06)B^3$

$B = 0.0897\ m = 8.97\ cm \qquad S = (1.06)(8.97\ cm) = 9.50\ cm$

(a) sonic velocity at inlet conditions using Eq. (3-1j)

$c = [kRT]^{1/2} = [(1.40)(287\ J/kg\text{-}K)(333\ K)]^{1/2} = 366\ m/sec$

Eq. (2-2) gives average piston velocity at maximum speed

$(\bar{U}_p)_{max} = 2SN = (2\ strokes/cycle)(0.0950\ m/stroke)(7000/60\ rev/sec) = 22.17\ m/sec$

Eq. (5-4) gives area for the 2 valves

$A_i = CB^2[(\bar{U}_p)_{max}/c_i] = (1.3)(8.97\ cm)^2(22.17\ m/sec)/(366\ m/sec) = 6.34\ cm^2$

using Eqs. (5-1) and (5-3) for 1 valve

$A_i = 6.34/2 = 3.17\ cm^2 = \pi d_v l = \pi d_v(d_v/4) = (\pi/4)d_v^2 \qquad \underline{d_v = 2.01\ cm}$

(b) maximum flow velocity will be sonic $\quad \underline{V_{max} = c = 366\ m/sec}$ from above

(c) with proper design valves could be fit into combustion chamber with difficulty

(5-14)

mass of fuel in 1 injection from Example Problem 5-4 $\quad m_f = 0.0000396\ kg$

mass of 1 fuel droplet $\quad m_f = (Vol)\rho_f = (3 \times 10^{-14}\ m^3)(860\ kg/m^3) = 2.580 \times 10^{-11}\ kg$

(a) # of droplets = $(0.0000396\ kg)/(2.580 \times 10^{-11}\ kg/droplet) = \underline{1.535 \times 10^6\ droplets}$

(b) from Example Problem 5-9 $\quad V_d = 0.00064\ m^3$ for one cylinder

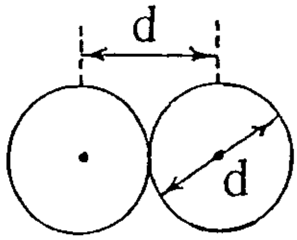
use Eq. (2-12) to find clearance volume

$r_c = 18 = (V_c + V_d)/V_c = (V_c + 0.00064)/V_c \qquad V_c = 0.0000376\ m^3$

volume occupied by 1 droplet = $Vol = V_c/\# = 0.0000376\ m^3/1.535 \times 10^6 = 2.450 \times 10^{-11}\ m^3$

if volume occupied by droplet is assumed a sphere

$Vol = (\pi/6)d^3 = 2.450 \times 10^{-11}\ m^3 \qquad d = 0.000360\ m = 0.360\ mm$



distance between droplets will be about equal to sphere diameter

$\underline{distance \approx 0.360\ mm}$

(5-15)

(a)

Eq.(2-71)

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

$=(0.61)(1.181 kg/m^3)(0.0022 m^3/cycle)(2100/60 rev/sec)/(2 rev/cycle)$

$\underline{= 0.0277\ kg/sec}$

(b)

Eq.(2-55) for fuel flow rate into engine

$\dot{m}_f = \dot{m}_a/AF = (0.0277\ kg/sec)/(21) = 0.00132\ kg/sec$

Eq.(2-65) gives brake power with this fuel flow rate

$\dot{W}_b = \eta_t \dot{m}_f Q_{HV} \eta_c = (0.45)(0.00132 kg/sec)(42,500 kJ/kg)(0.98) = 24.75 kW$

same equation to find fuel flow rate for two-cylinder engine

$(24.75 kW) = (0.42)\dot{m}_f(42,500 kJ/kg)(0.98)$ $\quad \dot{m}_f = 0.001415 kg/sec$

Eq.(2-55) gives air flow rate needed

$\dot{m}_a = \dot{m}_f(AF) = (0.001415\ kg/sec)(21)$ $\underline{= 0.0297\ kg/sec}$

(c)

Eq.(2-71) gives engine speed for this air flow rate

$(.0297 kg/sec) = (.82)(1.181 kg/m^3)(.0011 m^3/cycle)(N/60 rev/sec)/(2 rev/cycle)$

$\underline{N = 3348\ RPM}$

(5-16)

(a)

engine speed at 3000 RPM

$(3000/60\ rev/sec)(360°/rev) = 18,000°/sec$

crank angle rotation in 0.004 seconds

$\angle = (18,000\ °/sec)(0.004\ sec) = 72°$

angle when intake valve opens

$x + 72° = 20°$ aTDC $\quad$ $\underline{x = 52°\ bTDC}$

(b)

engine speed at 1200 RPM

$(1200/60\ rev/sec)(360°/rev) = 7200°/sec$

crank angle rotation in 0.002 seconds

$\angle = (7200°/sec)(0.002\ sec) = 14.4°$

angle when intake valve opens

$x + 14.4° = 20°$ aTDC $\quad$ $\underline{x = 5.6°\ aTDC}$

(5-17)

(a)

Eq. (2-71)

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

$= (0.93)(1.181 kg/m^3)(0.460 m^3/cycle)(195/60 rev/sec)/(2 rev/cycle)$

$\underline{= 1.642\ kg/sec}$

(b)

Eq. (2-55)

$\dot{m}_f = \dot{m}_a/AF = [(1.642\ kg/sec)(0.92)]/(6.5)$ $\underline{= 0.232\ kg/sec}$

(c)

average flow rate of diesel fuel

$\dot{m}_{df} = [(1.642\ kg/sec)(0.08)]/(14.5) = 0.00906\ kg/sec$

diesel fuel for one cylinder for one cycle

$m = (0.00906 kg/sec)/[(195/60 rev/sec)(12 cylinders)(1 cycle/rev)]$

$= 0.000232\ kg/cycle\text{-}cyl$

engine speed = $(195/60\ rev/sec)(360°/rev) = 1170°/sec$

time of one injection $t = (21°)/(1170°/sec) = 0.0180 sec$

flow rate through injector

$\dot{m}_f = (0.000232\ kg)/(0.0180\ sec)$ $\underline{= 0.0130\ kg/sec}$

(5-18)

(a)

air-fuel mass trapped in cylinder after valves are closed

$m_{mt} = (0.000440\ kg)(1 - 0.046) = 0.000420\ kg$

Eq. (5-24) gives mass of air-fuel ingested

$m_{mi} = m_{mt}/\lambda_{te} = (0.000420\ kg)/(0.760) = 0.000553\ kg$

Eq. (5-22)

$\lambda_{dr} = m_{mi}/V_d\rho_a = (0.000553 kg)/[(0.0015/3 m^3)(1.181 kg/m^3)]$ $\underline{= 0.936}$

(b)

Eq. (5-23)

$\lambda_{ce} = m_{mt}/V_d\rho_a = (0.000420 kg)/[(0.0005 m^3)(1.181 kg/m^3)]$ $\underline{= 0.711}$

(c)

Eq. (5-25)

$\lambda_{se} = m_{mt}/m_{tc} = (0.000420\ kg)/(0.000440\ kg)$ $\underline{= 0.955}$

(d)

Eq. (5-26)

$\lambda_{rc} = m_{tc}/V_d\rho_a = \lambda_{ce}/\lambda_{se}$

$= (0.000440 kg)/[(1.181 kg/m^3)(0.0005 m^3)] = (0.711)/(0.955)$

$\underline{= 0.745}$

(5-19)

(a)

Eq.(5-22) gives air-fuel flow into engine

$\dot{m}_{mi} = \lambda_{dr} V_d \rho_a = (0.95)(0.003\ m^3)(1.181\ kg/m^3) = 0.1683\ kg/sec$

air flow only

$\dot{m}_a = (0.1683\ kg/sec)[(14.6)/(15.6)]$ $\underline{= 0.1575\ kg/sec}$

(b)

fuel flow into engine

$\dot{m}_f = (0.1683\ kg/sec)[(1)/(15.6)] = 0.0108\ kg/sec$

oil flow into engine

$\dot{m}_o = (0.0108\ kg/sec)/(25)$ $\underline{= 0.00043\ kg/sec}$

(c)

85% of intake is trapped and burned,

15% escapes during scavanging

$\dot{m}_o = (0.00043\ kg/sec)(0.15)$ $\underline{= 0.000065\ kg/sec = 0.23\ kg/hr}$

(5-20)

chemical reaction equation with nitrous oxide

$C_8H_{18} + 5\ N_2O + 10\ O_2 + 10(3.76)\ N_2 \rightarrow 8\ CO_2 + 9\ H_2O + 47.6\ N_2$

Eq.(4-5) using enthalpy values from reference [90]

$Q_{in} = \Sigma_{PROD} N_i H_i - \Sigma_{REACT} N_i H_i$

$= (8)[(-393,522)+(33,397)]+(9)[(-241,826)+(26,000)]$

$+(47.6)[(0)+(21,463)]-(1)[(-259,280)+(0)]$

$-(5)[(-81,600)+(0)]-(10)[(0)+(0)]-(37.6)[(0)+(0)]$

$= -3,134,515\ kJ$

this heat amount is increased because of less air required

$Q_{in} = (-3,134,515\ kJ0[(12.5)/(10)] = -3,918,144\ kJ$

cooling by evaporation of nitrous oxide

$mc_p\Delta T = h_{fg}(\text{number of moles})$

$10(4.76)\text{kgmoles}(29\ kg/kgmole)(1.005\ kJ/kg\text{-}K)\Delta T$

$= (11,037\ kJ/kgmole)(5\ kgmoles)$

$\Delta T = 40\ K$ $\qquad T_{final} = 298\ K - 40 = 258\ K$

this increases density of air and increases heat in

$Q_{in} = (-3,918,144\ kJ)[(298)/(258)] = -4,525,608\ kJ$

$\Delta\% = [(4,525,600-3,555,000)/(3,555,000)](100)$ $\underline{= 27.3\%\ \text{increase}}$

<u>200 kW becomes 255 kW</u>

CHAPTER 6

(6-1)

Eq. (2-8) for 1 cylinder
$V_d = 2.4/3 = 0.8\ L = 0.0008\ m^3 = (\pi/4)B^2S = (\pi/4)B^2(0.0979\ m)$

$B = 0.102\ m = 10.2\ cm$

Eq. (6-1) during compression stroke
$(SR)_1 = \omega/N = 4.8 = \omega/(2100/60\ rev/sec)$

$\omega = 168\ rev/sec$

Eq. (6-3) gives mass moment of inertia during compression
$I = mB^2/8 = (0.001\ kg)((0.102\ m)^2/8 = 1.30 \times 10^{-6}\ kg\text{-}m^2$

Eq. (6-4) gives angular momentum
$\Gamma = I\omega = (1.30 \times 10^{-6}\ kg\text{-}m^2)(168\ rev/sec)(2\pi\ radians/rev) = 0.001372\ kg\text{-}m^2/sec$

(a)

mass moment of inertia at TDC
$I = (0.001\ kg)(0.060\ m)^2/8 = 4.50 \times 10^{-7}\ kg\text{-}m^2$

using Eq. (6-4) keeping angular momentum constant
$\omega = \Gamma/I = (0.001372\ kg\text{-}m^2/sec)/[(4.5 \times 10^{-7}\ kg\text{-}m^2)(2\pi\ radians/rev)] \underline{= 485\ rev/sec}$

(b)

$u_t = \omega r = (485\ rev/sec)(2\pi\ radians/rev)(0.03\ m) \underline{= 91.4\ m/sec}$

(c)

Eq. (2-2)
$\bar{U}_p = 2SN = (2\ strokes/rev)(0.0979\ m/stroke)(2100/60\ rev/sec) = 6.853\ m/sec$

Eq. (6-2)
$(SR)_2 = u_t/\bar{U}_p = (91.4\ m/sec)/(6.853\ m/sec) \underline{= 13.3}$

(6-2) Eq. (2-8) for 1 cylinder

$V_d = 150/4 = 37.5\ \text{in.}^3 = (\pi/4)B^2S = (\pi/4)B^2(0.95\ B)$

$B = 3.69\ \text{in.} \qquad S = (0.95)(3.69\ \text{in.}) = 3.51\ \text{in.}$

Eq. (2-2) gives average piston speed

$\bar{U}_p = 2SN = (2\ \text{strokes/rev})(3.51\ \text{in./stroke})(3600/60\ \text{rev/sec}) = 421.2\ \text{in./sec} = 35.1\ \text{ft/sec}$

(a) Eq. (6-2)

$(SR)_2 = 8 = u_t/\bar{U}_p = u_t/(35.1\ \text{ft/sec}) \qquad \underline{u_t = 281\ \text{ft/sec}}$

(b) $u_t = \omega r = 281\ \text{ft/sec} = \omega(2\pi\ \text{radians/rev})(3.69/2\ \text{in.})/(12\ \text{in./ft})$

$\underline{\omega = 291\ \text{rev/sec}}$

(c) $(SR)_1 = \omega/N = (291\ \text{rev/sec})/(3600/60\ \text{rev/sec}) \underline{= 4.85}$

(6-3)

(a)

Eq.(6-1)

$(SR)_1 = \omega/N = (250\ \text{rev/sec})/(2800/60\ \text{rev/sec}) \underline{= 5.36}$

(b)

$S = 0.92\ B = (0.92)(0.0856\ m) = 0.07875\ m$

Eq.(2-2)

$\bar{U}_p = 2SN$

$=(2\text{strokes/rev})(0.07875\text{m/stroke})(2800/60\text{rev/sec})=7.35\text{m/sec}$

tangential speed

$u_t=\omega r = (250\text{rev/sec})(2\pi\ \text{radians/rev})(0.0428\text{m}) = 67.23\ \text{m/sec}$

Eq.(6-2)

$(SR)_2 = u_t/U_p = (67.23\ \text{m/sec})/(7.35\ \text{m/sec}) \underline{= 9.15}$

(c)

Eq.(6-3) during compression

$I_1 = mB^2/8 = (\text{mass})(0.856\ m)^2/(8) = (\text{mass})(0.000916\text{m}^2)$

at TDC

$I_2 = (\text{mass})(0.050\ m)^2/(8) = (\text{mass})(0.0003125\text{m}^2)$

conservation of momentum using Eq.(6-4)

$\Gamma_1 = \Gamma_2$

$I_1\omega_1 = I_2\omega_2$

$(\text{mass})(0.000916\text{m}^2)(250\ \text{rev/sec}) = (\text{mass})(0.0003125\text{m}^2)\omega_2$

$\underline{\omega_2 = 732.8\ \text{rev/sec}}$

(6-4)

(a)

Eq.(6-5)

ω_t = (TR)N = (1.78)(3200/60 rev/sec) = 94.93 rev/sec

tangential velocity

$u_t = \omega_t r$ = (94.93rev/sec)(2π radians/rev)(0.0090m) $\underline{= 5.37 \text{ m/sec}}$

(b)

Eq.(6-3)

I = $mB^2/8$ = (0.0012 kg)(0.0180 m)^2/8 = 4.86 x 10^{-8} kg-m^2

rotational kinetic energy

KE = $I\omega^2/2g_c$

=4.86x10^{-8}kg-m^2[(94.93rev/sec)(2π radians/rev)]^2/[2(1kg-m/N-sec^2)]

$\underline{= 0.00865 \text{ N-m} = 0.00865 \text{ J}}$

(6-5)

(a)

at end of compression

$T_2 = T_1(r_c)^{k-1}$ = (333 K)(10.2)$^{1.35-1}$ = 751 K

$P_2 = P_1(r_c)^k$ = (100 kPa)(10.2)$^{1.35}$ = 2299 kPa

mass in crevice

m_{crev} = $_{PVcrev}$/RT

= (2299 kPa)[(0.03)V_2]/[(0.287 kJ/kg-K)(453 K)] = 0.5305 V_2

mass in clearance volume

m_{clear}=PV/RT=(2299kPa)V_2/[(0.287kJ/kg-K)(751 K)] = 10.666 V_2

percent mass in crevice

% = {(0.5305 V_2)/[(0.05305 V_2) + (10.666 V_2)]}(100) $\underline{= 4.74\%}$

(b)

m=(0.0042kg/sec)(0.0474trapped)(0.15 not burned)(3600sec/hr)

$\underline{= 0.1075 \text{ kg/hr}}$

(c)

Energy = mQ_{HV} = [(0.0042)(0.0474)(0.15)kg/sec](43,000kJ/kg)

$\underline{= 1.28 \text{ kJ/sec} = 1.28 \text{ kW}}$

(6-6)

Eqs. (3-4) and (3-5) and Fig. 3-2

$T_2 = T_1(r_c)^{k-1} = (338\ K)(10.9)^{0.35} = 780\ K$

$P_2 = P_1(r_c)^k = (98\ kPa)(10.9)^{1.35} = 2465\ kPa$

(a) mass in combustion chamber (clearance volume) at TDC

$m_{cc} = PV_c/RT = (2465\ kPa)V_c/(0.287\ kJ/kg\text{-}K)(780\ K) = 11.011\ V_c$

mass in crevice volume

$m_c = (2465\ kPa)(0.025\ V_c)/(0.287\ kJ/kg\text{-}K)(463\ K) = 0.464\ V_c$

percent of mass in crevice

$\% = \{(0.464\ V_c)/[(0.464\ V_c) + (11.011\ V_c)]\}(100) \underline{= 4.04\%}$

(b) Eq. (3-11)

$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2)$

$(43{,}000\ kJ/kg)(1.0) = (14.6 + 1)(0.821\ kJ/kg\text{-}K)(T_3 - 780)K$

$T_3 = 4137\ K$

at constant volume

$P_3 = P_2(T_3/T_2) = (2465\ kPa)(4137/780) = 13{,}074\ kPa$

mass in clearance volume

$m_{cc} = (13{,}074\ kPa)V_c/(0.287\ kJ/kg\text{-}K)(4137\ K) = 11.011\ V_c$

mass in crevice volume

$m_c = (13{,}074\ kPa)(0.025\ V_c)/(0.287\ kJ/kg\text{-}K)(463\ K) = 2.460\ V_c$

percent of mass in crevice

$\% = \{(2.460\ V_c)/[(2.460\ V_c) + (11.011\ V_c)]\}(100) \underline{= 18.3\%}$

(6-7)

(a)

for 1 cylinder $V_d = 6.8/8 = 0.85\ L = 0.00085\ m^3$

use Eq. (2-12) to find clearance volume of 1 cylinder

$r_c = 18.5 = (V_d + V_c)/V_c = (0.00085 + V_c)/V_c$

$V_c = 0.00004857\ m^3 = 48.57\ cm^3$

$V_{crevice} = (0.03)(0.00004857\ m^3) = 1.46 \times 10^{-6}\ m^3 \underline{= 1.46\ cm^3}$

(b)

Eqs. (3-52) and (3-53) and Fig. 3-11

$T_2 = T_1(r_c)^{k-1} = (348\ K)(18.5)^{0.35} = 966\ K$

$P_2 = P_1(r_c)^k = (120\ kPa)(18.5)^{1.35} = 6164\ kPa$

$P_2 < P_{peak}$ which means engine is operating on Dual cycle and not on Diesel cycle

mass in combustion chamber after compression (clearance volume)

$m = PV_c/RT = (6164\ kPa)V_c/(0.287\ kJ/kg\text{-}K)(966\ K) = 22.233\ V_c$

mass in crevice volume

$m = (6164\ kPa)(0.03\ V_c)/(0.287\ kJ/kg\text{-}K)(463\ K) = 1.392\ V_c$

percent of mass in crevice

$\% = \{(1.392\ V_c)/[(1.392\ V_c) + (22.233\ V_c)]\}(100) \underline{= 5.89\%}$

(c)

$P_x = P_{peak} = 11{,}000\ kPa$ given

at constant volume

$T_x = T_2(P_x/P_2) = (966\ K)(11{,}000/6164) = 1724\ K$

Eq. (3-85) $T_3 = \beta T_x = (2.3)(1724\ K) = 3965\ K$

$P_3 = P_x = 11{,}000\ kPa$

mass in combustion chamber at end of combustion

$m = (11{,}000\ kPa)(2.3\ V_c)/(0.287\ kJ/kg\text{-}K)(3965\ K) = 22.233\ V_c$

mass in crevice volume at end of combustion

$m = (11{,}000\ kPa)(0.03\ V_c)/(0.287\ kJ/kg\text{-}K)(463\ K) = 2.483\ V_c$

percent of mass in crevice

$\% = \{(2.483\ V_c)/[(2.483\ V_c) + (22.233\ V_c)]\}(100) \underline{= 10.05\%}$

(6-8)

(a) engine speed in degrees/sec

(1800/60 rev/sec)(360°/rev) = 10,800 degrees/sec

22° bTDC to 4° aTDC = 26°/injection

time t = (26°/injection)/(10,800 degrees/sec) = <u>0.0024 sec/injection</u>

(b) Eq. (6-1)

$(SR)_1 = 2.8 = \omega/N = \omega/(1800/60 \text{ rev/sec})$ $\omega = 84$ rev/sec

period of swirl = $1/\omega$ = 1/(84 rev/sec) = <u>0.012 sec/rev</u>

(c) Eq. (6-5)

injection time = (period of swirl)/(number of holes)

0.0024 = 0.012/(number of holes) <u>number of holes = 5 holes</u>

(6-9)

(a) for 1 cylinder $V_d = 2.6/4 = 0.65$ L $= 0.00065$ m^3

Eq. (2-12)

$r_c = 10.5 = (V_d + V_c)/V_c = (0.00065 + V_c)/V_c$ $V_c = 0.0000684$ m^3

volume of secondary chamber $V_2 = (0.18)(0.0000684 \text{ m}^3) = 0.0000123$ m^3

volume of primary chamber $V_1 = 0.0000684 - 0.0000123 = 0.0000561$ m^3

in secondary chamber

m_2 = PV/RT = (2100 kPa)(0.0000123 m^3)/(0.287 kJ/kg-K)(700 K)

$= 0.000129 \text{ kg} = m_{a2} + m_{f2} = (AF + 1)m_{f2} = (13.2 + 1)m_{f2}$

$m_{f2} = 0.00000908$ kg

$m_{a2} = (13.2)(0.00000908 \text{ kg}) = 0.0001200$ kg

in primary chamber

m_1 = PV/RT = (2100 kPa)(0.0000561 m^3)/(0.287 kJ/kg-K)(700 K)

$= 0.000586 \text{ kg} = m_{a1} + m_{f1} = (AF + 1)m_{f1} = (20.8 + 1)m_{f1}$

$m_{f1} = 0.0000269$ kg

$m_{a1} = (20.8)(0.0000269 \text{ kg}) = 0.0005595$ kg

overall air-fuel ratio

$AF = (m_{a1}+m_{a2})/(m_{f1}+m_{f2}) = (0.0005595+0.0001200)/(0.0000269+0.00000908)$ = <u>18.9</u>

(b)

Eq. (3-11)

$Q_{HV}\eta_c = (AF + 1)c_v(T_3 - T_2)$

$(43{,}000 \text{ kJ/kg})(0.98) = (13.2 + 1)(0.821 \text{ kJ/kg-K})(T_3 - 700 \text{ K})$

$T_3 = 4315 \text{ K} \underline{= 4042° \text{ C}}$

at constant volume

$P_3 = P_2(T_3/T_2) = (2100 \text{ kPa})(4315/700) \underline{= 12{,}945 \text{ kPa}}$

(c)

mass in secondary chamber before expansion = 0.000129 kg

mass in secondary chamber after expansion (approximate)

$m = PV/RT = (2100 \text{ kPa})(0.0000123 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(4315 \text{ K}) = 0.0000209 \text{ kg}$

amount of mass through orifice during expansion

$\Delta m = 0.000129 - 0.0000209 = 0.000108 \text{ kg}$

expansion takes 7° of engine rotation, so time of expansion

$t = (7/360 \text{ rev})/(2600/60 \text{ rev/sec}) = 0.000449 \text{ sec}$

mass flow rate

$\dot{m} = (0.000108 \text{ kg})/(0.000449 \text{ sec}) = 0.241 \text{ kg/sec} = \rho(\text{Vel})A$

density $\rho = P/RT = (12{,}945 \text{ kPa})/(0.287 \text{ kJ/kg-K})(4315 \text{ K}) = 10.45 \text{ kg/m}^3$

velocity $\text{Vel} = \dot{m}/\rho A = (0.241 \text{ kg/sec})/[(10.45 \text{ kg/m}^3)(0.0001 \text{ m}^2)]$

$\underline{\text{Vel} = 231 \text{ m/sec}}$

CHAPTER 7

(7-1)

(a)

flame travel distance = bore/2 + offset
D_f = (10.2 cm)/2 + 0.6 cm = 5.7 cm = 0.057 m

time = $D_f/(Vel)_f$ = (0.057 m)/(15.8 m/sec) $\underline{= 0.0036 \text{ sec}}$

(b)

combustion starts at 13.5° bTDC

time of combustion in degrees of engine rotation
(0.0036 sec)(1200/60 rev/sec)(360°/rev) = 25.9°

crank position at end of combustion 25.9° - 13.5° $\underline{= 12.4° \text{ aTDC}}$

(7-2)

(a)

$(Vel)_{2000}$ = (0.92)(2000/1200)(15.8 m/sec) $\underline{= 24.23 \text{ m/sec}}$

(b)

real time of combustion development
t = (6.5°)/[(360°/rev)(1200/60 rev/sec)] = 0.00090 sec

time of combustion at 2000 RPM
t = $D_f/(Vel)_f$ = (0.057 m)/(24.23 m/sec) = 0.00235 sec

total time of ignition and combustion at 2000 RPM
t = (0.00090 sec) + (0.00235 sec) = 0.00325 sec

total time in degrees of engine rotation
(0.00325 sec)(2000/60 rev/sec)(360°/rev) = 39.0°

for combustion to end at 12.4° aTDC, spark plug must be fired
39.0° - 12.4° $\underline{= 26.6° \text{ bTDC}}$

(c)

engine rotation during combustion
(0.00235 sec)(2000/60 rev/sec)(360°/rev) = 28.2°

combustion must start 28.2° - 12.4° $\underline{= 15.8° \text{ bTDC}}$

(7-3)

(a) ignition delay of first fuel injected = 8° of rotation
$t = (8°)/[(360°/\text{rev})(1850/60\ \text{rev/sec})] = \underline{0.00072\ \text{sec}}$

(b) $16° - 8° = \underline{8°}$ from problem statement

(c) ignition delay is half of original ID
ID = (0.00072 sec)/2 = 0.00036 sec

time between start of injection and final ignition of last fuel droplets
t = (0.0019 sec) + (0.00036 sec) = 0.00226 sec

in degrees of engine rotation (0.00226 sec)(1850/60 rev/sec)(360°/rev) = 25.1°

crank position when last droplets start to combust 16° bTDC + 25.1° $= \underline{9.1°\ \text{aTDC}}$

(7-4)

(a) using Eq. (2-8) for 1 cylinder of a 4 cylinder engine
$V_d = (3.2\ \text{L})/4 = 0.8\ \text{L} = 0.0008\ \text{m}^3 = (\pi/4)B^2S = (\pi/4)(0.95)B^3$
B = 0.10235 m S = (0.95)(0.10235 m) = 0.0972 m

use Eq. (2-2) to find engine speed
$\bar{U}_p = 8\ \text{m/sec} = 2SN = (2\ \text{strokes/rev})(0.0972\ \text{m/stroke})N$
N = 41.15 rev/sec = 2469 RPM

time of flame	$t = (25°)/[(360°/\text{rev})(41.15\ \text{rev/sec})] = 0.00169\ \text{sec}$
distance of flame travel	$D_f = B/4 = (0.10235\ \text{m})/4 = 0.02559\ \text{m}$
flame speed	$(\text{Vel})_f = D_f/t = (0.02559\ \text{m})/(0.00169\ \text{sec}) = \underline{15.15\ \text{m/sec}}$

(b) using Eq. (2-8) for 1 cylinder of V8 engine
$V_d = (3.2\ \text{L})/8 = 0.4\ \text{L} = 0.0004\ \text{m} = (\pi/4)B^2S = (\pi/4)(0.95)B^3$
B = 0.08124 m S = (0.95)(0.08124 m) = 0.07718 m

use Eq. (2-2) to find engine speed
$\bar{U}_p = 8\ \text{m/sec} = 2SN = (2\ \text{strokes/rev})(0.07718\ \text{m/stroke})N$
N = 51.83 rev/sec = 3110 RPM

time of flame	$t = (25°)/[(360°/\text{rev})(51.83\ \text{rev/sec})] = 0.00134\ \text{sec}$
distance of flame travel	$D_f = B/4 = (0.08124\ \text{m})/4 = 0.02031\ \text{m}$
flame velocity	$(\text{Vel})_f = D_f/t = (0.02031\ \text{m})/(0.00134\ \text{sec}) = \underline{15.15\ \text{m/sec}}$

<u>flame speeds for both engines are the same !!</u>

(7-5)

(a) ID = (0.0065 sec)(310/60 rev/sec)(360°/rev) $\underline{= 12.1°}$

(b) 21° bTDC + 12.1° $\underline{= 8.9° \text{ bTDC}}$

(c) engine rotation per injection (0.019 sec)(310/60 rev/sec)(360°/rev) = 35.3°/injection

crank position 21° bTDC + 35.3° $\underline{= 14.3° \text{ aTDC}}$

(7-6)

Advantages:

shorter flame travel distance - closer to constant volume combustion (higher real thermal efficiency)

less chance of knock

less chance of poor ignition or misfire

Disadvantages:

hard to fit valves and spark plugs into combustion chamber

cost

need for more complex ignition system

(7-7)

(a) actual total fuel $m_f = m_{f1} + m_{f2}$

actual overall fuel-air ratio $(FA)_{act} m_a = (FA)_1 m_{a1} + (FA)_2 m_{a2}$
$(FA)_{act} = [(FA)_1 m_{a1} + (FA)_2 m_{a2}]/m_a$

equivalence ratio using Eq. (2-57)
$\phi = (FA)_{act}/(FA)_{stoich} = [(FA)_1 m_{a1} + (FA)_2 m_{a2}]/[m_a (FA)_{stoich}]$
$= (\phi_1 m_{a1} + \phi_2 m_{a2})/m_a = \phi_1 (m_{a1}/m_a) + \phi_2 (m_{a2}/m_a) = \phi_1 (\text{volume }\%)_1 + \phi_2 (\text{volume }\%)_2$
$= (1.2)(0.22) + (0.75)(0.78) = 0.849$

Eq. (2-57)
$(AF)_{act} = (AF)_{stoich}/\phi = 14.6/0.849 \underline{= 17.2}$

(b) $\underline{\phi = 0.849}$ from above

(7-8)

(a) use Eq.(2-71) for air flow rate into engine
$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.002)(0.92)(3500/60)/2 = 0.06338$ kg/sec

Eq. (2-55) for fuel flow rate
$\dot{m}_f = \dot{m}_a/(AF) = (0.06338$ kg/sec$)/17.2 = 0.003685$ kg/sec

Eq.(2-64)
$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (0.003685$ kg/sec$)(43{,}000$ kJ/kg$)(0.99) = 156.87$ kJ/sec

using Eqs.(2-47) and (2-65)
$\dot{W}_b = \eta_t \dot{Q}_{in} \eta_m = (0.52)(156.87$ kJ/sec$)(0.86)$ $\underline{= 70.15 \text{ kW}}$

(b) Eq.(2-88) bmep = (1000)(70.15)(2)/(2)(3500/60) $\underline{= 1203 \text{ kPa}}$

(c) unburned fuel
$(\dot{m}_f)_{unburned} = \dot{m}_f(1 - \eta_c) = (0.003685$ kg/sec$)(1 - 0.99)(3600$ sec/hr$)$ $\underline{= 0.133 \text{ kg/hr}}$

(d) Eq.(2-60)
bsfc $= \dot{m}_f/\dot{W}_b = (3.685$ gm/sec$)(3600$ sec/hr$)/(70.15$ kW$)$ $\underline{= 189 \text{ gm/kW-hr}}$

(7-9)

(a) use Eq.(2-71) for air flow rate into engine
$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.002)(0.93)(3500/60)/2 = 0.06407$ kg/sec

Eq. (2-55) for fuel flow rate
$\dot{m}_f = \dot{m}_a/(AF) = (0.06407$ kg/sec$)/14.6 = 0.004388$ kg/sec

Eq.(2-64)
$\dot{Q}_{in} = \dot{m}_f Q_{HV} \eta_c = (0.004388$ kg/sec$)(43{,}000$ kJ/kg$)(0.98) = 184.9$ kJ/sec

using Eqs.(2-47) and (2-65)
$\dot{W}_b = \eta_t \dot{Q}_{in} \eta_m = (0.47)(184.9$ kJ/sec$)(0.86)$ $\underline{= 74.74 \text{ kW}}$

(b) Eq.(2-88) bmep = (1000)(74.74)(2)/(2)(3500/60) $\underline{= 1281 \text{ kPa}}$

(c) unburned fuel
$(\dot{m}_f)_{unburned} = \dot{m}_f(1-\eta_c) = (.004388\text{kg/sec})(1-0.98)(3600\text{sec/hr})$$\underline{=0.316 \text{ kg/hr}}$

(d) Eq.(2-60)
bsfc $= \dot{m}_f/\dot{W}_b = (4.388$ gm/sec$)(3600$ sec/hr$)/(74.74$ kW$)$ $\underline{= 211 \text{ gm/kW-hr}}$

(7-10)

(a) $\angle$ = (10° bTDC) - (20° bTDC) $\underline{= 10°}$

(b) t = (10°)/[(2400/60 rev/sec)(360°/rev)] $\underline{= 0.000694 \text{ sec}}$

(c) angle turned during flame propagation
$\angle$ = (2400/60 rev/sec)(360°/rev)(0.001667 sec) = 24°
final crank angle
$\angle$ = (10° bTDC) + (24°) $\underline{= 14° \text{ aTDC}}$

(7-11)

(a) angle turned during flame development
$\angle$ = (1200/60 rev/sec)(360°/rev)(0.00125 sec) = 9°

angle when flame propagation starts
$\angle$ = (19° bTDC) + (9°) $\underline{= 10° \text{ bTDC}}$

(b) time of flame propagation
t = (0.12 m)/(48 m/sec) = 0.0025 sec

angle of flame propagation
$\angle$ = (1200/60 rev/sec)(360°/rev)(0.0025 sec) = 18°

angle when flame propagation ends
$\angle$ = (10° bTDC) + (18°) $\underline{= 8° \text{ aTDC}}$

(c) flame speed at 2400 RPM
u_f = (0.80)(2400/1200)(48 m/sec) = 76.8 m/sec

angle turned during flame propagation
$\angle$ = [(0.12m)/(76.8m/sec)](2400/60rev/sec)(360°/rev) = 22.5°

angle when spark plug should be fired
$\angle$ = (8° aTDC) - (22.5°) $\underline{= 14.5° \text{ bTDC}}$

(d) Eq.(2-2) gives average piston speed
$\bar{U}_p$=2SN=(2strokes/rev)(0.35m/stroke)(1200/60rev/sec)=14.0m/sec

Eq.(2-5)
$U_p/\bar{U}_p = (\pi/2)\sin\theta[1 + (\cos\theta/\sqrt{R^2 - \sin^2\theta})]$
$= (\pi/2)\sin(8°)[1 + (\cos(8°)/\sqrt{(4.23)^2 - \sin^2(8°)})] = 0.2698$
$U_p = (0.2698)\bar{U}_p = (0.2698)(14.0 \text{ m/sec})$ $\underline{= 3.78 \text{ m/sec}}$

(e) Eq.(2-8) gives displacement volume of one cylinder
$V_d = (\pi/4)B^2S = (\pi/4)(0.24 \text{ m})^2(0.35 \text{ m}) = 0.01583 \text{ m}^3$

Eq.(2-12) gives clearance volume
$r_c=(V_c+V_d)/V_c=8.2=(V_c+0.01583)/V_c$ $V_c = 0.002199 \text{ m}^3$

Eq.(2-14)
$V/V_c = 1 + ½ (r_c - 1)[R + 1 - \cos\theta - \sqrt{R^2 - \sin^2\theta}]$
$=(1)+(½)(8.2-1)[(4.23)+(1)-\cos(8°)-\sqrt{(4.23)^2-\sin^2(8°)}] = 1.044$
$V = (1.044)V_c = (1.044)(0.002199 \text{ m}^3)$ $\underline{= 0.00229 \text{ m}^3 = 2.29 \text{ L}}$

(7-12)

(a)

Eq.(3-31)

high-load $\eta_t = 1-(1/r_c)^{1-k} = 1-(1/8.4)^{1-1.35}$ $\underline{= 0.525 = 52.5\%}$

low-load $\eta_t = 1-(1/13.7)^{1-1.35}$ $\underline{= 0.600 = 60.0\%}$

(b)

Eq.(2-71) gives air flow in at high-load

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

$= 1.20(.0739 lbm/ft^3)[380/(12)^3 ft^3/cycle](3200/60 rev/sec)/2 rev/cycle$

$= 0.5200$ lbm/sec

Eq.(2-55) gives fuel flow at high-load

$\dot{m}_f = \dot{m}_a/AF = (0.5200$ lbm/sec$)/(13.5)$ $\underline{= 0.0385 \text{ lbm/sec}}$

at low-load

$\dot{m}_a = (.78)(.0739 lbm/ft^3)([(380)/(12)^3 ft^3/cycle](2100/60 rev/sec)/2$

$= 0.2218$ lbm/sec

$\dot{m}_f = (0.2218$ lbm/sec$)/(22)$ $\underline{= 0.01008 \text{ lbm/sec}}$

(c)

Eq.(2-65) gives indicated power at high-load

$\dot{W} = \eta_t m_f Q_{HV} \eta_c$

$= .525(.0385 lbm/sec)(43000 kJ/kg)(.4299 BTU/lbm/kJ/kg)(.94)(3600 sec/hr)$

$= 1,264,000$ BTU/hr

$\dot{W} = (1,264,000$ BTU/hr$)/(2545$ BTU/hr/hp$)$ $\underline{= 497 \text{ hp}}$

at low-load

$\dot{W} = (0.600)(0.01008)[(43,000)(0.4299)](0.99)(3600)/(2545)$

$\underline{= 157 \text{ hp}}$

(d)

high-load

isfc = (.0385lbm/sec)(3600sec/hr)/(497 hp) $\underline{= 279 \text{ lbm/hp-hr}}$

low-load

isfc = (0.1008lbm/sec)(3600sec/hr)/(157 hp) $\underline{= 231 \text{ lbm/hp-hr}}$

CHAPTER 8

(8-1)

(a)

Eq. (8-3) and Fig. 8-1

$T_{ex} = T_7 = T_4(P_7/P_4)^{(k-1)/k} = (1000\ K)(100/520)^{(1.35-1)/1.35} = 652\ K \underline{= 379°\ C}$

(b)

Eq. (3-46)

$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/8.5)(1000/652)(100/520) = 0.035 \underline{= 3.5\%}$

(c)

Eq. (3-50)

$(T_m)_1 = x_r T_{ex} + (1 - x_r)T_a = (0.035)(652\ K) + (1 - 0.035)(308\ K) = 320\ K \underline{= 47°\ C}$

(d)

Eq. (3-16) $T_4 = 1000\ K = T_3(1/r_c)^{k-1} = T_3(1/8.5)^{0.35}$

$T_3 = 2115\ K \underline{= 1842°\ C}$

(e)

$T_{IVO} = T_{ex} \underline{= 379°\ C}$ from above

(8-2)

(a)

Eq. (8-3) and Fig. 8-1

$T_{ex} = T_7 = T_{EVO}(P_{ex}/P_{EVO})^{(k-1)/k} = (3220\ R)(14.6/70)^{(1.35-1)/1.35} = 2145°\ R \underline{= 1685°\ F}$

(b)

Eq. (3-46)

$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9)(3220/2145)(14.6/70) = 0.035 \underline{= 3.5\%}$

(c)

exhaust residual will be cooled by expansion cooling when intake valve opens

temperature of exhaust residual after intake valve opens

$T_{xr} = T_{ex}(T_{intake}/T_{ex})^{(k-1)/k} = (2145°\ R)(8.8/14.6)^{(1.35-1)/1.35} = 1881°\ R$

Eq. (3-50)

$(T_m)_1 = x_r T_{xr} + (1 - x_r)T_a = (0.035)(1881°\ R) + (1 - 0.035)(595°\ R) = 640°\ R \underline{= 180°\ F}$

$\underline{P_1 = 8.8\ psia}$ given

(8-3)

(a)

Eq. (3-1h) and Fig. 3-16

$P_2 = P_1(T_2/T_1)^{k/(k-1)} = (9000 \text{ kPa})(1548/3173)^{1.35/(1.35-1)}$ $\underline{= 565 \text{ kPa}}$

(b)

sonic velocity using Eq. (3-1j)

$Vel = c = [kRT]^{½} = [(1.35)(287 \text{ J/kg-K})(1548 \text{ K})(1 \text{ kg-m/N-sec}^2)]^{½}$ $\underline{= 774 \text{ m/sec}}$

(8-4)

Otto cycle engine

Eq. (3-16) and Fig. 3-2

$T_{EVO} = T_4 = T_3(1/r_c)^{k-1} = (2400 \text{ K})(1/8.5)^{0.35} = 1135 \text{ K}$ $\underline{= 862° \text{ C}}$

Diesel cycle engine

Eq. (3-62) and Fig. 3-8

$\beta = V_3/V_2$ $\qquad V_3 = \beta V_2$

Eqs. (3-64) and (2-12)

$T_4 = T_3(V_3/V_4)^{k-1} = T_3(\beta V_2/V_4)^{k-1} = T_3(\beta/r_c)^{k-1} = (2400 \text{ K})(1.95/20.5)^{0.35}$

$= 1053 \text{ K}$ $\underline{= 780° \text{ C}}$

(8-5)

1) There is a larger pressure differential pushing the essentially same mass amount through the exhaust valve.

2) When choked flow occurs, sonic velocity through the exhaust valve is greater due to the higher temperature.

(8-6)

(a) use Fig. 8-1

exhaust blowdown lasts for 56° of engine rotation

time $t = (56°)/[(4500/60 \text{ rev/sec})(360°/\text{rev})] = \underline{0.0021 \text{ sec}}$

(b) Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (2700 \text{ K})(1/10.1)^{0.35} = 1202 \text{ K}$

$P_4 = P_3(1/r_c)^k = (8200 \text{ kPa})(1/10.1)^{1.35} = 361 \text{ kPa}$

for 1 cylinder $V_d = (1.8 \text{ L})/3 = 0.6 \text{ L} = 0.0006 \text{ m}^3$

Eq. (2-12)

$r_c = 10.1 = (V_d + V_c)/V_c = (0.0006 + V_c)/V_c$ $V_c = 0.0000659 \text{ m}^3$

Eq. (2-11)

$V_{BDC} = V_c + V_d = 0.0000659 + 0.0006 = 0.0006659 \text{ m}^3$

$m_{EVO} = m_4 = P_4V_4/RT_4 = (361 \text{ kPa})(0.0006659 \text{ m}^3)/(0.287 \text{ kJ/kg-K})(1202 \text{ K})$
$= 0.000697 \text{ kg}$ at start of blowdown

after blowdown at state 7

$P_7 = P_{ex} = 98 \text{ kPa}$ $V = V_{BDC} = 0.0006659 \text{ m}^3$

Eq. (3-37)

$T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2700 \text{ K})(98/8200)^{(1.35-1)/1.35} = 857 \text{ K} = T_{ex}$

$m = PV/RT = (98)(0.0006659)/(0.287)(857) = 0.000265 \text{ kg}$

mass that exits cylinder during blowdown

$\Delta m = (0.000697 \text{ kg}) - (0.000265 \text{ kg}) = 0.000432 \text{ kg}$

$\%\Delta = [(0.000432)/(0.000697)](100) = \underline{62.0\%}$

(c) Eq.(2-8) to find stroke length

$V_d = (\pi/4)B^2S = 600 \text{ cm}^3 = (\pi/4)B^2(0.85B)$

$B = 9.65 \text{ cm}$ $S = (0.85)B = (0.85)(9.65 \text{ cm}) = 8.20 \text{ cm}$

crankshaft offset

$a = S/2 = (8.20 \text{ cm})/(2) = 4.10 \text{ cm}$

$R = r/a = (16.4 \text{ cm})/(4.10 \text{ cm}) = 4.0$

Eq.(2-14) for volume when exhaust valve opens

$V_{EVO}/V_c = 1 + \frac{1}{2}(r_c-1)[R + 1 - \cos\theta - \sqrt{R^2-\sin^2\theta}]$

$= 1 + \frac{1}{2}(10.1 - 1)[(4)+(1)-\cos(124°)-\sqrt{(4)^2-\sin^2(124°)}] = 8.490$

$T_{EVO} = T_3(V_3/V_{EVO})^{k-1} = T_c(V_c/V_{EVO})^{k-1} = (2700\text{K})(1/8.490)^{1.35-1} = 1277\text{K}$

Eq.(3-1)(j) for sonic velocity

$v=c=\sqrt{kRT}=[(1.35)(287\text{J/kg-K})(1277\text{K})(1 \text{ kg-m/N-sec}^2)]^{1/2} = \underline{703 \text{ m/sec}}$

(8-7)

(a) pseudo steady state temperature

$T_{ex} = T_7 = 857$ K $\underline{= 584° C}$ from Prob. (6)

(b) when velocity is dissipated, KE is changed to enthalpy increase

$(Vel)^2/2g_c = \Delta h = c_p \Delta T$

$\Delta T = (Vel)^2/2g_c c_p$

$= (703 m/sec)^2/[(2)(1\ kg\text{-}m/N\text{-}sec^2)(1.108 kJ/kg\text{-}K)(1000\ J/kJ)] = 223°$

$T_{max} = (857) + (223)$ $\underline{= 1080K = 807°C}$

(8-8)

(a)

Eq. (3-37) and Fig. 8-1

$T_7 = T_3(P_7/P_3)^{(k-1)/k} = (2500\ K)(101/6800)^{(1.35-1)/1.35} = 839\ K$ $\underline{= 566° C}$

(b)

Eqs. (3-16) and (3-17)

$T_4 = T_3(1/r_c)^{k-1} = (2500\ K)(1/9.6)^{0.35} = 1133\ K$

$P_4 = P_3(1/r_c)^k = (6800\ kPa)(1/9.6)^{1.35} = 321\ kPa$

Eq. (3-46)

$x_r = (1/r_c)(T_4/T_{ex})(P_{ex}/P_4) = (1/9.6)(1133/839)(101/321) = 0.044$ $\underline{= 4.4\%}$

(c)

total exhaust in cycle = x_r + EGR = 4.4 + 12 = 16.4%

temperature of exhaust after intake valve opens and expansion cooling occurs

$T_{ex} = (839\ K)(75/101)^{(1.35-1)/1.35} = 777\ K$

Eq. (3-50)

$T_1 = x_r T_{ex} + (1 - x_r)T_a = (0.164)(777\ K) + (1 - 0.164)(333\ K) = 406\ K$ $\underline{= 133° C}$

(d)

temperature of flow through intake valve with 12% EGR added to inlet air

Eq. (3-50)

$T_i = (0.12)(777\ K) + (1 - 0.12)(333\ K) = 386\ K$

Eq. (8-6) $\alpha = A_{ex}/A_i = (T_i/T_{ex})^{1/2} = (386/839)^{1/2} = 0.678 = [(\pi/4)d_{ex}^2]/[(\pi/4)d_i^2]$

$d_{ex}/d_i = (0.678)^{1/2}$ $\underline{= 0.82}$

(8-9)

(a) time of blowdown

$t = (48°)/[(3200/60 \text{ rev/sec})(360°/\text{rev})] = \underline{0.0025 \text{ sec}}$

(b) using Fig. 8-1 and Eq.(3-37)

$T_{ex}=T_7=T_{max}(P_{ex}/P_{max})^{k-1/k}=(2800K)(100/6500)^{1.35-1/1.35}\underline{= 949 \text{ K} = 676°C}$

(c) temperature when exhaust valve opens

$T_{EVO}=T_4=T_{max}(P_{EVO}/P_{max})^{k-1/k}=(2800K)(100/6500)^{1.35-1/1.35} = 1462 \text{ K}$

choked flow will be sonic, using eq (3-1)(j)

$u_{ex}=c=\sqrt{kRT}=\sqrt{(1.35)(0.287kJ/kg\text{-}K)(1462K)(1kg\text{-}m/N\text{-}sec^2)(1000J/kJ)}$
$\underline{= 753 \text{ m/sec}}$

(8-10)

(a) using Fig. 8-1 and eq (3-37)

$T_{ex}=T_7=T_{max}(P_{ex}/P_{max})^{k-1/k}=(3100K)(101/7846)^{1.35-1/1.35}\underline{= 1003 \text{ K} = 730°C}$

(b) cylinder volume at TDC

$V_3=mRT/P=(0.000622kg)(0.287kJ/kg\text{-}K)(3100K)/(7846kPa)=0.0000705m^3$

cylinder volume when exhaust valve opens

$V_{EVO} = V_4 = V_3/r_c = (0.0000705 \text{ m}^3)/(9.8) = 0.000691 \text{ m}^3$

cylinder mass at end of blowdown

$m_{ex}=P_{ex}V_4/RT_{ex}=(101kPa)(0.000691m^3)/(0.287kJ/kg\text{-}K)(1003K)$
$\underline{= 0.000242 \text{ kg}}$

(c) mass of one blowdown process in one cylinder

$\Delta m = m_3 - m_{ex} = (0.000622 \text{ kg}) - (0.000242 \text{ kg}) = 0.000380 \text{ kg}$

time valve must be open

$t = (0.000380 \text{ kg})/(0.218 \text{ kg/sec}) = 0.00174 \text{ sec}$

crank angle of blowdown

$\angle = (3800/60 \text{ rev/sec})(360°)(0.00174 \text{ sec}) = 39.7°$

open exhaust valve at $\underline{39.7° \text{ bBDC}}$

(8-11)

(a)

use Eq.(2-71) for mass flow rate of air into engine

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0056)(0.90)(2800/60)/2 = 0.1389 \text{ kg/sec}$

total exhaust flow = air flow + fuel flow

$\dot{m}_{ex} = (\dot{m}_a + \dot{m}_f) = \dot{m}_a(1 + FA) = (0.1389 \text{ kg/sec})(1 + 0.068) \underline{= 0.148 \text{ kg/sec}}$

(b)

Eq. (8-9)

$\dot{W}_t = \dot{m}c_p\Delta T = (0.148 \text{ kg/sec})(1.108 \text{ kJ/kg-K})(44°) \underline{= 7.22 \text{ kW}}$

(8-12)

(a)

density of air entering compressor

$\rho = P/RT = (96\ kPa)/(0.287\ kJ/kg\text{-}K)(300\ K) = 1.115\ kg/m^3$

use Eq. (2-70) for mass flow of air through compressor

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.115)(0.0015)(1.08)(2400/60)/2 \underline{= 0.0361\ kg/sec}$

(b)

mass flow rate of exhaust through turbine = air flow rate + fuel flow rate

$\dot{m}_{ex} = (\dot{m}_a + \dot{m}_f) = \dot{m}_a(1 + FA) = (0.0361\ kg/sec)(1 + 0.068) \underline{= 0.0386\ kg/sec}$

(c)

power needed for compressor using low temperature values of k and c_p

Eq. (5-15) gives T_{out} if compressor is isentropic

$T_{2s} = T_1(P_2/P_1)^{(k-1)/k} = (300\ K)(120/96)^{(1.40-1)/1.40} = 320\ K$

Eq. (5-13) for isentropic power needed to drive compressor

$(\dot{W}_s)_{comp} = \dot{m}_a(h_{out} - h_{in}) = \dot{m}_a c_p(T_{out} - T_{in})$

$= (0.0361\ kg/sec)(1.005\ kJ/kg\text{-}K)(320 - 300)K = 0.726\ kW$

actual power to drive compressor using Eq. (5-14)

$(\dot{W}_{act})_{comp} = (\dot{W}_s)_{comp}/\eta_s = (0.726\ kW)/0.78 = 0.931\ kW$

Eq. (5-13) for actual air temperature at compressor exit

$(\dot{W}_{act})_{comp} = \dot{m}_a c_p(T_{out} - T_{in}) = 0.931\ kW = (0.0361\ kg/sec)(1.005\ kJ/kg\text{-}K)(T_{out} - 300\ K)$

$T_{out} = 326\ K \underline{= 53°\ C}$

(d)

exit temperature if turbine is isentropic

$(T_{out})_s = T_{in}(P_{out}/P_{in})^{(k-1)/k} = (770\ K)(98/119)^{(1.35-1)/1.35} = 732\ K$

isentropic power from turbine

$(\dot{W}_s)_{turb} = \dot{m}_{ex}(h_{in} - h_{out}) = \dot{m}_{ex} c_p(T_{in} - T_{out})$

$= (0.0386\ kg/sec)(1.108\ kJ/kg\text{-}K)(770 - 732)K = 1.625\ kW$

actual power from turbine

$(\dot{W}_{act})_{turb} = \eta_s(\dot{W}_s)_{turb} = (1.625\ kW)(0.80) = 1.30\ kW$

$(\dot{W}_{act})_{turb} = \dot{m}_{ex} c_p(T_{in} - T_{out}) = 1.30\ kW = (0.0386\ kg/sec)(1.108\ kJ/kg\text{-}K)(770\ K - T_{out})$

$T_{out} = 740\ K \underline{= 467°\ C}$

CHAPTER 9

(9-1)

1 kgmole of $C_{12}H_{22}$ has 144 kg of carbon and 22 kg of hydrogen

mass % of carbon in fuel = 144/166 = 0.8675

carbon put into atmosphere
$\dot{m}_{carbon}$ = [(0.8675)(100 gm/mile)](15,000 miles/yr)(0.005) = 6500 gm/yr = <u>6.50 kg/yr</u>

(9-2)

(a)

CI engines operate overall lean.

Exhaust temperature is lower on CI engines.

Solid carbon in exhaust requires larger flow passages.

(b)

Generation of NOx is reduced by using EGR to lower combustion temperatures.

(c)

Less efficient combustion when EGR is used - more chance of slow combustion or misfire.

Lower combustion temperature gives lower cycle thermal efficiency.

Solid carbon in exhaust is abrasive on cylinder components and harmful to lubricating oil.

(9-3)

(a) 1) Not enough oxygen when engine operates fuel-rich.

2) Fuel gets trapped in crevice volume of cylinder.

3) Combustion is quenched in boundary layer of combustion chamber surface.

4) Intake fuel is exhausted during valve overlap.

5) Fuel vapor gets absorbed-desorbed in wall deposits.

6) Fuel vapor gets absorbed-desorbed in oil film on wall.

7) Poor combustion of oil in combustion chamber.

(b) Lean:

```
Engine generates lower HC and CO (Fig.9-1)
Slightly lean generates high NOx (Fig.9-1)
Catalytic converter is inefficient for NOx (Fig.9-11)
```

Stoichiometric:

```
Catalytic converter most efficient for all emissions (Fig.9-11)
High engine temperatures, so high generation of NOx
```

Rich:

```
Engine generates high levels of HC and CO (Fig.9-1)
Catalytic converter is inefficient for all emissions (Fig.9-11)
```

(c) A major percentage of emissions getting exhausted to the environment occurs at engine startup when the catalytic converter is cold. If a catalytic converter is placed near the engine there is less heat loss before the converter and it will reach efficient operating temperature quicker. This would reduce overall emissions.

If a catalytic converter is placed near the engine in the engine compartment it is much more difficult to cool the engine compartment properly because the converter is hot and it restricts air flow. Modern automobile design allows for very small engine compartments with no room for a catalytic converter. A converter mounted in the engine compartment would have a higher steady state operating temperature which would result in quicker thermal degradation.

(9-4)

stoichiometric combustion reaction

$CH_3OH + 1.5\ O_2 + 1.5(3.76)\ N_2 \longrightarrow CO_2 + 2\ H_2O + 1.5(3.76)\ N_2$

combustion reaction with equivalence $\phi = 1.25$

$CH_3OH + 1.2\ O_2 + 1.2(3.76)\ N_2 \longrightarrow a\ CO_2 + b\ CO + 2\ H_2O + 1.2(3.76)\ N_2$

conservation of carbon $\quad a + b = 1$
conservation of oxygen $\quad 2a + b + 2 = 3.4$

$a = 0.4 \qquad b = 0.6$

actual combustion reaction

$CH_3OH + 1.2\ O_2 + 1.2(3.76)\ N_2 \longrightarrow 0.4\ CO_2 + 0.6\ CO + 2\ H_2O + 1.2(3.76)N_2$

(a)

mole fraction of CO
$x_{CO} = N_{CO}/N_{total} = (0.6)/[0.4 + 0.6 + 2 + 1.2(3.76)] = 0.0799 \underline{= 7.99\%}$

(b)

mass flow rate of air into engine using Eq.(2-71)
$\dot{m}_a = \rho_a \eta_v V_d N/n$
$=(1.181 kg/m^3)(0.885)(0.0028 m^3/cycle)(2300/60 rev/sec)/(2 rev/cycle)$
$= 0.0561\ kg/sec$

actual fuel-air ratio using Eq. (2-57)
$(FA)_a = \phi(FA)_s = (1.25)(0.155) = 0.194$

flow rate of fuel into engine using Eq. (2-56)
$\dot{m}_f = (FA)_a\dot{m}_a = (0.194)(0.0561\ kg/sec) = 0.0109\ kg/sec$
$= (0.0109\ kg/sec)/(32\ kg/kgmole) = 0.00034\ kgmoles/sec$

for every 1 mole of fuel there are 0.6 moles of CO in exhaust

CO in exhaust
$\dot{m}_{CO} = (0.6)(0.00034\ kgmoles/sec) = 0.000204\ kgmoles/sec$

$\dot{Q}_{lost} = \dot{m}_{CO}Q_{HV} = (0.000204\ kgmoles/sec)(28\ kg/kgmole)(10{,}100\ kJ/kg) \underline{= 57.7\ kW}$

(9-5)

(a)

displacement volume of 1 cylinder

$V_d = (410\ \text{in.}^3)/8 = 51.25\ \text{in.}^3$

use Eq. (2-12) to find clearance volume

$r_c = 7.8 = (V_d + V_c)/V_c = (51.25 + V_c)/V_c$

$V_c = 7.537\ \text{in.}^3$

at TDC when combustion occurs V_c = combustion chamber volume

$V_c = 7.537\ \text{in.}^3 = (\pi/4)B^2h = (\pi/4)(3.98\ \text{in.})^2h$

$h = 0.606$ in. = height of combustion chamber at TDC

volume of boundary layer of thickness t

side $V_{side} = \pi Bht = \pi(3.98)(0.606)(0.004) = 0.0303\ \text{in.}^3$

top $V_{top} = (\pi/4)B^2t = (\pi/4)(3.98)^2(0.004) = 0.0498\ \text{in.}^3$

piston face $V_{face} = (\pi/4)B^2t = (\pi/4)(3.98)^2(0.004) = 0.0498\ \text{in.}^3$

total volume of boundary layer

$V_{BL} = (0.0303)+(0.0498)+(0.0498) = 0.130\ \text{in.}^3$

% of total volume = 0.130/7.537 = 0.0172 = 1.72%

with fuel equally distributed <u>% fuel not burned = 1.72%</u>

(b)

use Eq. (2-70) for air flow rate into engine

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

$= (0.0739\ \text{lbm/ft}^3)[410/(12)^3\ \text{ft}^3](0.90)(3000/60\ \text{rev/sec})/2 = 0.3945\ \text{lbm/sec}$

fuel flow rate into engine using Eq. (2-55)

$\dot{m}_f = \dot{m}_a/(AF) = (0.3945\ \text{lbm/sec})/15.2 = 0.02595\ \text{lbm/sec} = 93.43\ \text{lbm/hr}$

fuel lost in exhaust

$(\dot{m}_f)_{lost} = (93.43\ \text{lbm/hr})(0.0172) = \underline{1.61\ \text{lbm/hr}}$

(c)

$\dot{Q}_{lost} = \dot{m}_f Q_{HV} = (1.61\ \text{lbm/hr})(43{,}000\ \text{kJ/kg})/(2.326\ [\text{kJ/kg}]/[\text{BTU/lbm}])$

$= 29{,}764\ \text{BTU/hr} = (29{,}764\ \text{BTU/hr})/(2545\ \text{BTU/hr/hp}) = \underline{11.7\ \text{hp}}$

(9-6)

lead in gasoline = (0.15 gm/L)(3.785 L/gal)/(1000/2.205 gm/lbm) = 0.00125 lbm/gal

lead exhausted = (1/16 gal/mile)(0.00125 lbm/gal)(0.45) = <u>0.0000352 lbm/mile</u>

= (0.0000352 lbm/mile)(55 miles/hr)(24 hr/day) = <u>0.046 lbm/day</u>

(9-7)

(a)

use Eq.(2-71) for air flow rate into engine

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0022)(0.92)(2500/60)/2 = 0.0498$ kg/sec

Eq. (2-55) gives flow rate of fuel

$\dot{m}_f = \dot{m}_a/(AF) = (0.0498$ kg/sec$)/21 = 0.00237$ kg/sec

for 1 kgmole of $C_{12.3}H_{22.2}$ fuel

mass of carbon = (12.3)(12) = 147.6 kg

mass of hydrogen = (22.2)(1) = 22.2 kg

% of carbon by mass = (147.6/169.8)(100) = 86.93%

mass flow rate of soot

$\dot{m}_{soot}$ = (0.00237 kg/sec)(0.8693)(0.004)(1.2)(1.25)(3600 sec/hr) = <u>0.0445 kg/hr</u>

(b)

$\dot{Q}_{lost} = \dot{m}_{soot} Q_{HV}$ = (0.0445/3600 kg/sec)(33,800 kJ/kg) = <u>0.42 kW</u>

(c)

volume of soot exhausted

$\dot{V}_{soot} = \dot{m}/\rho$ = (0.0445 kg/hr)/(1400 kg/m^3) = 0.0000318 m^3/hr

volume of 1 particle

$V_{part} = (\pi/6)d^3 = (\pi/6)(20 \times 10^{-9}\ m)^3 = 4.19 \times 10^{-24}$ m^3/part

volume of 1 cluster

$V_{cluster} = (2000)(4.19 \times 10^{-24}\ m^3) = 8.38 \times 10^{-21}$ m^3/cluster

number of clusters

(0.0000318 m^3/hr)/(8.38 x 10^{-21} m^3/cluster) = <u>3.79 x 10^{15} clusters/hr</u>

(9-8)

(a)

use Eq. (2-65) for indicated power

$\dot{W}_i = \dot{Q}_{in}\eta_t = \dot{m}_f Q_{HV}\eta_c\eta_t = (0.00237\ \text{kg/sec})(42{,}500\ \text{kJ/kg})(0.98)(0.61) = 60.2\ \text{kW}$

use Eq. (2-62) for brake power

$\dot{W}_b = \dot{W}_i\eta_m = (60.2\ \text{kW})(0.71) = 42.8\ \text{kW}$

Eq. (2-60)

$bsfc = \dot{m}_f/\dot{W}_b = (0.00237\ \text{kg/sec})(3600\ \text{sec/hr})(1000\ \text{gm/kg})/(42.8\ \text{kW})$ $\underline{= 199\ \text{gm/kW-hr}}$

(b)

Eq. (2-73)

$(SE)_{soot} = \dot{m}_{soot}/\dot{W}_b = (0.0445\ \text{kg/hr})(1000\ \text{gm/kg})/(42.8\ \text{kW})$ $\underline{= 1.04\ \text{gm/kW-hr}}$

(c)

Eq. (2-74) $(EI)_{soot} = \dot{m}_{soot}/\dot{m}_f$

$= [(0.0445\ \text{kg/hr})(1000\ \text{gm/kg})]/[(0.00237\ \text{kg/sec})(3600\ \text{sec/hr})]$ $\underline{= 5.2\ \text{gm}_{soot}/\text{kg}_{fuel}}$

(9-9)

(a)

volume of boundary-layer in one cylinder

$V_{BL} = \pi(6\text{cm})(2\text{cm})(0.01\text{cm}) + (\pi/4)(6\text{cm})^2(0.01\text{cm})(2\text{sides}) = 0.942\text{cm}^3$

volume of clearance volume

$V_{clear} = (\pi/4)(6\ \text{cm})^2(2\ \text{cm}) = 56.55\ \text{cm}^3$

percent of total volume in boundary-layer (which=% of fuel)

$\% = [(0.942)/(56.55)](100)$ $\underline{= 1.67\ \%}$

(b)

$Q_{lost} = m_f Q_{HV} = [(0.040\ \text{kg/sec})(0.0167)](43{,}000\ \text{kJ/kg})$

$\underline{= 28.7\ \text{kJ/sec} = 28.7\ \text{kW}}$

(c)

$(EI)_{HC} = m_{HC}/m_f = [(0.0167)m_f]/(m_f) = 0.0167\text{kg}_{HC}/\text{kg}_f$ $\underline{= 16.7\ \text{gm}_{HC}/\text{kg}_f}$

(9-10)

(a)

for 1 cylinder $V_d = (6.4\ L)/8 = 0.8\ L = 0.0008\ m^3$

Eq. (2-12) for clearance volume of 1 cylinder
$r_c = 10.4 = (V_d + V_c)/V_c = (0.0008 + V_c)/V_c$ $V_c = 0.0000851\ m^3$

clearance volume of 8 cylinders $V_c = (0.0000851\ m^3)(8) = 0.000681\ m^3 = 681\ cm^3$

crevice volume $V_{crevice} = (681\ cm^3)(0.028) \underline{= 19.1\ cm^3}$

(b)

using Fig. 3-2 and Eqs. (3-4) and (3-5)
$T_2 = T_1(r_c)^{k-1} = (338\ K)(10.4)^{0.35} = 767\ K$
$P_2 = P_1(r_c)^k = (120\ kPa)(10.4)^{1.35} = 2833\ kPa$

mass in crevice
$m_{crev} = PV/RT = (2833\ kPa)(0.0000191\ m^3)/(0.287\ kJ/kg\text{-}K)(458\ K) = 0.000412\ kg$

mass in clearance volume
$m_{clear} = (2833\ kPa)(0.000681\ m^3)/(0.287\ kJ/kg\text{-}K)(767\ K) = 0.008764\ kg$

% of mass in crevice volume = $[(0.000412)/(0.008764 + 0.000412)](100) \underline{= 4.5\%}$

(9-11)

(a)

Eq. (2-71) for air flow rate into engine
$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0064)(0.89)(5500/60)/2 = 0.3083\ kg/sec$

Eq. (2-55) for fuel flow rate
$\dot{m}_f = \dot{m}_a/(AF) = (0.3083\ kg/sec)/14.2 = 0.0217\ kg/sec$

mass of fuel in exhaust
$(\dot{m}_f)_{ex} = [(0.0217)(3600)kg/hr](0.045\ \text{trapped})(0.40\ \text{not burned}) \underline{= 1.406\ kg/hr}$

(b)
$\dot{Q}_{lost} = \dot{m}_f Q_{HV} = (1.406\ kg/hr)(44{,}300\ kJ/kg)/(3600\ sec/hr) \underline{= 17.3\ kW}$

(9-12)

(a)

use time rate form of Eq.(5-22) for flow of air-fuel mixture

$\dot{m}_m = \lambda_{dr} V_d \rho_a N/n$ = (0.95)(0.196 m^3/cycle)(1.181 kg/m^3)(220/60 rev/sec)/(1 rev/cycle)
= 0.806 kg/sec

air flow in with AF = 22

$\dot{m}_a$ = (0.806 kg/sec)(22/23) = 0.7710 kg/sec = 2776 kg/hr = 95.72 kgmoles/hr

with air having 3.76 moles of N_2 for every 1 mole of O_2
moles of N_2 in per hour
(95.72 kgmoles/hr)(3.76/4.76) = 75.61 kgmoles/hr

for every mole of N_2 converted there will be 2 moles of NO

$N_2 + O_2 \longrightarrow 2\ NO$

NO generated
(75.61 kgmoles/hr)(2)(0.001 converted) = 0.1512 kgmoles/hr
$\dot{m}_{NO}$ = (0.1512 kgmoles/hr)(30 kg/kgmole) = 4.54 kg/hr

(b)

from Eq. (9-29) 1 mole of NH_3 is needed for every mole of NO
$\dot{m}_{NH_3}$ = (0.1512 kgmoles/hr)(17 kg/kgmole) = 2.57 kg/hr

(9-13)

(a)

stoichiometric combustion equation

$$C_2H_5OH + 3\ O_2 + 3(3.76)\ N_2 \longrightarrow 2\ CO_2 + 3\ H_2O + 3(3.76)\ N_2$$

to find temperature use Eqs. (4-8) and (4-5)
(using enthalpy values from <u>Introduction toThermodynamics,</u>
by Sonntag and Van Wylen, 3rd ed., John Wiley and Sons, 1991)

$$\Sigma_{PROD} N_i(h_f^o + \Delta h)_i = \Sigma_{REACT} N_i(h_f^o + \Delta h)_i$$

$$2[(-393{,}522)+\Delta h_{CO_2}]+3[(-241{,}826)+\Delta h_{H_2O}]+3(3.76)[(0)+\Delta h_{N_2}]$$
$$\longrightarrow [-199{,}000]+3[(0)+(12{,}499)]+3(3.76)[(0)+(11{,}937)]$$

$$2\ \Delta h_{CO_2} + 3\ \Delta h_{H_2O} + 11.28\ \Delta h_{N_2} = 1{,}485{,}668$$

find temperature to satisfy this by trial and error
<u>$T_{max} = 2652$ K</u>

(b)

add x amount of EGR (N_2) to lower T_{max} to 2400 K

$$C_2H_5OH + 3\ O_2 + 3(3.76)\ N_2 + x\ N_2 \longrightarrow 2\ CO_2 + 3\ H_2O + [3(3.76) + x]\ N_2$$

Eq. (4-8) at T = 2400 K

$$2[(-393{,}522)+(115{,}779)]+3[(-241{,}826)+(93{,}741)]+(11.28+x)[(0)+(70{,}640)]$$
$$= [-199{,}000]+3[(0)+(12{,}499)]+3(3.76)[(0)+(11{,}937)]+x[(0)+(21{,}463)]$$

x = 3.580 kgmoles for 1 kgmole of fuel burned
= (3.580 kgmoles)(28 kg/kgmole) = 100.2 kg

mass of air in for 1 kgmole of fuel
(3)(4.76)(29) = 414.1 kg

mass of fuel in for 1 kgmole of fuel
(1)(46) = 46.0 kg

total mass in for each mole of fuel
$m_m = 100.2 + 414.1 + 46.0 = 560.3$ kg

Eq. (9-31) for 1 kgmole of fuel
EGR = $[\dot{m}_{EGR}/\dot{m}_i](100)$ = [(100.2)/(560.3)](100) <u>= 17.9%</u>

(9-14)

from Sec. 9-8 volume of catalytic converter

$V_{cc} \approx \frac{1}{2} V_d = 1.4\ L = 0.0014\ m^3$

(a) heat needed

$Q = mc_p\Delta T = \rho V_{cc} c_p \Delta T$

$= (3970 kg/m^3)(0.0014 m^3)(20\%)(0.765\ kJ/kg\text{-}K)(125°)\ \underline{= 106.2\ kJ}$

(b) Power = (24 volts)(600 amps) = 14,400 W = 14.40 kW = 14.40 kJ/sec

time $t = (106.2\ kJ)/(14.40\ kJ/sec)\ \underline{= 7.4\ sec}$

(9-15)

(a) use a time rate form of Eq. (5-22) to get rate of air-fuel mixture ingested

$\dot{m}_{ing} = \lambda_{dr} V_d \rho_a N/n = (0.88)(0.00002\ m^3/cycle)(1.181\ kg/m^3)(900/60\ rev/sec)/(1\ rev/cycle)$

$= 0.000312\ kg/sec = 1.122\ kg/hr$

use a time rate form of Eq.(5-23)to get rate of air-fuel mixture trapped

$\dot{m}_{trap} = \lambda_{ce} V_d \rho_a N/n = (0.72)(0.00002\ m^3/cycle)(1.181\ kg/m^3)(900/60\ rev/sec)/(1\ rev/cycle)$

$= 0.000255\ kg/sec = 0.918\ kg/hr$

mass flow of air-fuel in exhaust due to valve
overlap = mass flow ingested - mass flow trapped

$(\dot{m}_{ex})_{overlap} = (1.122\ kg/hr) - (0.918\ kg/hr) = 0.204\ kg/hr$

use Eq. (2-57) for actual air-fuel ratio

$(AF)_{act} = (AF)_{stoich}/\phi = 14.6/1.08 = 13.52$

mass rate of fuel and oil in exhaust

$(\dot{m}_{HC})_{ex} = (0.204\ kg/hr)/14.52\ \underline{= 0.0140\ kg/hr}$

(b) mass rate of fuel and oil (HC) trapped in combustion chamber

$(\dot{m}_{HC})_{trap} = (0.918\ kg/hr)/14.52 = 0.0632\ kg/hr$

of this $\dot{m}_{fuel} = (0.0632\ kg/hr)(60/61) = 0.0622\ kg/hr$

$\dot{m}_{oil} = (0.0632\ kg/hr)(1/61) = 0.0010\ kg/hr$

94% of fuel gets burned, so 6% does not get burned

$(\dot{m}_{fuel})_{n.b.} = (0.0622\ kg/hr)(0.06) = 0.0037\ kg/hr$

$(\dot{m}_{oil})_{n.b.} = (0.0010\ kg/hr)(0.28) = 0.0003\ kg/hr$

total rate of HC not burned $\dot{m}_{HC} = 0.0037 + 0.0003\ \underline{= 0.0040\ kg/hr}$

(c) $(\dot{m}_{HC})_{total} = (0.014\ kg/hr) + (0.0040\ kg/hr)\ \underline{= 0.018\ kg/hr}$

(9-16)

(a)

air flow into engine using Eq.(2-71)

$\dot{m}_f = \eta_v \rho_a V_d N/n$

$=(.93)(1.181 kg/m^3)(.0032 m^3/cycle)/(3600/60 rev/sec)/(2 rev/cycle)$

$= 0.1054$ kg/sec $= 379.58$ kg/hr

Eq.(2-55) for fuel flow

$\dot{m}_f = \dot{m}_a(AF) = (379.58$ kg/hr$)/(22)$ $\underline{= 17.25 \text{ kg/hr}}$

(b)

$\dot{m}_{sulfur} = (17.25$ kg/hr$)[(450)/(1{,}000{,}000)] = 0.00776$ kg/hr

$\underline{= 7.76 \text{ gm/hr}}$

(c)

Eq.(2-73)

$(SE)_{sulfur} = \dot{m}_{sulfur}/\dot{W}_b = (7.76$ kg/hr$)/(92$ kW$)$ $\underline{= 0.0844 \text{ gm/kW-hr}}$

(d)

flow rate of sulfur into environment

$\dot{m}_{sulfur} = (7.76$gm/hr$) = (.00776$kg/hr$)/(32$kg/kgmole$) = .000243$ kgmole/hr

using Eqs.(9-15) and (9-18)

one mole of sulfur produces one mole of sulfurous acid

$\dot{m}_{acid} = (0.000243$ kgmole/hr$)(82$ kg/kgmole$)(24$ hr/day$)$

$\underline{= 0.477 \text{ kg/day}}$

(9-17)

use Eq.(2-71) for flow rate of air into engine

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0052)(0.96)(2800/60)/2 = 0.1376$ kg/sec

Eq. (2-55) for fuel flow rate

$\dot{m}_f = \dot{m}_a/(AF) = (0.1376$ kg/sec$)/20 = 0.00688$ kg/sec

(a)

flow of sulfur through engine

$\dot{m}_{sulfur} = (0.00688$ kg/sec$)(500/1{,}000{,}000) = 3.44 \times 10^{-6}$ kg/sec

$= (3.44 \times 10^{-6}$ kg/sec$)(3600$ sec/hr$)(1000$ gm/kg$)$ $\underline{= 12.4 \text{ gm/hr}}$

$= (0.0124$ kg/hr$)/(32$ kg/kgmole$) = 0.000388$ kgmoles/hr

(b)

from Eq. (9-15)

for 1 mole of S there is 1 mole of SO_2 formed

from Eq. (9-18) for 1 mole of SO_2 there is 1 mole of H_2SO_3 formed

mass flow of sulfurous acid to environment

$m_{H_2SO_3} = (0.000388$ kgmoles/hr$)(82$ kg/kgmole$)$ $\underline{= 0.032 \text{ kg/hr}}$

(9-18)

(a)

rate of fuel used

$\dot{m}_f$ = (8 kg/km)(100 km/hr) = 8 kg/hr

flow rate of CO

$\dot{m}_{CO}$ = (12 gm/kg)(8 kg/hr) = 96 gm/hr

Eq.(2-73)

$(SE)_{CO} = \dot{m}_{CO}/\dot{W}_b$ = (96 gm/hr)/(40 kW) <u>= 2.40 gm/kW-hr</u>

(b)

$[(SE)_{CO}]_{ave}$=(2.40gm/kW-hr)(1-.95)(90%of time)+(2.40)(10%of time)
hot cold

<u>= 0.348 gm/kW-hr</u>

(c)

% = [(0.240)/(0.348)](100) <u>= 69.0%</u>

(9-19)

More exhaust smoke would be expected. Fuel with the lower cetane number will not self-ignite as readily and there will be a longer ignition delay between start of injection and start of combustion. More fuel will be injected before ignition occurs and the overall air-fuel ratio will be more fuel-rich when combustion starts. Solid carbon (smoke) is generated in the fuel-rich part of the combustion chamber where there is not enough oxygen to form CO_2. This fuel-rich zone would be larger under these conditions.

(9-20)

(a)

yearly consumption of gasoline by 1 automobile

(16,000 km/year)[(15 L)/(100 km)] = 2400 L/year

lead into atmosphere by average automobile

$\dot{m}_L$ = (2400 L/year)((0.15 gm/L)(0.35 exhausted) = 126 gm/yr <u>= 0.126 kg/yr</u>

(b)

(2.33 x 10^9 bbl/yr)(160 L/bbl)(0.15 gm/L)(0.35 exhausted) = 1.96 x 10^{10} gm/yr

<u>= 1.96 x 10^7 kg/yr</u>

(9-21) exhaust flow rate

$\dot{m}_{ex} = \dot{m}_f + \dot{m}_a = \dot{m}_f(1 + AF) = (5\ \text{lbm/hr})(1 + 14.6) = 78\ \text{lbm/hr}$

flow rate of CO

$\dot{m}_{CO} = (0.006)(78\ \text{lbm/hr}) = 0.468\ \text{lbm/hr}$
$= (0.468\ \text{lbm/hr})/(28\ \text{lbm/lbmmole}) = 0.0167\ \text{lbmmole/hr}$

moles of air in garage

$N_{air} = PV/RT = [(14.7)(144)\text{lbf/ft}^2][(20)(20)(8)\text{ft}^3]/(1545\ \text{ft-lbf/lbmmole-°R})(500°\ \text{R})$
$= 8.769\ \text{lbmmoles}$

to become dangerous

$CO = 10\ \text{ppm of air} = (10 \times 10^{-6})(8.769\ \text{lbmmoles}) = 8.769 \times 10^{-5}\ \text{lbmmoles}$

time $t = (8.769 \times 10^{-5}\ \text{lbmmoles})/(0.0167\ \text{lbmmoles/hr})$
$= 0.00525\ \text{hr} \underline{= 0.315\ \text{min}} = 19\ \text{sec}$

(9-22)

(a) mass flow rate of HC

$\dot{m}_{HC} = (1.4\ \text{gm/km})(100\ \text{km/hr}) = 140\ \text{gm/hr}$

Eq. (2-73) $(SE)_{HC} = \dot{m}_{HC}/\dot{W}_b = (140\ \text{gm/hr})/(32\ \text{kW}) \underline{= 4.4\ \text{gm/kW-hr}}$

(b) mass flow rate of CO upstream of converter

$\dot{m}_{CO} = (12\ \text{gm/km})(100\ \text{km/hr}) = 1200\ \text{gm/hr}$

mass flow rate of CO downstream of converter

$\dot{m}_{CO} = (1200\ \text{gm/hr})(0.05\ \text{not removed}) = 60\ \text{gm/hr}$

$(SE)_{CO} = (60\ \text{gm/hr})/(32\ \text{kW}) \underline{= 1.88\ \text{gm/kW-hr}}$

(c) exhaust flow out = mass flow in

$\dot{m}_{ex} = \dot{m}_{in} = \dot{m}_a + \dot{m}_f = \dot{m}_f(AF + 1)$
$= [(6\ \text{kg}/100\ \text{km})(100\ \text{km/hr})](14.6 + 1) = 93.6\ \text{kg/hr} = 93{,}600\ \text{gm/hr}$

mass flow rate of NOx upstream of converter

$\dot{m}_{NOx} = (1.1\ \text{gm/km})(100\ \text{km/hr}) = 110\ \text{gm/hr}$

mole fraction of NOx using Eq. (4-1)

$x_{NOx} = N_{NOx}/N_{total} = (\dot{m}_{NOx}/M_{NOx})/(\dot{m}_{total}/M_{air}) = (110/46)/(93{,}600/29) = 0.00074 \underline{= 740\ \text{ppm}}$

(d) $(1.4)(1 - 0.95)(0.9) + (1.4)(0.1) \underline{= 0.203\ \text{gm/km}}$

(e) $\% = [(1.4)(0.1)]/0.203 = 0.690 \underline{= 69.0\%}$

CHAPTER 10

(10-1)

(a) for 1 cylinder $V_d = (6.6 \text{ L})/6 = 1.1 \text{ L} = 0.0011 \text{ m}^3$

Eq. (2-71)
$\dot{m}_a = \rho V_d \eta_v N/n = (1.181)(0.0011)(0.89)(3000/60)/2 \underline{= 0.0289 \text{ kg/sec}}$

$Vel = \dot{m}_a/\rho A = (0.0289 \text{ kg/sec})/(1.181 \text{ kg/m}^3)[(\pi/4)(0.04 \text{ m})^2] \underline{= 19.47 \text{ m/sec}}$

(b) Reynolds number using property values from Ref. [63]
$Re = (Vel)d\rho/\mu = (19.47 \text{ kg/sec})(0.04 \text{ m})(1.181 \text{ kg/m}^3)/(1.846 \times 10^{-5} \text{ kg/m-sec})$
$\underline{= 49{,}825}$ turbulent flow

(c) Nusselt number using Dittus-Boelter equation and property values from Ref. [63]
$Nu = 0.023\, Re^{0.8} Pr^{0.4} = (0.023)(49{,}825)^{0.8}(0.708)^{0.4} = 114.7 = hd/k$

where: Pr = Prandtl number
h = convection heat transfer coefficient
d = inside diameter of runner
k = thermal conductivity
c_p = specific heat
A = inside surface area of runner #1
ΔT = temperature difference between air and wall

let $\Delta T = T_{wall} - (T_a)_{in} = 67° \text{ C} - 27° \text{ C} = 40°$

$h = (Nu)k/d = (114.7)(0.02624 \text{ W/m-K})/(0.04 \text{ m}) = 75.2 \text{ W/m}^2\text{-K}$

$\dot{Q} = hA\Delta T = \dot{m}c_p(T_{out} - T_{in}) = (75.2 \text{ W/m}^2\text{-K})[\pi(0.04 \text{ m})(0.4 \text{ m})](40°)$
$= (0.0289 \text{ kg/sec})(1005 \text{ J/kg-K})(T_{out} - 27° \text{ C})$

temperature out of runner = temperature entering cyl #1
$T_{out} = \underline{T_{enter} = 32.2° \text{ C}}$

(d) in runner #3, $\dot{m}$, Re, Pr, Nu, and h are all the same as in runner #1

$\dot{Q} = (75.2 \text{ W/m}^2\text{-K})[\pi(0.04 \text{ m})(0.15 \text{ m})]\Delta T = (0.0289 \text{ kg/sec})(1005 \text{ J/kg-K})(5.2°)$
$\Delta T = 107° \text{ C}$

$T_{wall} = T_{in} + \Delta T = 27° + 107° \underline{= 134° \text{ C}}$

(10-2)

(a)

use Eq. (2-55) for fuel flow rate

$\dot{m}_f = \dot{m}_a/(AF) = (0.0289\ kg/sec)/14.6 = 0.00198\ kg/sec$

$\dot{Q}_{evap} = \dot{m}_f h_{fg}(\%\ evaporated) = (0.00198\ kg/sec)(307\ kJ/kg)(0.40) = 0.2431\ kJ/sec$

this cools the air-fuel mixture (use low temp value of c_p)

$\dot{Q}_{evap} = \dot{m}_m c_p \Delta T = (0.0289 + 0.00198)kg/sec(1.005\ kJ/kg\text{-}K)\Delta T$

$$\Delta T = 7.8^\circ\ C$$

$T_{entering} = 32.2^\circ - \Delta T = 32.2^\circ - 7.8^\circ \underline{= 24.4^\circ\ C}$

(b)

$\dot{m}_f = (0.0289\ kg/sec)/9 = 0.00321\ kg/sec$

$\dot{Q}_{evap} = (0.00321\ kg/sec)(873\ kJ/kg)(0.40) = 1.121\ kJ/sec$
$= (0.0289 + 0.00321)kg/sec(1.005\ kJ/kg\text{-}K)\Delta T$

$$\Delta T = 34.7^\circ\ C$$

$T_{entering} = 32.2^\circ - 34.7^\circ \underline{= -2.5^\circ\ C}$

(10-3)

Eq. (2-8) for 1 cylinder

$V_d = 0.0011\ m^3 = (\pi/4)B^2S = (\pi/4)B^2(0.9\ B)$

$$B = 0.1159\ m = 11.59\ cm$$

Eq. (2-15) gives area of piston face

$A_p = (\pi/4)B^2 = (\pi/4)(0.1159\ m)^2 = 0.01055\ m^2$

Eq. (10-7) using viscosity value from Ref. [63]

$Re = [(\dot{m}_a + \dot{m}_f)B]/(A_p\mu_g)$
$= [(0.0289 + 0.00321)(0.1159)]/[(0.01055)(1.846 \times 10^{-5})] \underline{= 19,109}$

(10-4)

assume $\Delta T = (T_{in} - T_{out}) = 100° C$

average bulk temperature
$T_{bulk} = (477° + 377°)/2 = 427° C = 700 K$

air property values from Ref. [63] at average bulk temperature:

density	$\rho = 0.5030 kg/m^3$
kinematic viscosity	$\nu = 66.25 \times 10^{-6} m^2/sec$
thermal conductivity	$k = 0.05230 W/m\text{-}K$
specific heat	$c_p = 1075.2 J/kg\text{-}K$
Prandtl number	$Pr = 0.684$

mass flow rate of exhaust for entire engine
$\dot{m}_{ex} = \dot{m}_a + \dot{m}_f = 0.0289 + 0.00321 = (0.03211 kg/sec)(6 cyl) = 0.19266 kg/sec$

$Vel = \dot{m}_{ex}/\rho A = (0.19266 kg/sec)/(0.5030 kg/m^3)[(\pi/4)(0.065 m)^2] = 115.4 m/sec$

Reynolds number
$Re = (Vel)d/\nu = (115.4 m/sec)(0.065 m)/(66.25 \times 10^{-6}) = 113{,}223$

Nusselt number using Dittus-Boelter equation from Ref. [63]
$Nu = 0.023 Re^{0.8}Pr^{0.3} = (0.023)(113{,}223)^{0.8}(0.684)^{0.3} = 226.6$

this is increased by a factor of 2 due to pulsed flow of exhaust
$Nu = (226.6)(2) = 453.2 = hd/k$

convection heat transfer coefficient
$h=(Nu)k/d=(453.2)(0.05230 W/m\text{-}K)/(0.065 m)= 364.7 W/m^2\text{-}K$

convection heat transfer
$\dot{Q} = h(\text{surface area})(T_{bulk}-T_{wall})$
$=(364.7 W/m^2\text{-}K)[\pi(0.065 m)(1.5 m)](700-500)K=22{,}342 W=\dot{m}_{ex}c_p\Delta T$
$= (0.19266 kg/sec)(1075.2 J/kg\text{-}K)\Delta T$

$\Delta T = 108°$

temperature of exhaust entering catalytic converter
$T_{ex} = 477°C - \Delta T = 477°C - 108° = 369°C = 642K$

2nd iteration using $\Delta T=108°C$ to get better bulk temperature:

average bulk temperature	$T_{bulk} = 696$ K
density	$\rho = 0.5056$ kg/m^3
kinematic viscosity	$\nu = 65.63\times10^{-6}$ m^2/sec
thermal conductivity	$k = 0.05199$ W/m-K
specific heat	$c_p = 1074.3$ J/kg-K
Prandtl number	$Pr = 0.684$
velocity	Vel = 114.8 m/sec
Reynolds number	Re = 113,698
Nusselt number	Nu = 454.8
convection heat transfer coefficient	$h = 363.8$ W/m^2-K
heat transfer	$\dot{Q} = 21{,}841$ W
change in temperature	$\Delta T = 106°C$
exhaust temperature entering catalytic converter	$\underline{T_{ex} = 371°C = 644\ K}$

these values are close enough so a 3rd iteration is not needed

(10-5)

(a)

using Fig. 10-1 at 2000 RPM
$\dot{Q}_{ex} \approx \dot{W}_b \underline{= 20\ kW}$

(b)

$\dot{Q}_{friction} \approx \frac{1}{4}\dot{W}_b = \frac{1}{4}(20\ kW) \underline{= 5\ kW}$

(c)

$\dot{Q}_{coolant} \approx 1.3\,\dot{W}_b = 1.3(20\ kW) \underline{= 26\ kW}$

(10-6)

(a) using Fig. 10-1 at 2500 RPM $\dot{Q}_{coolant} \approx 1.11\ \dot{W}_b = 1.11(30hp) = 33.3hp$

mass flow rate of coolant flow
$\dot{m}_c = (25\ gal/min)(60\ min/hr)(62.4\ lbm/ft^3)/(7.481\ gal/ft^3) = 12{,}512\ lbm/hr$

$\dot{Q}_{coolant} = \dot{m}_c c_p \Delta T = (33.3\ hp)(2545\ BTU/hr/hp) = (12{,}512\ lbm/hr)(1\ BTU/lbm\text{-}^\circ R)\Delta T$
$\Delta T = 7^\circ\ F$

$T_{exit} = T_{in} + \Delta T = 220^\circ + 7^\circ \underline{= 227^\circ\ F}$

(b) velocity of air through radiator
$Vel = [(30\ miles/hr)(5280\ ft/mile)/(3600\ sec/hr)](1.1) = 48.4\ ft/sec$

mass flow of air
$\dot{m}_a = \rho(Vel)A = (0.0739\ lbm/ft^3)(48.4\ ft/sec)(4.5\ ft^2) = 16.1\ lbm/sec$

33.3 hp must be dissipated
$\dot{Q}_{radiator} = \dot{m}_a c_p \Delta T$
$(33.3\ hp)(2545/3600\ BTU/sec/hp) = (16.1\ lbm/sec)(0.240\ BTU/lbm\text{-}^\circ R)\Delta T$
$\Delta T = 6^\circ\ F$

$T_{exit} = T_{in} + \Delta T = 75^\circ + 6^\circ \underline{= 81^\circ\ F}$

(10-7)
approximate ratio of cylinder volumes
$R_{vol} = 320/290 = 1.103$
approximate ratio of linear dimensions
$R_{lin} = (1.103)^{1/3} = 1.033$
approximate ratio of area dimensions
$R_{area} = (1.033)^2 = 1.068$

(a) $\dot{Q}_{in}$ will be proportional to cylinder volume for each engine
heat losses will be proportional to cylinder surface area
$(\eta_t)_{320}/(\eta_t)_{290} \approx R_{vol}/R_{area} = 1.103/1.068 = 1.033$

<u>3.3% greater indicated thermal efficiency in larger engine</u>

(b) if all temperatures are the same, heat transfer
to coolant will be proportional to surface area
$\dot{Q}_{320} \approx 1.068\ \dot{Q}_{290}$

<u>6.8% greater heat flow to coolant in larger engine</u>

(10-8)

Table 10-1 using propylene glycol-water table at -30° C gives a specific gravity of 1.038

using ethylene glycol-water table for a solution with a specific gravity of 1.038 gives:
$\underline{T_{freezing\ pt} = -13.5° C}$

(10-9)

(a) $Q = mc_p\Delta T = (10\ kg)(900\ J/kg\text{-}K)(110 - 80)°C = 270{,}000\ J$
time $t = Q/\dot{Q}_{loss} = (270{,}000\ J)/(3\ J/sec) = 90{,}000\ sec \underline{= 25\ hr}$

(b) time $t = (80\ W\text{-}hr/kg)(10\ kg)/(3\ W) \underline{= 267\ hr} = 11.1$ days

(c) to cool solid $Q = (350\ J/kg\text{-}K)(10\ kg)(80 - 10)°C = 245{,}000\ J$
time $t = Q/\dot{Q}_{loss} = (245{,}000\ J)/(3\ J/sec) = 81{,}667 sec = 22.7 hr$

time to cool $t = 25 + 267 + 22.7 \underline{= 314.7\ hr} = 13.1$ days

(d) energy to change phase $Q = (80\ W\text{-}hr/kg)(10\ kg) = 800\ W\text{-}hr$

energy needed to heat coolant using c_p=4200J/kg-K for coolant (water)
$\dot{Q}' = \dot{m}c_p\Delta T = (0.09\ kg/sec)(4200\ J/kg\text{-}K)(80 - 20)°C = 22{,}680\ W$

time $t = Q/\dot{Q}' = (800\ W\text{-}hr)/(22{,}680\ W) = 0.03527\ hr \underline{= 2.12\ min} = 127\ sec$

(10-10)

heat loss from 215°F to 175°F from Example Problem 10-5
$Q_1 = 54.56$ BTU

heat loss during phase change
$Q_2 = (6.2\ lbm)(0.60\ of\ total)(125\ BTU/lbm) = 465$ BTU

total heat loss
$Q = Q_1 + Q_2 = (54.56) + (465) = 519.56$ BTU

time of heat loss
t = (519.56 BTU)/(11 BTU/hr) <u>= 47.23hr = 1day 23hr 14min</u>

(10-11)

(a)

heat exchange in engine

$Q = mc_p\Delta T$

$=(1000\ BTU/min)=[(20\ gal/min)(8.41\ bm/gal)](1\ BTU/lbm\text{-}°R)\Delta T$

$\Delta T = 6°$

$T_{exit} = T_{inlet} + \Delta T = (200°F) + (6°)$ $\underline{= 206°F}$

(b)

mass flow rate of air

$m_a = \rho_a VA = (0.0739 lbm/ft^3)(50 ft/sec)(4 ft^2) = 14.78\ lbm/sec$

for air

$Q=mc_p\Delta T=(1000/60 BTU/sec)=(14.78 lbm/sec)(0.240 BTU/lbm\text{-}°R)\Delta T$

$\underline{\Delta T = + 4.7°F}$

(10-12)

(a) Eq. (2-9) $V_d = N_c(\pi/4)B^2S = (12\ cyl)(\pi/4)(0.142\ m)^2(0.245\ m) = 0.0466\ m^3$

air flow rate using Eq. (2-71)

$\dot{m}_a = \rho_a V_d \eta_v N/n = (1.181)(0.0466)(0.96)(980/60)/2 = 0.4315\ kg/sec$

fuel flow rate using Eq. (2-55)

$\dot{m}_f = \dot{m}_a/(AF) = (0.4315\ kg/sec)/21 = 0.0205\ kg/sec$

exhaust flow rate $\dot{m}_{ex} = \dot{m}_a + \dot{m}_f = 0.4315 + 0.0205 = 0.4520\ kg/sec$

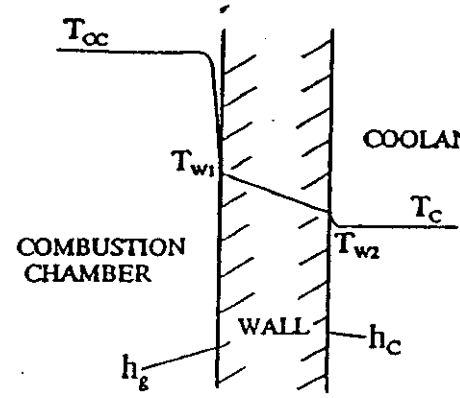
rate of exhaust enthalpy change in heat exchanger

$\dot{\Delta H} = \dot{m}_{ex}c_p\Delta T = (0.4520\ kg/sec)(1.108\ kJ/kg\text{-}K)(577 - 227)K$ $\underline{= 175.3\ kW}$

(b)

$\dot{m}_{steam} = \dot{\Delta H}/h_{fg} = [(175.3\ kJ/sec)(0.98\ efficiency)(3600\ sec/hr)/(2257\ kJ/kg)$ $\underline{= 274\ kg/hr}$

(10-13)



(a) $\dot{q} = \dot{Q}/A = h_g \Delta T = 67{,}000$ BTU/hr-ft^2 = (22 BTU/hr-ft^2-°R)(3800° R - T_{w1})
T_{w1} = 755° R = <u>295° F</u>

(b) $\dot{q} = \dot{Q}/A = k(\Delta T/\Delta x) = 67{,}000$ BTU/hr-ft^2 = (34 BTU/hr-ft-°R)ΔT/(0.4/12 ft)
ΔT = 66° F $\quad\quad$ $T_{w2} = T_{w1} - \Delta T$ = 295° - 66° = <u>229° F</u>

(c) $\dot{q} = \dot{Q}/A = h_c(T_{w2} - T_c) = 67{,}000$ BTU/hr-ft^2 = h_c(229 - 185)°F
<u>h_c = 1523 BTU/hr-ft^2-°R</u>

(10-14)

(a) Engine A will have higher volumetric efficiency. Engine B will have higher steady state operating temperatures including cylinder wall temperature. This will heat the incoming air to a higher temperature which will reduce the air density, and thus reduce volumetric efficiency.

(b) Engine B will have higher thermal efficiency because heat losses will be minimum due to the insulated walls.

Engine B will operate hotter than engine A so $(\dot{Q}_{in})_B$ will be at a higher temperature. By thermodynamic laws the higher the temperature at which energy is used ($\dot{Q}_{in}$) the higher will be the efficiency of that use.

Engine B would have to be a CI engine. Its walls would be too hot to operate as a SI engine, the air-fuel mixture would self-ignite during compression. CI engines operate at higher compression ratios and thus have higher thermal efficiency.

(c) Engine B would have hotter exhaust. All temperatures in engine B would be higher. This reduces the thermal efficiency of engine B and contradicts some of part (b).

(d) The higher temperatures of engine B would make it much more difficult to lubricate. There would be problems of thermal degradation of the lubricating oil.

(e) Engine A would be a better SI engine. Engine B would operate too hot to be a SI engine, the air-fuel mixture would self-ignite during compression.

CHAPTER 11

(11-1)

(a)

$\tan \phi = 3/9.10 = 0.3297 \qquad \phi = 18.246°$

Eq. (11-26) $\quad F_t = F_r \sin \phi = (1000\ N)\sin(18.246°) \underline{= 313\ N}$

(b)

using Figs. 2-1 and 11-9

$s = [a^2 + r^2]^{1/2} = [(3\ cm)^2 + (9.10\ cm)^2]^{1/2} = 9.5818\ cm$

$x = a + r - s = 3 + 9.10 - 9.5818 \underline{= 2.52\ cm}$

(c)

stroke and bore lengths

$S = 2a = 2(3\ cm) = 6\ cm \qquad\qquad B = S/0.94 = (6\ cm)/0.94 = 6.38\ cm$

Eq. (2-9) $\quad V_d = N_c(\pi/4)B^2S = (4\ cyl)(\pi/4)(6.38\ cm)^2(6\ cm) = 767\ cm^3 \underline{= 0.767\ L}$

(d)

at TDC $\phi = 0°$

Eq. (11-26) $\qquad F_t = F_r \sin \phi = F_r \sin(0°) \underline{= 0}$

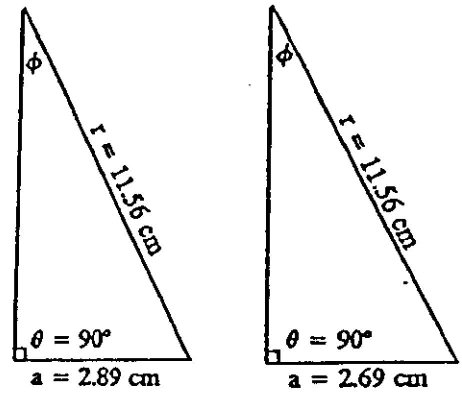
(11-2)

Cylinders get out-of-round because the side thrust force between the piston and cylinder wall is not uniform around the circumference of the cylinder. It is greatest (with the greatest wear) on the major thrust side, substantial on the minor thrust side, and less in other planes.

Wear is non-uniform along the length of the cylinder because of the changing force magnitude and the changing angle between the connecting rod and the centerline of the cylinder. This results in a changing side thrust force along the length of the cylinder, and a resulting non-uniform wear pattern.

Friction force on the piston should be zero at TDC and BDC because in theory the piston is stopped (no motion) at these points. In reality the piston assembly does not all stop at the same instance because of the very high acceleration rates at these points. Deflections in the connecting components and stretching or compression of the piston occur due to high mass inertia.

(11-3)



(a) (c)

(a)

using Fig. 11-9

crank offset $a = S/2$

$= (5.78 \text{ cm})/2 = 2.89 \text{ cm}$

$\sin\phi = 2.89/11.56 = 0.250$

$\phi = 14.478°$

Eq. (11-25)

$m(dU_p/dt) = 0 = -F_r\cos\phi + P(\pi/4)B^2 - F_f$

$= -F_r\cos(14.478°) + (4500 \text{ kN/m}^2)(\pi/4)(0.06 \text{ m})^2 - 0.85 \text{ kN}$

$\underline{F_r = 12.27 \text{ kN} \quad \text{compressive}}$

(b)

Eq. (11-27)

$F_t = [-m(dU_p/dt) + P(\pi/4)B^2 - F_f]\tan\phi = [0 + (4500)(\pi/4)(0.06)^2 - 0.85]\tan(14.478°)$

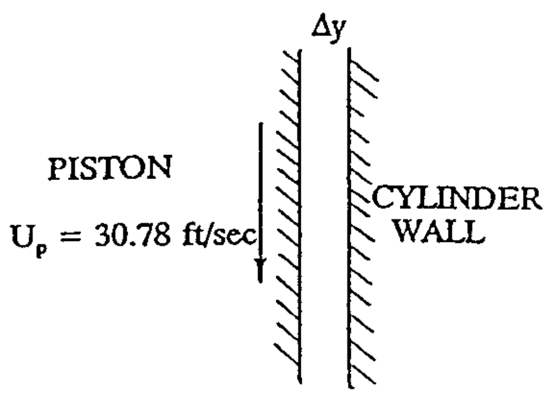
$\underline{F_t = 3.06 \text{ kN} \quad \text{on major thrust side}}$

(c)

with wrist pin offset 2 mm $\quad \sin\phi = 2.69/11.56 = 0.233 \quad \phi = 13.456°$

$F_t = [0 + (4500)(\pi/4)(0.06)^2 - 0.85]\tan(13.456°) \underline{= 2.84 \text{ kN}}$

(11-4)



clearance between piston and wall

$\Delta y = (3.1203 - 3.12)/2 = 0.00015 \text{ in.} = 0.0000125 \text{ ft}$

Eq. (11-13)

$\tau = \mu(\Delta u/\Delta y) = (0.000042 \text{ lbf-sec/ft}^2)[(30.78 \text{ ft/sec})/(0.0000125 \text{ ft})] = 103.42 \text{ lbf/ft}^2$

force on piston with interface surface area $A = \pi B(\text{height})$

$F = \tau A = (103.42 \text{ lbf/ft}^2)[\pi(3.12/12 \text{ ft})(2.95/12 \text{ ft})] \underline{= 20.8 \text{ lbf}}$

(11-5)

(a)

Eq. (2-88)

$828 = (1000)\dot{W}_b(2)/(2.8)(2000/60)$

$\underline{\dot{W}_b = 38.64 \text{ kW}}$

(b)

using Eq. (2-37) at 1000 RPM

imep = bmep/η_m = (828 kPa)/0.90 = 920 kPa

fmep = imep - bmep = 920 - 828 = 92 kPa

at 2000 RPM

imep = (828 kPa)/0.88 = 941 kPa

fmep = 941 - 828 = 113 kPa

at 3000 RPM

imep = (646 kPa)/0.82 = 788 kPa

fmep = 788 - 646 = 142 kPa

Eq. (11-12)

fmep = A + B N + C N^2

92 = A + 1000 B + 1,000,000 C

113 = A + 2000 B + 4,000,000 C

142 = A + 3000 B + 9,000,000 C

A = 79 B = 0.009 C = 0.000004

at 2500 RPM

fmep = 79 + (0.009)(2500) + (0.000004)$(2500)^2$ $\underline{= 126.5 \text{ kPa}}$

(c)

Eq. (2-88)

$126.5 = (1000)\dot{W}_f(2)/(2.8)(2500/60)$

$\underline{\dot{W}_f = 7.38 \text{ kW}}$

(11-6)

(a) fuel rate

$\dot{m}_f$ = (65 miles/hr)/(21 miles/gal) = 3.095 gal/hr

= (3.095 gal/hr)(46.8 lbm/ft^3)/(7.481 gal/ft^3) = 19.36 lbm/hr

oil use rate

$\dot{m}_{oil}$ = (3.095 gal/hr)/40 $\underline{= 0.0774 \text{ gal/hr}}$

(b) using time rate form of Eq. (5-26) for mixture trapped

$\lambda_{tc} = 0.64 = \dot{m}_{tc}/[V_d \rho_a (N/n)]$

$= \dot{m}_m/\{[110/(12)^3 \text{ ft}^3/\text{cycle}](0.0739 \text{ lbm/ft}^3)(1850/60 \text{ cycle/sec})\}$

$\dot{m}_m$ trapped = 0. 0928 lbm/sec

fuel trapped with 0.06 exhaust residual and AF = 17.8

$\dot{m}_f$ = (0.0928 lbm/sec)(0.94)(1/18.8) = 0.00464 lbm/sec = 16.71 lbm/hr

fuel flow time rate form of Eq. (5-24)

$\lambda_{te} = \dot{m}_{mt}/\dot{m}_{tc}$ = 16.71/19.36 = 0.863 $\underline{= 86.3\%}$

(c) $(\dot{m}_{oil})_{ex} = \dot{m}_{oil}(1 - \lambda_{te})$

(0.0774 gal/hr)(1 - 0.863) $\underline{= 0.0106 \text{ gal/hr}}$

(11-7)

(a) Eq. (3-31)

$\eta_t = 1 - (1/r_c)^{k-1} = 1 - (1/9.2)^{0.35} = 0.540$ $\underline{= 54.0\%}$

(b) with supercharger

η_t = (54.0)(1 - 0.06) $\underline{= 50.8\%}$

(c) $\dot{Q}_{in}$ will be proportional to air flow in $\dot{m}_a$

indicated power

$\dot{W}_i \propto \eta_t \dot{Q}in$

$(\dot{W}_{with\ s.c.})/(\dot{W}_{without}) = (\eta_t \dot{Q}_{in})_{with}/(\eta_t \dot{Q}_{in})_{without}$ = [(0.508)(1.22)]/[(0.540)(1.00)] = 1.148

<u>14.8% increase with supercharger</u>

(d) increase in brake power

(1.148)(1 - 0.04 to drive s.c.) = 1.102 <u>= 10.2% increase</u>