

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Mechanical Engineering
2.61 Internal Combustion Engine
Final Examination (Open book; no access to internet)

Date: Tuesday, 5/17/2016

There are 3 problems in this exam

Problem 1 (15 points)

In the car racing business, it is known that substantial power increase may be obtained by injecting nitrous oxide (N_2O) into the intake manifold. That it works is because:

- (a) N_2O has a higher molecular weight than air. The denser gas means that more oxidizer mass can be packed into the combustion chamber.
- (b) N_2O has much higher O to N ratio than air; so one can burn more fuel for the same charge mass and produce more output.
- (c) N_2O itself is a fuel, although the energy release is much less than that from hydrocarbon combustion.

Using isooctane as fuel, we are to compare the power output of the same engine using a stoichiometric isooctane/ air mixture and a stoichiometric mixture of isooctane and a gas comprising of **70% air and 30% nitrous oxide by volume**.

The heat of formation of N_2O Δh_f^0 is +82.5KJ/mole. See Tables D2 and D4 of the Heywood text book for properties of the working fluids.

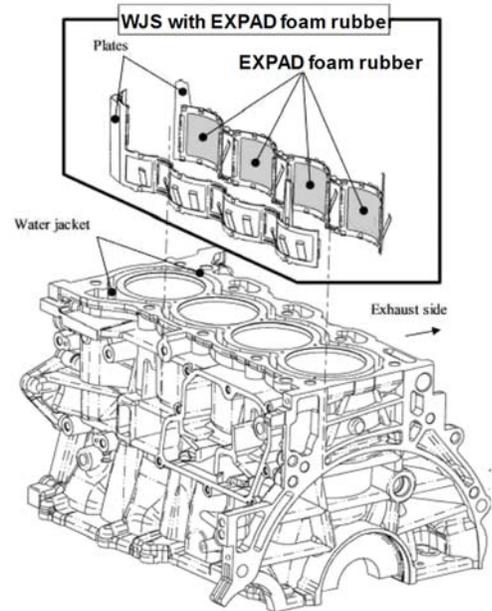
- (i) What is the molecular weight of a stoichiometric iso-octane air mixture? (2 points)
- (ii) What is the lower heating value (LHV) of a stoichiometric iso-octane air mixture (i.e., heating value per unit mass of the mixture, *NOT* per unit mass of the fuel)? (2 points)
- (iii) What is the molar composition of the air and N_2O mixture (i.e. for 1 mole of O_2 , how many moles are there of N_2 and N_2O)? (2 points)
- (iv) What is the molecular weight of the stoichiometric iso-octane/air/ N_2O mixture? (2 points)
- (v) What is the heating value of the stoichiometric iso-octane/air/ N_2O mixture? (2 points)
- (vi) Using the above results, with the same engine operating at stoichiometric condition, what is the ratio of the power output at wide-open-throttle obtained by operating with the iso-octane/air/ N_2O mixture to that obtained by operating with iso-octane/air only? (5 points)

Problem 2 (15 point)

- (a) Recently (2016), Toyota has introduced the EXPAD technology to enable a gain in the engine fuel economy. The method essentially involves wrapping a rubber pad in the mid-section of the cylinder liner; see Fig. 2a. Explain how does this technology work. (3 points)

Fig. 2a Toyota EXPAD technology; from SAE Paper 2016-01-0684, 2016 (WJS stands for water jacket system).

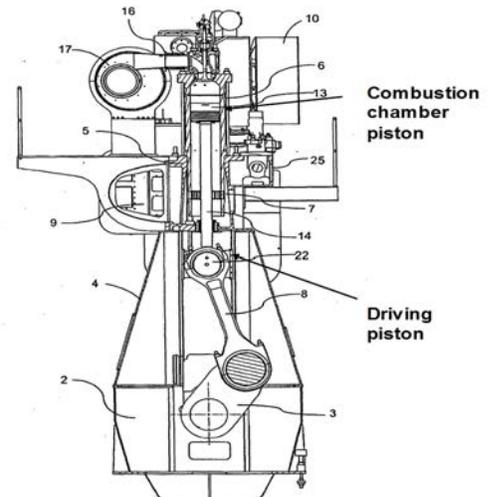
© Society of Automotive Engineers. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <https://ocw.mit.edu/help/faq-fair-use>.



- (b) High BMEP marine engines with large bore are constructed with a cross-head arrangement; see Fig. 2b. In this arrangement, the piston of the combustion chamber is driven by a second piston which is in rectilinear motion. The second piston is connected to the crank shaft through the usual connecting rod / crank-arm arrangement. Obviously, the additional components add cost to the engine, and render the engine much taller (although the latter is not a problem for marine engines since there is plenty of head room in a ship). Explain why would the engine designer choose such a configuration. (3 points)

Fig. 2b Cross-head engine.

© Source unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see <https://ocw.mit.edu/help/faq-fair-use>.



- (c) An inventor proposed that a turbo-charged diesel engine be configured that an additional power turbine is used to extract mechanical energy out of the exhaust gas to the drive shaft. The novelty of the proposal is that much of the shaft power is to be derived from the power turbine instead of the engine. Comment on the efficiency of the overall system compared to the original engine (1 points). Give two further comments on whether the concept is good or bad (each comment could either be positive or negative respectively). (2 points)
- (d) Give two reasons why retarding the spark timing at constant idle speed at cold start would make the catalyst to light-off faster. (2 points)
- (e) Give two consequences from operating a SI engine on Miller cycle; i.e. with a configuration such that the compression ratio is less than the expansion ratio. (2 points)
- (f) For a spark ignition engine, why would one pursue a cylinder-deactivation strategy, i.e. deactivate some of the cylinders in certain part of the engine map? (1 point). Do you want to keep the valves open or closed for the deactivated cylinders and why? (1 point)

Problem 3 (15 points)

The 3-way catalyst significantly reduces the SI engine emissions. The emission reduction capability of a warmed-up catalyst is limited by the diffusion of the gaseous species to the catalyst surface so that the concentration c of the emission species is governed by

$$c(x) = c(0) \exp\left(-\frac{4Sh}{h^2/DUL} x\right)$$

Here x is the distance along the catalyst, Sh is the Sherwood number ($Sh = 4$ for a square channel), h is the hydraulic diameter of the cell-channel, D is the diffusivity of the emission species in the exhaust gas, L is the length of the catalyst, and U is the flow velocity through the cell-channel.

For a targeted catalyst efficiency, $\eta_{\text{cat}} = 1 - c(L)/c(0)$ is specified.

- (a) The major cost of the catalyst is that of the precious metal. How does the cost (\$) scales with h ? You need to justify your answer. (6 points)

In part (a), you'll find that the cost goes down with a smaller h . However, h is limited by the manufacturing process and the pressure drop requirement of the catalyst.

The catalyst is sized to get the targeted conversion efficiency at maximum power, which closely corresponds to the maximum exhaust mass flow rate. Do the following analysis for a modern engine with the following specifications.

Catalyst:	Ceramic monolith with 600 cpsi (cells per square inch), and a wall thickness of 0.2 mm. The frontal area is a 15 by 9 cm ellipse (of area = 117.8 cm ²). Catalyst operates at 800K and 1 bar.
Engine:	120 kW gasoline SI engine at $\lambda = 1$; fuel conversion efficiency = 32%; exhaust gas molecular weight = 29
Other useful properties:	fuel LHV = 44 MJ/kg; universal gas constant = 8314 J/kmol-K

The targeted efficiency for reducing propane (a surrogate for the hydrocarbons) is 99.7%. The diffusivity of propane in exhaust gas at 800K and 1 bar is 5.63×10^{-5} m²/s.

- (b) What is the exhaust mass flow rate? (2 points)
- (c) What is the flow velocity inside the channels of the catalyst? (2 points)
- (d) What is the minimum length of the catalyst to attain the targeted catalyst efficiency? (2 points)
- (e) The exhaust gas viscosity μ at 1 bar and 800K is 3.6×10^{-5} kg/m-s. Calculate the Reynolds number of the flow in the catalyst. You should find that the flow should be in the laminar regime with the friction coefficient $f = 64/Re$.

What is the pressure drop through the catalyst? (The pressure drop is $0.5\rho U^2 f(L/h)$. Note that the pressure drop can be reduced by having a bigger frontal area.) (3 points)

MIT OpenCourseWare
<https://ocw.mit.edu>

2.61 Internal Combustion Engines
Spring 2017

For information about citing these materials or our Terms of Use, visit: <https://ocw.mit.edu/terms>.