Introduction to Aerospace Propulsion

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Lecture No - 13

In this lecture ...

- Solve problems related to
  - First law of thermodynamics for closed and open systems
  - Heat engines
  - Refrigerators and heat pumps

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Problem 1

- A 50 kg iron block at 80°C is dropped into an insulated tank that contains 0.5 m^3 of liquid water at 25°C. Determine the temperature when thermal equilibrium is reached.

  Specific heat iron: 0.45 kJ/kg°C, specific heat of water: 4.184 kJ/kg°C

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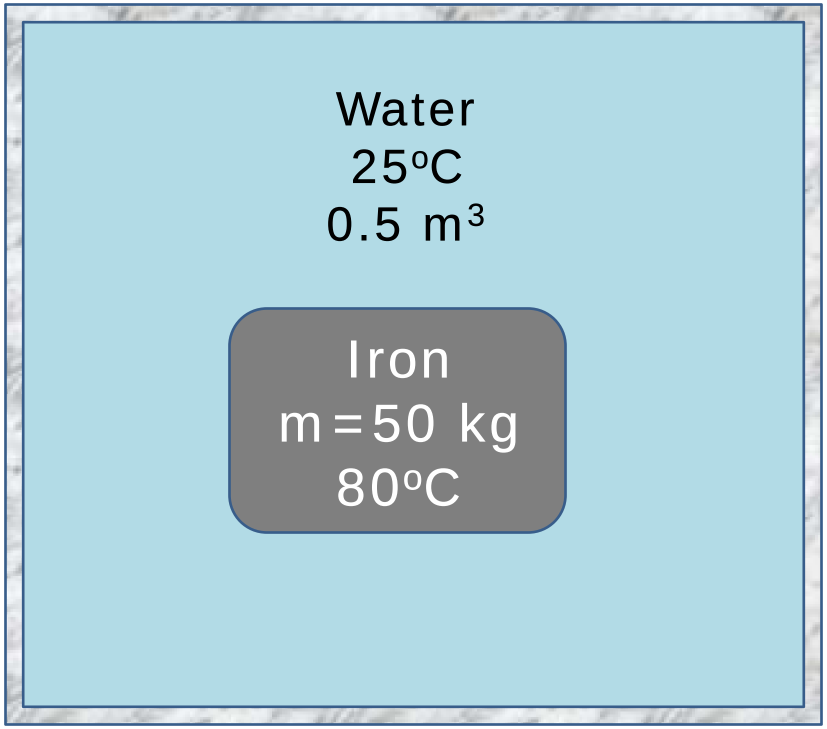
Solution: Problem 1



Solution: Problem 1

- Assumptions:
  - Both water and the iron block are incompressible substances.
  - Constant specific heats at room temperature can be used for water and the iron.
  - The system is stationary and thus the kinetic and potential energy changes are zero, $\Delta KE, \Delta PE=0$ and $\Delta E= \Delta U$.
  - There are no electrical, shaft, or other forms of work involved.
  - The system is well-insulated and thus there is no heat transfer.

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Solution: Problem 1

- The energy balance can be expressed as:

$$\underbrace{E_{in}-E_{out}}_{\text{Net energy transfer by heat, work and mass}} = \underbrace{\Delta E_{system}}_{\text{Change in internal, kinetic potential etc. energies}} \quad \text{(kJ)}$$

$$0 = \Delta U$$

$$\Delta U_{system} = \Delta U_{iron} + \Delta U_{water} = 0$$

$$[mc(T_2-T_1)]_{iron} + [mc(T_2-T_1)]_{water} = 0$$

$$\text{Mass of water, } m = V/v = 0.5\ m^3/0.001\ m^3/kg$$

$$= 500\ kg$$

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Solution: Problem 1

- Substituting the above values,

$$(50kg)(0.45\ kJ/kg\ ^oC)(T_2 - 80^oC) + (500\ kg)(4.18\ kJ/kg\ ^oC)(T_2 - 25^oC) = 0$$

Therefore, $T_2 = 25.6^oC$

This will be the temperature of water and iron after the system attains thermal equilibrium.

Note: The marginal change in the temperature of water. Why is this so?

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Problem 2

- A stationary mass of gas is compressed without friction from an initial state of 0.3 m^3 and 0.105 MPa to a final state of 0.15 m^3 and 0.105 MPa. There is a transfer of 37.6 kJ of heat from the gas during the process. What is the change in internal energy of the gas during this process?

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Solution: Problem 2

- From the first law for a stationary system,

$$Q = \Delta U + W$$

- In this example, the process is a constant pressure process. The work done during such a process is

$$W = \int P dV = P(V_2 - V_1)$$

$$= 0.105(0.15 - 0.30) = -15.75\ kJ$$

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Solution: Problem 2

- It is given that the heat transfer from the system is $Q = -37.6\ kJ$
- Therefore, $-37.6 = \Delta U - 15.75$

  or, $\Delta U = -21.85$ kJ

- The change in internal energy of the gas is -21.85 kJ (decrease in internal energy during the process)

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Problem 3

- Air at a temperature of 15°C passes through a heat exchanger at a velocity of 30 m/s where its temperature is raised to 800°C. It then passes through a turbine with the same velocity of 30 m/s and expands until the temperature falls to 650°C. On leaving the turbine, the air is taken at a velocity of 60 m/s to a nozzle where it expands until its temperature has fallen to 500°C. If the air flow rate is 2 kg/s, find (a) rate of heat transfer from the heat exchanger (b) the power output from the turbine (c) velocity at nozzle exit assuming no heat loss
- Assume c_p = 1.005 kJ/kg K

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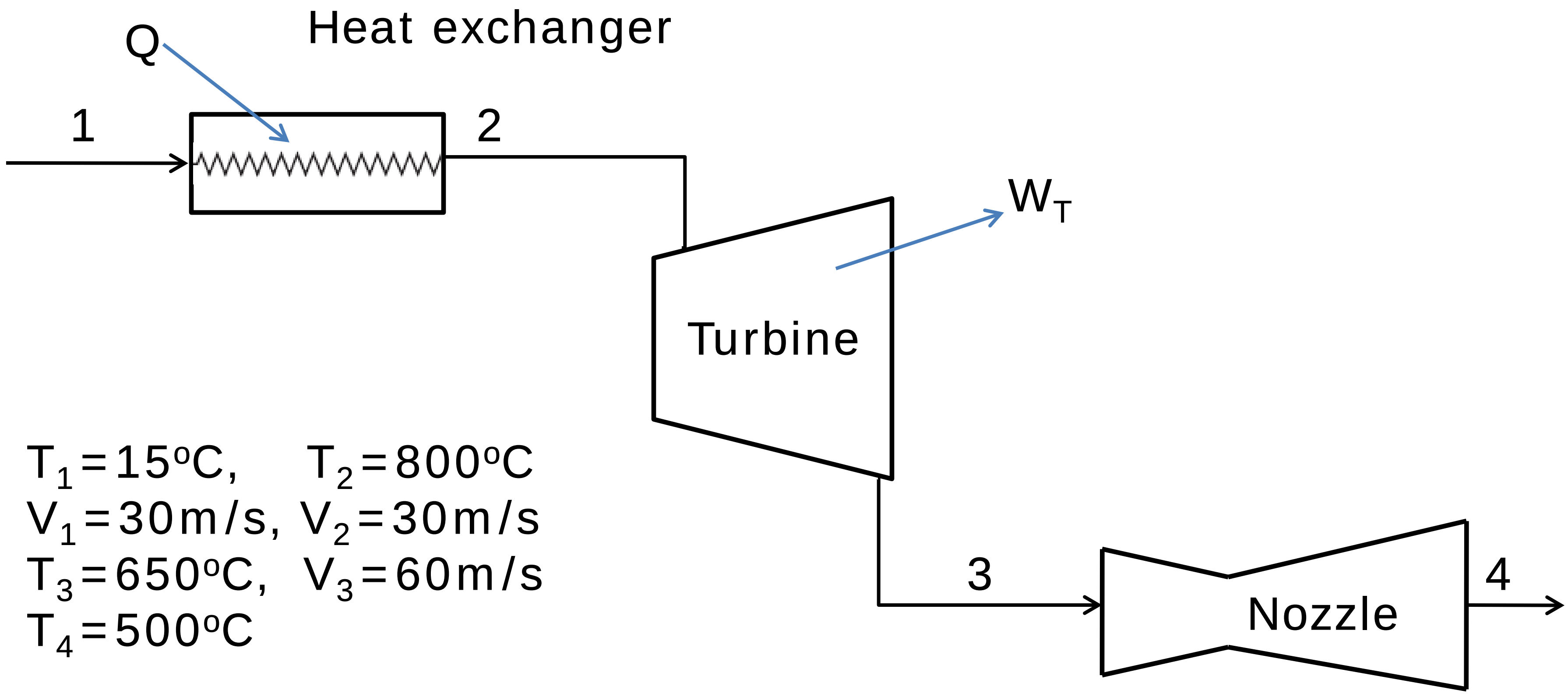
Solution: Problem 3



$T_1 = 15^oC$, $T_2 = 800^oC$
$V_1 = 30 m/s$, $V_2 = 30 m/s$
$T_3 = 650^oC$, $V_3 = 60 m/s$
$T_4 = 500^oC$

Solution: Problem 3

- Applying the energy equation across 1-2 (heat exchanger)

$$\dot{Q} - \dot{W} = \dot{m}\left[h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right]$$

For a heat exchanger, this reduces to,

$$\dot{Q}_{1-2} = \dot{m}(h_2 - h_1) = \dot{m}\,c_p(T_2 - T_1)$$

$$= 2 \times 1.005 \times (1073.16 - 288.16) = 1580 \text{ kJ/s}$$

- The rate of heat exchanger to the air in the heat exchanger is 1580 kJ/s

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Solution: Problem 3

- The energy equation the turbine 2-3

$$\dot{W} = \dot{m}\left[h_2 - h_3 + \frac{V_2^2 - V_3^2}{2}\right]$$

$$\dot{W} = 2\times\left[1005\times(1073.16 - 923.16) + \frac{(30^2 - 60^2)}{2}\right]$$

$$= 298.8\,\mathrm{kW}$$

- The power output from the turbine is 298.8 kW

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Solution: Problem 3

- For the nozzle (3-4)

$$\frac{V_3^2}{2}+h_3=\frac{V_4^2}{2}+h_4$$

$$\frac{60^2}{2}+1.005\times(923.16)=\frac{V_4^2}{2}+1.005\times(773.16)$$

$$\therefore V_4=554\ m/s$$

- The velocity at the exit from the nozzle is 554 m/s.

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Problem 4

- Heat is transferred to a heat engine from a heat source at a rate of 80 MW. If the rate of waste heat rejection to sink is 50 MW, determine the net power output and the thermal efficiency for this heat engine.

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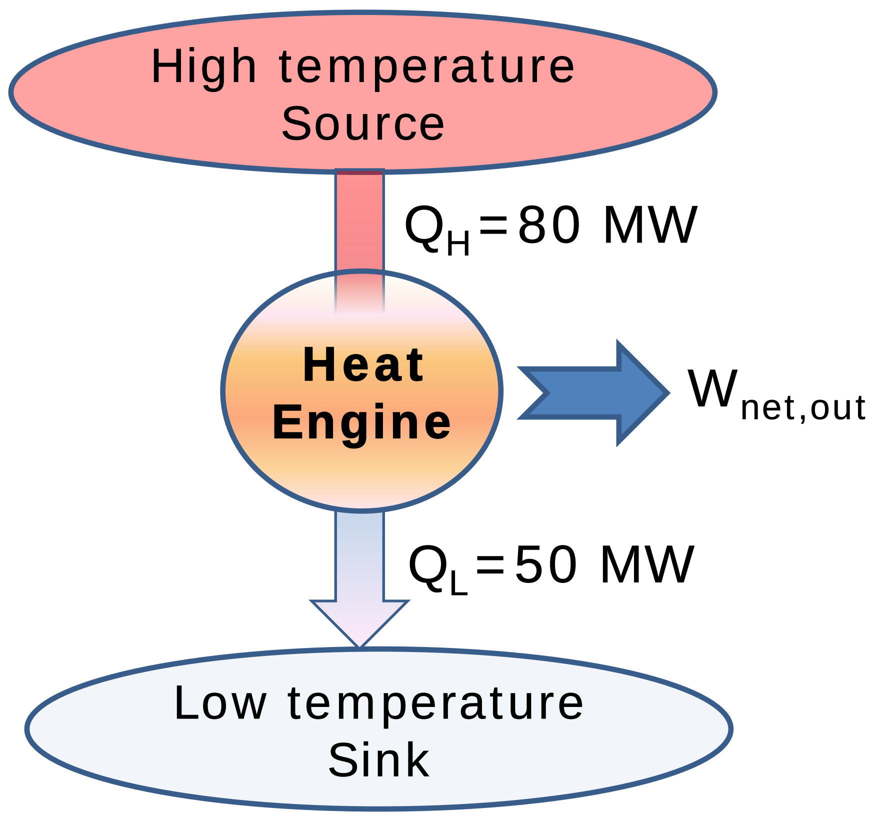
Solution: Problem 4



Solution: Problem 4

- We know that the net power output is the difference between the heat input and the heat rejected (cyclic device)

$$W_{net,out} = Q_H + Q_L$$
$$= 80 – 50 MW = 30 MW$$

- The net work output is 30 mW.
- The thermal efficiency is the ratio of the net work output and the heat input.

$$\eta_{th} = W_{net,out}/Q_H = 30/80 = 0.375$$

- The thermal efficiency is 0.375 or 37.5 %

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Problem 5

- The food compartment of a refrigerator is maintained at 4°C by removing heat from it at a rate of 360 kJ/min. If the required power input to the refrigerator is 2 kW, determine (a) the coefficient of performance of the refrigerator and (b) the rate of heat rejection to the room that houses the refrigerator.

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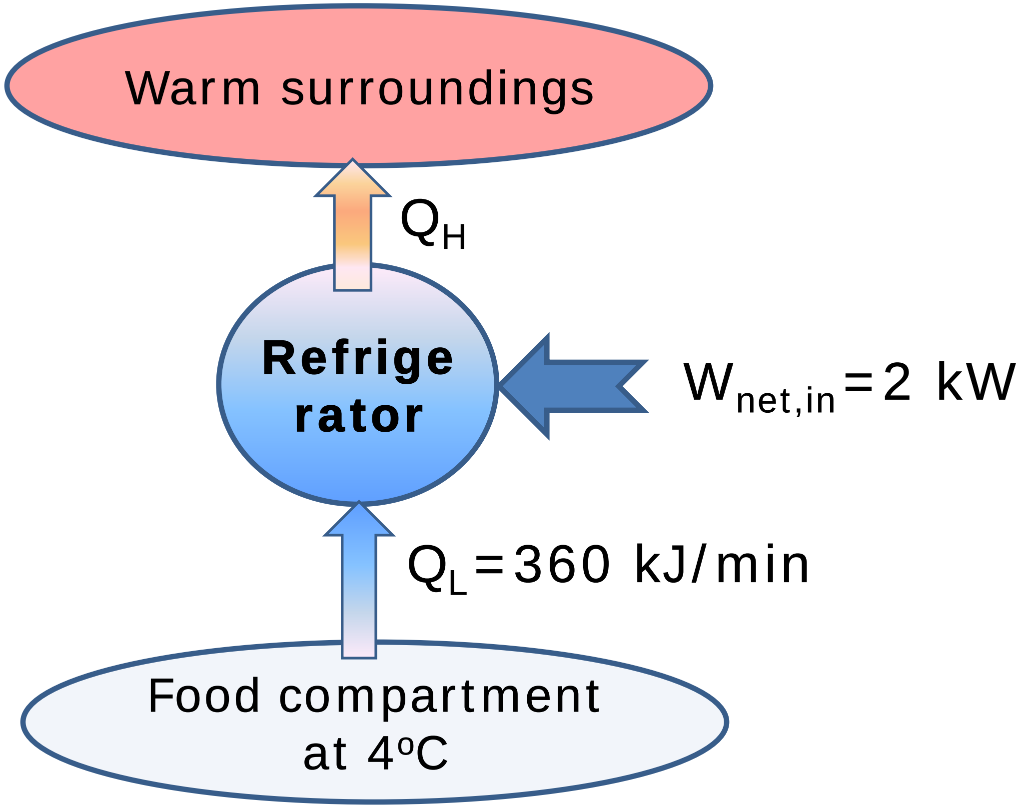
Solution: Problem 5



Problem 5

- COP of the refrigerator,

  COP_R = Desired effect/work input = $Q_L/W_{net,in}$

  $= (360/60\ kJ/s)/2 = 3$

- The COP of the refrigerator is 3 (3 kJ of heat is removed per kJ of work supplied).
- The rate of heat rejection can be obtained by applying the first law of thermodynamics

  $Q_H = Q_L + W_{net,in} = 6\ kW + 2\ KW = 8\ kW$

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Problem 6

- A heat engine is used to drive a heat pump. The heat transfers from the heat engine and the heat pump are rejected to the same sink. The efficiency of the heat engine is 27% and the COP of the heat pump is 4. Determine the ratio of the total heat rejection rate to the heat transfer to the heat engine.

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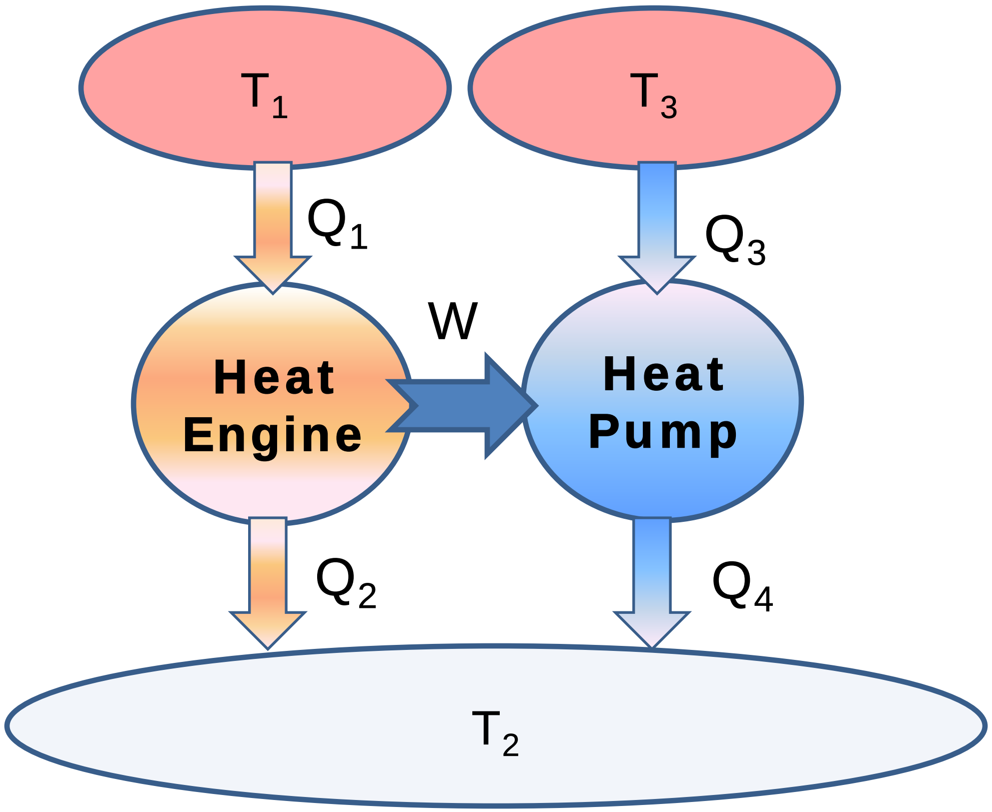
Solution: Problem 6



Solution: Problem 6

- The efficiency of the heat engine, η

  η = Net work output/heat input = W/Q_1

  $W = 0.27Q_1$

- COP_{HP} = desired effect/work input

  $= Q_4/W = 4$ or, $W = Q_4/4$

- Therefore, $0.27Q_1 = Q_4/4$

  or, $Q_4/Q_1 = 1.08$

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Solution: Problem 6

- We know that $\eta = 1 - Q_2/Q_1 = 0.27$

  Or, $Q_2/Q_1 = 0.73$

- Hence, $(Q_2+Q_4)/Q_1 = 1.08 + 0.73 = 1.81$
- The ratio of the total heat rejection rate (Q_2+Q_4) to the heat transfer to the heat engine (Q_1) *is 1.81.*

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Exercise Problem 1

- A mass of 8 kg gas expands within a flexible container as per $pv^{1.2}$ = constant. The initial pressure is 1000 kPa and the initial volume is 1 m^3. The final pressure is 5 kPa. If the specific internal energy of the gas decreases by 40 kJ/kg, find the heat transfer in magnitude and direction.
- Ans: +2615 kJ

Exercise Problem 2

- Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity.
- Determine (*a) the mass flow rate of the air and (b) the temperature of* the air leaving the diffuser.
- Ans: 78.8 kg/s, 303K

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Exercise Problem 3

- A refrigerator is maintained at a temperature of 2^{o}C. Each time the door is opened, 420 kJ of heat is introduced inside the refrigerator, without changing the temperature of the refrigerator. The door is opened 20 times a day and the refrigerator operates at 15% of the ideal COP. The cost of work is Rs. 2.50 kWh. Determine the monthly bill for this refrigerator if the atmosphere is at 30^{o}C.
- Ans: Rs. 118.80

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Exercise Problem 4

- An automobile engine consumes fuel at a rate of 28 L/h and delivers 60 kW of power to the wheels. If the fuel has a heating value of 44,000 kJ/kg and a density of 0.8 g/cm^3, determine the efficiency of this engine.
- Ans: 21.9%

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In the next lecture …

- The Carnot cycle
- The reversed Carnot cycle
- The Carnot principles
- The thermodynamic temperature scale
- Carnot heat engine
- Quality of energy
- Carnot refrigerator and heat pump

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