

***Fundamentals of Thermodynamics 11th edition
Borgnakke Test Bank***

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Thermo I, FINAL EXAM, 2 hours

Open book, no solved problems

Problem 1 (30 Points)

A 3.3 L American minivan engine running at 2000 RPM has a compression ratio of 10:1. The state before compression is 50 kPa, 280 K and after expansion the T is 750 K. Use constant specific heats for solution.

- a) What is the highest T and P in the cycle?
- b) What is the specific heat transfer added by combustion?
- c) What is the mean effective pressure?
- d) How much power does the engine produce?

Problem 2 (20 Points)

An adiabatic mixing chamber receives a flow of 1 kg/s steam at 400 kPa, 600°C and a flow of 2 kg/s steam at 1000 kPa, 200°C which is being throttled down to 400 kPa. The steady flow exits at 400 kPa.

- a) What is the exit temperature?
- b) Find the total entropy generation rate.

Problem 3 (20 Points)

Nitrogen at 600 kPa, 127°C is in a 0.5 m³ piston-cylinder and now goes through a polytropic compression to 1800 kPa with $n = 1.3$.

- a) Find the final temperature.
- b) Find the process work.
- c) Find the heat transfer in the process.

Problem 4 (30 Points)

An insulated tank contains 0.5 m³ air at 100 kPa, 300 K. A reversible adiabatic compressor pushes ambient air at 100 kPa, 300 K into the tank until the tank pressure is 1000 kPa and stops.

- a) How much mass was in the tank at the start of the process?
- b) What is the final mass in the tank?
- c) How much work input does the compressor require?

Thermo I FINAL EXAM, SOLUTION

Problem 1 (30 Points) This is a basic 4-stroke Otto cycle given by: CR, P_1 , T_1 , T_4

$$v_1 = RT_1/P_1 = 0.287 \text{ kJ/kg-K} \times 280 \text{ K}/50 \text{ kPa} = 1.6072 \text{ m}^3/\text{kg} = v_4$$

$$v_2 = v_1/\text{CR} = 0.16072 \text{ m}^3/\text{kg}$$

Combustion $v_3 = v_2$. Highest T and P are after combustion.

Expansion $T_4 = 750 \text{ K}$ so relate back to state 3

$$P_4 = RT_4/v_4 = 0.287 \text{ kJ/kg-K} \times 750 \text{ K}/1.6072 \text{ m}^3/\text{kg} = 133.93 \text{ kPa}$$

$$P_3 = P_4 \text{CR}^k = 133.93 \text{ kPa} \times 10^{0.4} = \mathbf{3364.1 \text{ kPa}}$$

$$T_3 = T_4 (v_4/v_3)^{k-1} = T_4 \text{CR}^{k-1} = 750 \times (10)^{0.4} = \mathbf{1883.9 \text{ K}}$$

Compression: $T_2 = T_1(\text{CR})^{k-1} = 280 \text{ K} \times (10)^{0.4} = 703.33 \text{ K}$

$$q_H = u_3 - u_2 = C_v(T_3 - T_2) = 0.717 (1883.9 - 703.33) = \mathbf{846.49 \text{ kJ/kg}}$$

To get the net work

$$\eta = 1 - \text{CR}^{1-k} = 1 - 10^{-0.4} = 0.602$$

$$w_{\text{net}} = \eta q_H = 0.602 \times 846.49 = 509.5 \text{ kJ/kg}$$

OR

$$q_L = u_4 - u_1 = C_v(T_4 - T_1) = 0.717 \text{ kJ/kg-K}(750 - 280)\text{K} = 336.99 \text{ kJ/kg}$$

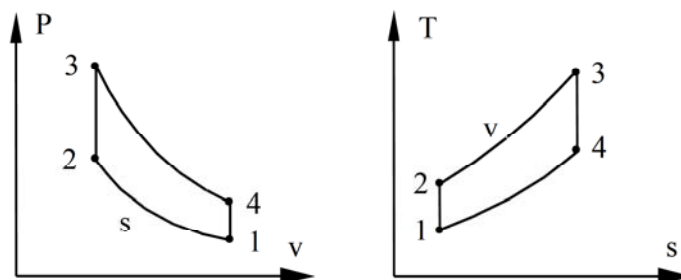
$$w_{\text{net}} = q_H - q_L = 846.49 - 336.99 = 509.5 \text{ kJ/kg} \quad]$$

Displacement and mep from net work

$$P_{\text{meff}} = w_{\text{net}}/(v_1 - v_2) = 509.5 \text{ kJ/kg} / (1.6072 - 0.16072) \text{ m}^3/\text{kg} = \mathbf{352.2 \text{ kPa}}$$

Total power from Eq. 10.11 and 4 stroke cycle

$$\begin{aligned} \dot{W} &= P_{\text{meff}} V_{\text{displ}} \frac{\text{RPM}}{60} \frac{1}{2} = 352.2 \text{ kPa} \times 0.0033 \text{ m}^3 \times \frac{2000}{60} \text{ s}^{-1} \times \frac{1}{2} \\ &= \mathbf{19.4 \text{ kW}} \end{aligned}$$



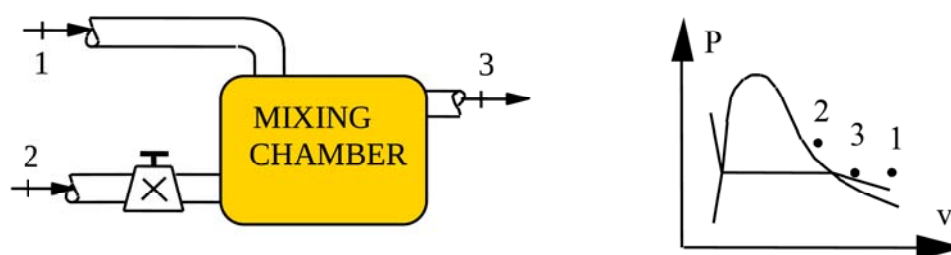
Problem 2 (20 Points)

CV: Mixing chamber including valve, $\dot{Q} = 0$.

Continuity Eq.4.9: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy Eq.4.10: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

Entropy Eq.7.7: $\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{\text{gen}} = \dot{m}_3 s_3$



From the energy equation, properties from B.1.3:

$$h_3 = (\dot{m}_1/\dot{m}_3) h_1 + (\dot{m}_2/\dot{m}_3) h_2 = \frac{1}{3} h_1 + \frac{2}{3} h_2$$

$$= [3702.44 + 2 \times 2827.86] / 3 = 3119.39 \text{ kJ/kg}$$

Now state 3 (P, h)

$$T_3 = 300 + 100 \times \frac{3119.39 - 3066.75}{3273.41 - 3066.75} = 300 + 100 \times 0.2547 = \mathbf{325.5^\circ\text{C}}$$

$$s_3 = 7.5661 + 0.2547 (7.8984 - 7.5661) = 7.65074 \text{ kJ/kgK}$$

Entropy generation from entropy equation

$$\dot{S}_{\text{gen}} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2$$

$$= 3 \times 7.65074 - 8.4557 - 2 \times 6.6939 = \mathbf{1.109 \text{ kW/K}}$$

Problem 3 (20 Points)

CV nitrogen, this is a control mass.

$$\text{Energy Eq.: } m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

Process eq.: polytropic: $Pv^n = C$, with $n = 1.3$

State 1 (P_1, T_1):

$$m_1 = P_1 V_1 / RT_1 = 600 \text{ kPa} \times 0.5 \text{ m}^3 / (0.2968 \text{ kJ/kg-K} \times 400 \text{ K}) = 2.527 \text{ kg}$$

State 2 (P_2 , on process path) polytropic and ideal gas gives

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} = 400 \times \left(\frac{1800}{600} \right)^{0.3/1.3} = \mathbf{515.42 \text{ K}}$$

Polytropic process work term from Eq.6.29

$$\begin{aligned} {}_1W_2 &= m \frac{R}{1-n} (T_2 - T_1) = 2.527 \text{ kg} \times \frac{0.2968}{-0.3} \text{ kJ/kg-K} \times (515.42 - 400) \text{ K} \\ &= \mathbf{-288.55 \text{ kJ}} \end{aligned}$$

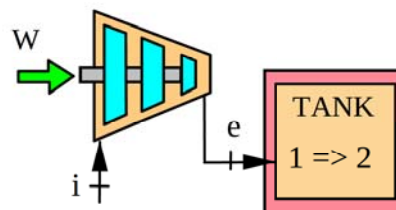
From the energy equation (use constant specific heats)

$$\begin{aligned} {}_1Q_2 &= m(u_2 - u_1) + {}_1W_2 = mC_v(T_2 - T_1) + {}_1W_2 \\ &= 2.527 \text{ kg} \times 0.745 \text{ kJ/kg-K} \times (515.42 - 400) \text{ K} - 288.55 \text{ kJ} \\ &= \mathbf{-71.26 \text{ kJ}} \end{aligned}$$

Comment: process is internally reversible (Q leaves at local T which varies through process) but potentially externally irreversible.

Problem 4 (30 Points)

C.V. The tank volume and the compressor.
This is a transient problem (filling of tank).



Continuity Eq.4.20: $m_2 - m_1 = m_{in}$

Energy Eq.4.21: $m_2 u_2 - m_1 u_1 = {}_1Q_2 - {}_1W_2 + m_{in} h_{in}$

Entropy Eq.7.12: $m_2 s_2 - m_1 s_1 = \int dQ/T + {}_1S_2_{gen} + m_{in} s_{in}$

Process: Adiabatic ${}_1Q_2 = 0$, Process ideal ${}_1S_2_{gen} = 0$, $s_1 = s_{in}$

$$m_2 s_2 = m_1 s_1 + m_{in} s_{in} = (m_1 + m_{in}) s_1 = m_2 s_1 \Rightarrow s_2 = s_1$$

Constant s : Assume constant specific heats leads to polytropic process Eq.6.28

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} = 300 \left(\frac{1000}{100} \right)^{0.2857} = 579.19 \text{ K}$$

$$m_1 = P_1 V_1 / RT_1 = 100 \text{ kPa} \times 0.5 \text{ m}^3 / (0.287 \text{ kJ/kg-K} \times 300 \text{ K}) = \mathbf{0.5807 \text{ kg}}$$

$$m_2 = P_2 V_2 / RT_2 = 1000 \text{ kPa} \times 0.5 \text{ m}^3 / (0.287 \text{ kJ/kg-K} \times 579.19 \text{ K})$$

$$= \mathbf{3.0079 \text{ kg}}$$

$$m_{in} = m_2 - m_1 = 2.4272 \text{ kg}$$

Work from the energy equation

$${}_1W_2 = m_{in} h_{in} + m_1 u_1 - m_2 u_2 = m_{in} C_p T_{in} + m_1 C_v T_1 - m_2 C_v T_2$$

$$= [2.4272 \times 1.004 \times 300 + 0.5807 \times 0.717 \times 300$$

$$- 3.0079 \times 0.717 \times 579.19] \text{ kg} \times \text{kJ/kg-K} \times \text{K}$$

$$= -393.14 \text{ kJ}$$

$$W_{in} = \mathbf{393.14 \text{ kJ}}$$