KING ABDULAZIZ UNIVERSITY.
Faculty of Engineering, Rabigh Branch.
Mechanical Engineering Department.
Subject: Thermodynamics (I) MEP261.
Spring 1433 H. **Final Exam.**

Student Name:
Student Number:
Time: 2 hr. Group: ZA.
Property Tables are allowed.

Question No.	1	2	3	4	5	6	
Mark							
Total							/30

Answer the following questions:

Question (1) **(2 Marks)**

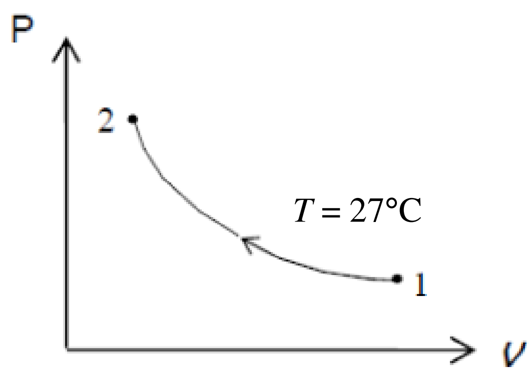
A mass of 2.0 kg of air at 200 kPa and 27°C is contained in a gas-tight, frictionless piston-cylinder device. The air is now compressed to a 800 kPa. During the process, heat is transferred from the air such that the temperature inside the cylinder remains constant. Calculate the work input during this process.

Solution Air in a cylinder is compressed at constant temperature until its pressure rises to a specified value. The boundary work done during this process is to be determined.

Assumptions 1 The process is quasi-equilibrium. 2 Air is an ideal gas.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K (Table A-1).

Analysis The boundary work is determined from its definition to be



$$W_{b,out} = \int_1^2 P\,dV = P_1V_1 \ln\frac{V_2}{V_1} = mRT \ln\frac{P_1}{P_2}$$

$$T = T_2 = T_1 = 27+273 \text{ K} = 300 \text{ K}$$

 Examiner: Dr. Walid Aniss.

Hence, $W_{b,out} = (2.0\text{ kg})(0.287\text{ kJ/kg.K})(300\text{ K}) \ln \dfrac{\mathbf{200\ kPa}}{\mathbf{800\ kPa}}$

i.e. $W_{b,out} = -238.7$ kJ

Discussion: Negative sign indicates that the work is done on the system (work input).

Question (2) **(3 Marks)**

Consider a 270-L storage tank of a solar water heating system initially filled with warm water at 45°C. Warm water is withdrawn from the tank through a 1.8-cm diameter hose at an average velocity of 0.45 m/s while cold water enters the tank at 20°C at a rate of 4.5 L/min. Determine the amount of water in the tank after a 18-minute period. Assume the pressure in the tank remains constant at 1 atm.

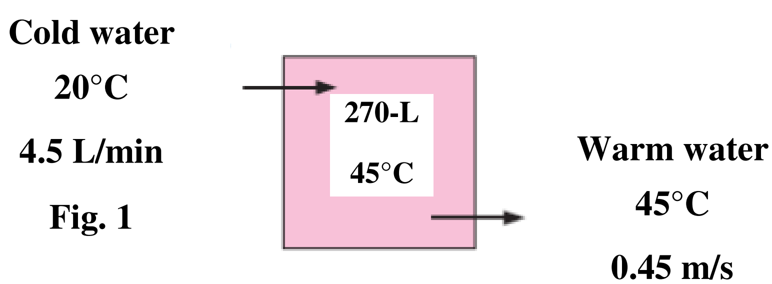


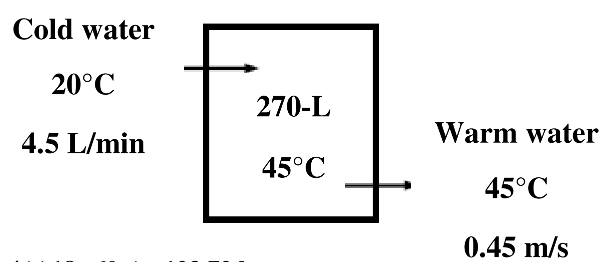
Fig. 1

Solution Warm water is withdrawn from a solar water storage tank while cold water enters the tank. The amount of water in the tank in a 20-minute period is to be determined.

Properties The density of water is taken to be 1000 kg/m^3 for both cold and warm water.

Analysis The initial mass in the tank is first determined from

$m_1 = \rho V_{tank} = (1000\text{ kg/m}) \ (\mathbf{0.27 m^3}) = \mathbf{270\ kg}$



The amount of warm water leaving the tank during a **18 min period is**

$m_e = \rho A_c V \Delta t = (1000\text{ kg/m}^3)\dfrac{\pi(\mathbf{0.018\ m})^2}{4}(\mathbf{0.45 m/s})(\mathbf{18 \times 60\ s}) = \mathbf{123.72\ kg}$

The amount of cold water entering the tank during a **18 min period is**

$m_i = \rho \dot{V}_c \Delta t = (1000\text{ kg/m}^3)(\mathbf{0.0045\ m^3/min})(\mathbf{18\ min}) = \mathbf{81\ kg}$

The final mass in the tank can be determined from a mass balance as

$m_i - m_e = m_2 - m_1 \longrightarrow m_2 = m_1 + m_i - m_e = \mathbf{270\ kg + 81\ kg - 123.72\ kg = 227.3\ kg}$

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Spring 1433 H. **Final Exam.** **Property Tables are allowed.**

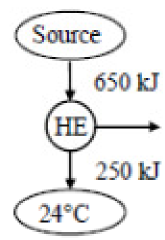
Question (3) **(3 Marks)**

A Carnot heat engine receives 800 kJ of heat from a source of unknown temperature and produces 400 kJ of net work and rejects heat to a sink at 27°C. Determine (*a*) the temperature of the source and (*b*) the thermal efficiency of the heat engine.

Solution The sink temperature of a Carnot heat engine and the rates of heat supply and heat rejection are given. The source temperature and the thermal efficiency of the engine are to be determined.

Assumption The Carnot heat engine operates steadily.

Analysis (a) For reversible cyclic devices we have $\left(\frac{Q_H}{Q_L}\right)_{rev} = \left(\frac{T_H}{T_L}\right)$



$Q_L = Q_H - W =$ 800 kJ - 400 kJ = 400 kJ,

Thus the temperature of the source: T_H must be

$$T_H = \left(\frac{Q_H}{Q_L}\right)_{rev} T_L = \left(\frac{800\text{ KJ}}{400\text{ KJ}}\right)(300\text{ K}) = 600\text{ K}$$

(*b*) The thermal efficiency of a Carnot heat engine depends on the source and the sink temperature only, and is determined from

$$\eta_{th,C} = 1 - \frac{T_L}{T_H} = 1 - \frac{300\text{ K}}{600\text{ K}} = 0.5*100\% = 50\%$$

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Question (4) **(4 Marks)**

A well-insulated rigid tank contains 3 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, one-fourth of the mass is in the liquid phase. An electric resistance heater placed in the tank is now turned on and kept on until all the liquid in the tank is vaporized. Determine the entropy change of the steam during this process.

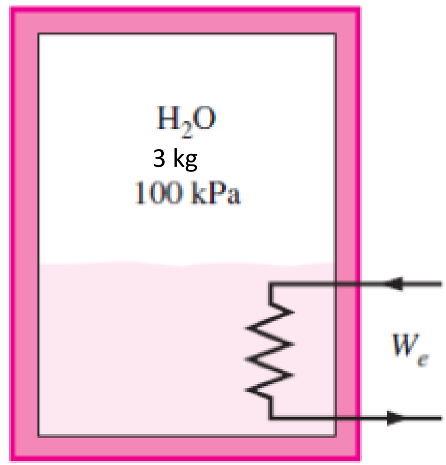
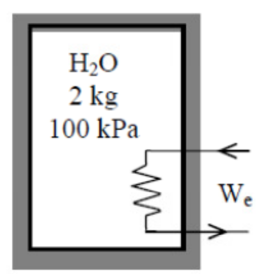


FIGURE P7–34

Solution An insulated rigid tank contains a saturated liquid-vapor mixture of water at a specified pressure. An electric heater inside is turned on and kept on until all the liquid vaporized. The entropy change of the water during this process is to be determined.

Analysis From the steam tables (Tables A-4 through A-6)

$$\left.\begin{array}{l} P_1 = 100 \text{ kPa} \\ x_1 = 0.75 \end{array}\right\} \begin{array}{l} v_1 = v_f + x_1 v_{fg} = 0.001 + (0.75)(1.6941 - 0.001) = 1.271 \quad \text{m}^3/\text{kg} \\ s_1 = s_f + x_1 s_{fg} = 1.3028 + (0.75)(6.0562) = 5.845 \quad \text{kJ/kg}\cdot\text{K} \end{array}$$



State 2 is saturated vapor

$v_2 = v_1 = 1.271$ m^3/kg

For saturated vapor, $v_g = 1.271$ m^3/kg

s_g is evaluated by interpolation

(s_g – 7.2231 KJ/kg.K)(7.2841 KJ/kg.K-7.2231 KJ/kg.K)=(1.271 -1.1594) m^3/kg/(1.3750 -1.1594) m^3/kg

$s_2 = s_g$ = 7.2539 KJ/kg.K

Hence, the entropy change of steam becomes;

$\Delta S = m(s_2 - s_1)$= 3 kg (7.2539 KJ/kg.K – 5.845 KJ/kg.K) = 4.23 KJ/K

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Question (5) **(7 Marks)**

An ideal Otto cycle has a compression ratio of 8. At the beginning of the compression process, air is at 95 kPa and 27°C, and 750 kJ/kg of heat is transferred to air during the constant-volume heat-addition process. Taking into account the variation of specific heats with temperature, determine (*a*) the pressure and temperature at the end of the heat addition process, (*b*) the net work output, (*c*) the thermal efficiency, and (d) the mean effective pressure for the cycle.

Solution An ideal Otto cycle with air as the working fluid has a compression ratio of 8. The pressure and temperature at the end of the heat addition process, the net work output, the thermal efficiency, and the mean effective pressure for the cycle are to be determined.

Assumptions 1 The air-standard assumptions are applicable. 2 Kinetic and potential energy changes are negligible. 3 Air is an ideal gas with variable specific heats.

Properties The gas constant of air is $R = 0.287$ kJ/kg.K. The properties of air are given in Table A-17.

Analysis (*a*) Process 1–2: isentropic compression.

From Table A-17, for $T_1 = 300\ K$, $u_1 = 214.07\ kJ/kg$

$Tv^{k-1} = C$,

Hence, $T_1 v_1^{k-1} = T_2 v_2^{k-1}$, Hence, $T_2 = T_1 (v_1/v_2)^{k-1}$

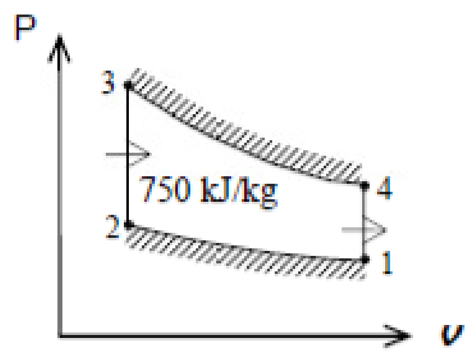
For T = 300 K, k = 1.4 (from Table A-2)

i.e., $T_2 = 300K\,(8)^{1.4-1} = 689.2\ K$

Hence, From Table A-17, for $T_2 = 689.2\ K$, $u_2 = 504.45\ kJ/kg$

From Ideal gas equation,

$pv = RT$, Hence, $p_2 v_2 / T_2 = p_1 v_1 / T_1$



Hence, $p_2 = p_1 (v_1 / v_2) (T_2 / T_1)$

Hence, $p_2 = 95\ kPa\,(8)\,(689.2\ K / 300\ K) = 1745.97\ kPa$

Process 2–3: v = constant heat addition.

$$q_{23,\text{in}} = u_3 - u_2 = c_v (T_3 - T_2)$$

$$750\ \text{kJ/kg} = (0.718\ \text{kJ/kg}\cdot\text{K})(T_3 - 689)\text{K}$$

$$T_3 = \mathbf{1734\ K}$$

$$\frac{P_3 v_3}{T_3} = \frac{P_2 v_2}{T_2} \longrightarrow P_3 = \frac{T_3}{T_2} P_2 = \left(\frac{1734\ \text{K}}{689\ \text{K}}\right)(1745\ \text{kPa}) = \mathbf{4392\ kPa}$$

(*b*) Process 3–4: isentropic expansion.

$$T_4 = T_3 \left(\frac{v_3}{v_4}\right)^{k-1} = (1734\ \text{K})\left(\frac{1}{8}\right)^{0.4} = 755\ \text{K}$$

Process 4-1: v = constant heat rejection.

$$q_{\text{out}} = u_4 - u_1 = c_v (T_4 - T_1) = (0.718\ \text{kJ/kg}\cdot\text{K})(755 - 300)\text{K} = 327\ \text{kJ/kg}$$

$$w_{\text{net,out}} = q_{\text{in}} - q_{\text{out}} = 750 - 327 = \mathbf{423\ kJ/kg}$$

(*c*) $$\eta_{\text{th}} = \frac{w_{\text{net,out}}}{q_{\text{in}}} = \frac{423\text{kJ/kg}}{750\text{kJ/kg}} = \mathbf{56.4\%}$$

(*d*) $$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(300\ \text{K})}{95\ \text{kPa}} = 0.906\ \text{m}^3/\text{kg} = v_{\max}$$

$$v_{\min} = v_2 = \frac{v_{\max}}{r}$$

$$\text{MEP} = \frac{w_{\text{net,out}}}{v_1 - v_2} = \frac{w_{\text{net,out}}}{v_1(1 - 1/r)} = \frac{423\ \text{kJ/kg}}{(0.906\ \text{m}^3/\text{kg})(1 - 1/8)}\left(\frac{\text{kPa}\cdot\text{m}^3}{\text{kJ}}\right) = \mathbf{534\ kPa}$$

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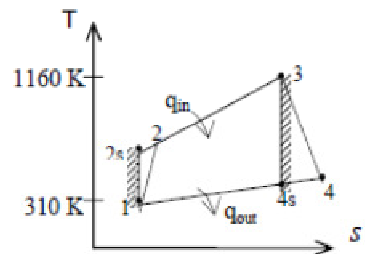
Question (6) **(12 Marks)**

A simple Brayton cycle using air as the working fluid has a pressure ratio of 8. The minimum and maximum temperatures in the cycle are 310 and 1160 K.

Assuming an isentropic efficiency of 75 percent for the compressor and 82 percent for the turbine, determine (*a*) the air temperature at the turbine exit, (*b*) the net work output, and (*c*) the thermal efficiency

Solution A simple Brayton cycle with air as the working fluid has a pressure ratio of 8. The air temperature at the turbine exit, the net work output, and the thermal efficiency are to be determined.

Assumptions **1** Steady operating conditions exist. **2** The air-standard assumptions are applicable. **3** Kinetic and potential energy changes are negligible. **4** Air is an ideal gas with variable specific heats.



Properties The properties of air are given in Table A-17.

Analysis (*a*) Noting that process 1–2 is isentropic,

a) Evaluation of Temperature at turbine exit; T_4

From Table A-2b, for $T_1 = 310$K k is obtained by interpolation.

$(k-1.400)/(1.398-1.400) = (310-300)/(350-300)$

$k = 1.3996$

From Table A-17, for , $T_1 = 310$ K, $h_1 = 310.24$ kJ/kg,

Process 1-2s is isentropic process,

Hence, $T_1 p_1^{(1-k)/k} = T_{2s} p_{2s}^{(1-k)/k}$

Hence, $T_{2s} = T_1 [p_1/p_{2s}]^{(1-k)/k} = 310\text{K } [1/8]^{(1-1.3996)/\,1.3996}$

Hence, $T_{2s} = 561.31$ K

Hence, $T_{avg} = (T_1 + T_{2s})/2 = (310 + 561.31)/2 = 435.66$ K

From Table A-2b, for $T_{avg} = 435.66$ K, k is obtained by interpolation.

$(k-1.395)/(1.391-1.395) = (435.66 - 400)/(450-400)$

$k = 1.3921$

Hence, $T_{2s} = T_1 [p_1/p_{2s}]^{(1-k)/k} = 310\text{K } [1/8]^{(1-1.3921)/\,1.3921}$

Hence, $T_{2s} = 566.86$ K

From Table A-17, for $T_{2s} = 561.31$ K, h_{2s} is evaluated by interpolation,

$(h_{2s} - 565.17)/(575.59 - 565.17) = (566.86 - 560)/(570 - 560)$, Hence,
$h_{2s} =$ 572.32 kJ/kg.

$$\eta_c = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Hence,

$$h_2 = h_1 + \frac{h_{2s} - h_1}{\eta_c}$$

h_2 = 310.24 kJ/kg + [(572.32 kJ/kg - 310.24 kJ/kg)/0.75]
Hence, h_2 = 659.68 kJ/kg
T_3 = 1160 K.
From Table A-17, for $T_3 = 1160\ K$, h_3 = 1230.92 kJ/kg,

<u>Process 3-4s is isentropic process,</u>

From Table A-2b, for T_3 = 1160K, $k \cong 1.336$.
Hence, $T_3 p_3^{(1-k)/k} = T_{4s} p_{4s}^{(1-k)/k}$
Hence, $T_{4s} = T_3\ [p_3/p_{4s}]^{(1-k)/k}$ = 1160K $[8/1]^{(1-1.336)/\ 1.336}$
Hence, $T_{4s} = 687.6$ K
Hence, $T_{avg} = (1160+687.6)/2$ K= 923.8 K
From Table A-2b, for T_{avg} = 923.8 K, k is obtained by interpolation.
$(k-1.344)/(1.336-1.344) = (923.8-900)/(1000-900)$
$k = 1.342$
Hence, $T_{4s} = T_3\ [p_3/p_{4s}]^{(1-k)/k}$ = 1160K $[8/1]^{(1-1.342)/\ 1.342}$
Hence, $T_{4s} = 682.75$ K
From Table A-17, for $T_{4s} = 682.75$ K, h_{4s} is evaluated by interpolation,
$(h_{4s} - 691.82)/(702.52 - 691.82) = (682.75 - 680)/(690 - 680)$, Hence,
$h_{4s} =$ 694.76 kJ/kg.

$$\eta_T = \frac{h_3 - h_4}{h_3 - h_{4s}}$$

Hence,

$$h_4 = h_3 - \eta_T (h_3 - h_{4s})$$

h_4 = 1230.92 kJ/kg - [0.82 *(1230.92 kJ/kg - 694.76 kJ/kg)]
Hence, h_4 = 791.27 kJ/kg
Hence, From Table A-17, for h_4 = 791.27 kJ/kg , T_4 is evaluated by interpolation,
$(T_4 - 760)/(780 - 760) = (791.27 - 778.18)/(800.03 - 778.18)$, Hence,
Hence, T_4 = 771.98 K

b) Evaluation of net work output
   $q_{in} = h_3 - h_2$ =1230.92 kJ/kg - 659.68 kJ/kg = 571.24 kJ/kg
   $q_{out} = h_4 - h_1$ =791.27 kJ/kg - 310.24 kJ/kg = 481.03 kJ/kg
   $w_{net,out} = q_{in} - q_{out}$ =571.24 kJ/kg - 481.03 kJ/kg = 90.21 kJ/kg

$$\eta_{th} = \frac{w_{net,out}}{q_{in}} = \frac{90.21\ \text{kJ/kg}}{571.24\ \text{kJ/kg}} = 0.15792 * 100\% = 15.79.$$