Fayoum University
Faculty of Engineering
Electrical Department

First Year
January 2009
Time:3 Hrs.

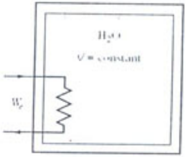
Mechanical Engineering (Engineering Thermodynamics)

The Examination consists of eight questions in two pages (85 Mark)

Solve the following questions:

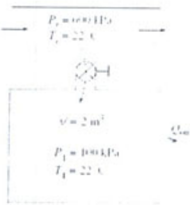
[1] A piston–cylinder device initially contains 0.07 m^3 of nitrogen gas at 130 kPa and 20°C. The nitrogen is now expanded polytropically to a state of 100 kPa and 100°C. Determine the boundary work done during this process.

[2] A well-insulated rigid tank contains 5 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source, and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a T-v diagram with respect to saturation lines.



[3] Steam enters the condenser of a steam power plant at 20 kPa and a quality of 95 percent with a mass flow rate of 20,000 kg/h. It is to be cooled by water from a nearby river by circulating the water through the tubes within the condenser. To prevent thermal pollution, the river water is not allowed to experience a temperature rise above 10°C. If the steam is to leave the condenser as saturated liquid at 20 kPa, determine the mass flow rate of the cooling water required.

[4] A 2-m3 rigid tank initially contains air at 100 kPa and 22°C. The tank is connected to a supply line through a valve. Air is flowing in the supply line at 600 kPa and 22°C. The valve is opened, and air is allowed to enter the tank until the pressure in the tank reaches the line pressure, at which point the valve is closed. A thermometer placed in the tank indicates that the air temperature at the final state is 77°C. Determine (*a*) the mass of air that has entered the tank and (*b*) the amount of heat transfer.



[5] A Carnot heat engine receives heat at 750 K and rejects the waste heat to the environment at 300 K. The entire work output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at -15°C at a rate of 400 kJ/min and rejects it to the same environment at 300 K. Determine (*a*) the rate of heat supplied to the heat engine and (*b*) the total rate of heat rejection to the environment.

[6] Steam at 6000 kPa and 500°C enters a steady-flow turbine. The steam expands in the turbine while doing work until the pressure is 1000 kPa. When the pressure is 1000 kPa, 10 percent of the steam is removed from the turbine for other uses. The remaining 90 percent of the steam continues to expand through the turbine while doing work and leaves the turbine at 10 kPa. The entire expansion process by the steam through the turbine is reversible and adiabatic. (*a*) Sketch the process on a *T-s* diagram with respect to the saturation lines. Be sure to label the data states and the lines of constant pressure. (*b*) If the turbine has an isentropic efficiency of 85 percent, what is the work done by the steam as it flows through the turbine per unit mass of steam flowing into the turbine, in kJ/kg?

[7] **(a)** Using both P-v and T-s diagrams illustrate Otto, Diesel, and Dual cycles. Then find an expression for the thermal efficiency of the Otto cycle.

(b) An air-standard Carnot cycle is executed in a closed system between the temperature limits of 350 and 1200 K. The pressures before and after the isothermal compression are 150 and 300 kPa, respectively. If the net work output per cycle is 0.5 kJ, determine (*a*) the maximum pressure in the cycle, (*b*) the heat transfer to air, and (*c*) the mass of air. Assume variable specific heats for air.

[8] A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle and (*b*) the net power output of the power plant.

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Solution of Mechanical Engineering (Engineering Thermodynamics)

[1] A piston–cylinder device initially contains 0.07 m^3 of nitrogen gas at 130 kPa and 20°C. The nitrogen is now expanded polytropically to a state of 100 kPa and 100°C. Determine the boundary work done during this process.

For Nitrogen $R = 0.2968$ KJ/kg K

$V_1 = 0.07\ m^3$ $\quad P_1 = 130$ KPa $\quad T_1 = 273.15 + 20 = 293.15$

$P_1 V_1 = m R T_1$

$\therefore m = 0.1046$ Kg

$P_2 = 100$ KPa $\quad T_2 = 273.15 + 100 = 373.15$ K

$P_2 V_2 = m R T_2$

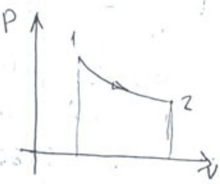
$\therefore V_2 = 0.115833\ m^3$

For polytropic process $P_1 V_1^n = P_2 V_2^n$

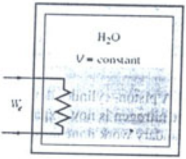
$$\therefore n = \frac{\ln(P_1/P_2)}{\ln(V_2/V_1)} = 0.521$$

$$W = \frac{P_2 V_2 - P_1 V_1}{1-n} = 5.18434 \text{ KJ}$$

$$= 49.5635 \text{ KJ/kg}$$



[2] A well-insulated rigid tank contains 5 kg of a saturated liquid–vapor mixture of water at 100 kPa. Initially, three-quarters of the mass is in the liquid phase. An electric resistor placed in the tank is connected to a 110-V source, and a current of 8 A flows through the resistor when the switch is turned on. Determine how long it will take to vaporize all the liquid in the tank. Also, show the process on a *T*-*v* diagram with respect to saturation lines.



$P_1 = 100$ KPa

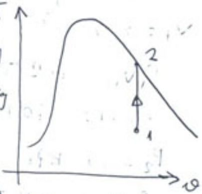
$x_1 = 0.25$

$v_f = 0.001043$ m³/kg $v_g = 1.694$ m³/kg

$u_f = 417.36$ KJ/kg $u_g = 2506.1$ KJ/kg

$v_1 = v_f + x_1 (v_g - v_f) = 0.42428$ m³/kg

$u_1 = u_f + x_1 (u_g - u_f) = 939.545$ KJ/kg



Rigid tank, $v_2 = v_1 = 0.42428$ m³/kg (sat. vapor)

$\therefore u_2 = 2556.752$ KJ/kg

By interpolation

v	u
0.4625	2553.6
0.414	2557.6

1st law of Thermodynamics

$E_{in} - E_{out} = \Delta E_{system}$

$W_{e,in} = m (u_2 - u_1)$

$V I \Delta t = m (u_2 - u_1)$

$(110)(8) \Delta t = 5 (2556.752 - 939.545) * 1000$

$\Delta t = 9188.5$ sec

$\cong 153.142$ min.

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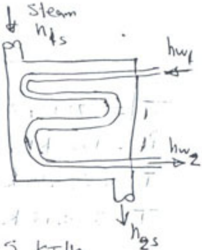
[3] Steam enters the condenser of a steam power plant at 20 kPa and a quality of 95 percent with a mass flow rate of 20,000 kg/h. It is to be cooled by water from a nearby river by circulating the water through the tubes within the condenser. To prevent thermal pollution, the river water is not allowed to experience a temperature rise above 10°C. If the steam is to leave the condenser as saturated liquid at 20 kPa, determine the mass flow rate of the cooling water required.



$\dot{m}_s = 20000$ Kg/h

$P_s = 20$ KPa

$x_1 = 0.95$

$x_2 = 0$

$h_f = 251.4$ KJ/kg

$h_g = 2609.7$ KJ/kg

$h_{1s} = h_f + x_1(h_g - h_f) = 2491.785$ KJ/kg

$h_{2s} = h_f = 251.4$ KJ/kg

For the water side

$\Delta h_w = h_{2w} - h_{1w} = c_{p_w} \Delta t$

$= 4.18 \times 10 = 41.8$ KJ/kg

OR let $P_w = 1$ bar $\quad t_1 = 15°C \quad t_2 = 25°$

$\therefore h_{w_1} = 62.99$ KJ/kg $\qquad h_{w_2} = 104.89$ KJ/kg

$\therefore \Delta h_w = 41.9$ KJ/kg

For heat exchanger:

$\dot{m}_s (h_{s_1} - h_{s_2}) = \dot{m}_w \Delta h_w$

$\therefore m_w = 297.765$ kg/sec.

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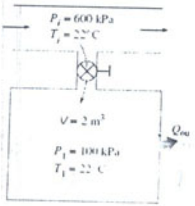
[4] A 2-m3 rigid tank initially contains air at 100 kPa and 22°C. The tank is connected to a supply line through a valve. Air is flowing in the supply line at 600 kPa and 22°C. The valve is opened, and air is allowed to enter the tank until the pressure in the tank reaches the line pressure, at which point the valve is closed. A thermometer placed in the tank indicates that the air temperature at the final state is 77°C. Determine (*a*) the mass of air that has entered the tank and (*b*) the amount of heat transfer.



$T_1 = 273.15 + 22 = 295.15$ K

$P_1 = 100$ KPa $\qquad V = 2\ m^3$

$T_i = 295.15$ K $\qquad P_i = 600$ KPa

$T_2 = 350.15$ K $\qquad P_2 = 600$ KPa

For Air $\quad R = 0.287$ KJ/kgK

$c_p = 1.0035$ KJ/kgK $\quad c_v = 0.7165$ KJ/kgK

$$m_1 = \frac{P_1 V}{R T_1} = 2.361 \text{ Kg}$$

$$m_2 = \frac{P_2 V}{R T_2} = 11.941 \text{ Kg}$$

$m_i = m_2 - m_1$ (mass balance)

$= 9.58$ kg

Energy Balance

$Q_{in} = -m_i h_i + m_2 u_2 - m_1 u_1$

$= -m_i c_p T_i + m_2 c_v T_2 - m_1 c_v T_1$

$= -340.94$ KJ

Note: -ve sign indicates that the assumed direction is wrong. Therefore reverse direction.

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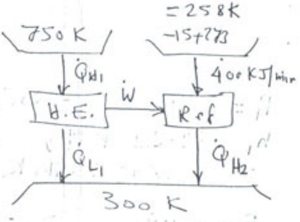
[5] A Carnot heat engine receives heat at 750 K and rejects the waste heat to the environment at 300 K. The entire work output of the heat engine is used to drive a Carnot refrigerator that removes heat from the cooled space at -15°C at a rate of 400 kJ/min and rejects it to the same environment at 300 K. Determine (*a*) the rate of heat supplied to the heat engine and (*b*) the total rate of heat rejection to the environment.



$$COP_R = \frac{258}{300-258} = 6.143$$

$$= \frac{\dot{Q}_{L_2}}{\dot{W}}$$

$$\therefore \dot{W} = 65.116 \text{ KJ/min}$$

$$\eta_E = 1 - \frac{300}{750} = 0.6$$

$$= \frac{\dot{W}}{\dot{Q}_{H_1}}$$

$$\therefore \dot{Q}_{H_1} = 108.527 \text{ KJ/min}$$

$$\dot{Q}_{L_1} = \dot{Q}_{H_1} - \dot{W} = 43.411 \text{ KJ/min}$$

$$\dot{Q}_{H_2} = 400 + \dot{W} = 465.116 \text{ KJ/min.}$$

$$\therefore \dot{Q}_{ambient} = \dot{Q}_{L_1} + \dot{Q}_{H_2} =$$

$$= 508.527 \text{ KJ/min}$$

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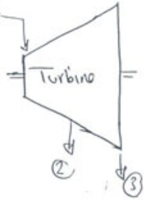
[6] Steam at 6000 kPa and 500°C enters a steady-flow turbine. The steam expands in the turbine while doing work until the pressure is 1000 kPa. When the pressure is 1000 kPa, 10 percent of the steam is removed from the turbine for other uses. The remaining 90 percent of the steam continues to expand through the turbine while doing work and leaves the turbine at 10 kPa. The entire expansion process by the steam through the turbine is reversible and adiabatic. (*a*) Sketch the process on a *T-s* diagram with respect to the saturation lines. Be sure to label the data states and the lines of constant pressure. (*b*) If the turbine has an isentropic efficiency of 85 percent, what is the work done by the steam as it flows through the turbine per unit mass of steam flowing into the turbine, in kJ/kg?



$P_1 = 6$ MPa $\quad t_1 = 500°C$

$h_1 = 3422.2$ KJ/kg

$s_1 = 6.8803$ KJ/kg K

$P_2 = 1$ MPa $\quad s_2 = s_1$

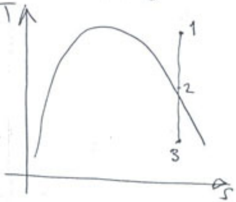
$s_g = 6.5865$

∴ state 2 is superheated

Using interpolation

h	s
2942.6	6.9247
2827.9	6.694

∴ $h_2 = 2920.53$ KJ/kg



$P_3 = 10$ kPa $\quad s_3 = s_1$

$s_f = 0.6493 \quad s_g = 8.1502$

$\therefore x_3 = \dfrac{s - s_f}{s_g - s_f} = 0.831$

$h_f = 191.83 \quad h_g = 2584.7$ KJ/kg

$h_3 = h_f + x_3(h_g - h_f) = 2179.59$ KJ/kg

$E_{in} = E_{out}$

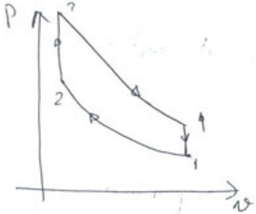
$\dot{m}_1 h_1 = W_{out} + m_2 h_2 + m_3 h_3$

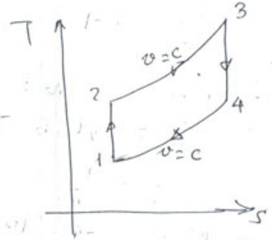
∴ $W_{out} = 1168.52$ KJ/kg

Actual work = ηW_{out} = 990.24 KJ/kg

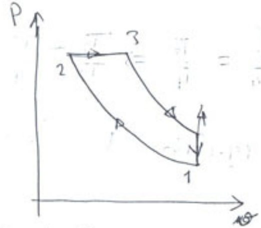
[7] **(a)** Using both P-v and T-s diagrams illustrate Otto, Diesel, and Dual cycles. Then find an expression for the thermal efficiency of the Otto cycle.

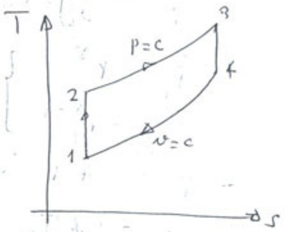
Otto Cycle



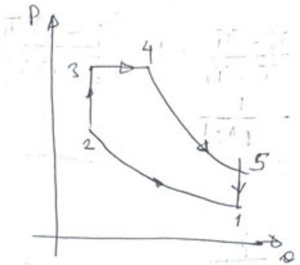


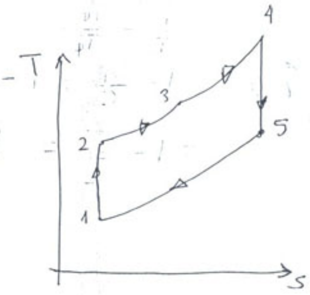
Diesel Cycle





Dual Cycle





Thermal Efficiency of Otto Cycle

- process 1-2 Isentropic compression

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^{\gamma} = r^{\gamma}$$

$$\frac{T_2}{T_1} = r^{\gamma - 1}$$

- process 2-3 heat addition at const volume.

$$Q_A = c_v (T_3 - T_2)$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

- process 3-4 isentropic expansion

$$\frac{P_4}{P_3} = \left(\frac{v_3}{v_4}\right)^{\gamma} = \left(\frac{v_2}{v_1}\right)^{\gamma} = \left(\frac{1}{r}\right)^{\gamma}$$

$$\left.\begin{aligned} \frac{P_3}{P_4} &= r^{\gamma} \\ \frac{T_3}{T_4} &= r^{\gamma-1} \end{aligned}\right\} \quad \frac{T_3}{T_4} = \frac{T_2}{T_1} \Rightarrow \frac{T_3}{T_2} = \frac{T_4}{T_1} \quad (1)$$

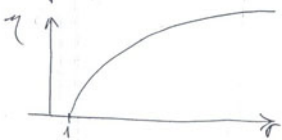
- process 4-1 heat rejection at const. volume

$$Q_R = c_v (T_4 - T_1)$$

$$\frac{P_1}{T_1} = \frac{P_4}{T_4}$$

$$\eta_{otto} = 1 - \frac{Q_R}{Q_A} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{\left(\frac{T_4}{T_1} - 1\right) T_1}{\left(\frac{T_3}{T_2} - 1\right) T_2}$$

$$= 1 - \frac{T_1}{T_2} = 1 - \frac{1}{r^{\gamma - 1}}$$



(b) An air-standard Carnot cycle is executed in a closed system between the temperature limits of 350 and 1200 K. The pressures before and after the isothermal compression are 150 and 300 kPa, respectively. If the net work output per cycle is 0.5 kJ, determine (*a*) the maximum pressure in the cycle, (*b*) the heat transfer to air, and (*c*) the mass of air. Assume variable specific heats for air.

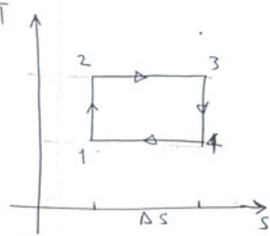
$T_1 = T_4 = 350\ K$

$T_2 = T_3 = 1200\ K$

$P_4 = 150\ KPa$

$P_1 = 300\ KPa$

$W = 0.5\ KJ$



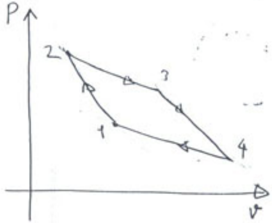
$\Delta S = c_p \ln \frac{T_1}{T_4} - R \ln \frac{P_1}{P_4}$

$S_1 - S_4 = -0.1999\ KJ/kgK$

$W = (S_3 - S_2)(T_H - T_L)$

$= 169.1\ KJ/Kg$

$\therefore\ m = \frac{0.5}{169.1} = 2.957 \times 10^{-3}\ kg$



$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{1200}{350}\right)^{\frac{1.4}{0.4}}$

$P_2 = 22388.11\ KPa$

$Q_H = \frac{W_{net}}{\eta}$, $\eta = 1 - \frac{T_L}{T_H} = 0.7083$

$Q_H = 0.70588\ KJ$

$= 238.72\ KJ/kg$

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[8] A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a *T-s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle and (*b*) the net power output of the power plant.

$P_2 = P_3 = 3\ MPa$

$P_1 = P_4 = 50\ kPa$

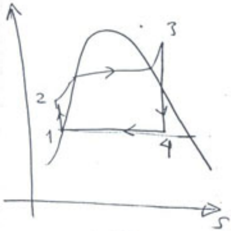
$t_3 = 300°C$

$\dot{m}_s = 35\ Kg/sec.$

$h_1 = 340.49$

$v_1 = 0.00103\ m^3/kg$

$h_3 = 2993.5$



$S_3 = S_4 = 6.5398$

$$x_4 = \frac{S_4 - S_f}{S_{g-f}} = \frac{6.539 - 1.091}{7.5939 - 1.091} = 0.8378$$

$$h_4 = h_f + x_4 (h_g - h_f)$$
$$= 340.49 + x_4 (2645.9 - 340.49) = 2271.92\ KJ/kg$$

$$Q_A = h_3 - h_2 \quad ; h_2 = h_1 + v_1 (P_2 - P_1)$$
$$= 2649.97\ KJ/kg \quad = 343.5265\ KJ/kg$$

$$Q_R = h_4 - h_1 = 1931.43\ KJ/kg$$

$$\eta = 1 - \frac{Q_R}{Q_A} = 0.271$$

$$W = Q_A - Q_R = 718.54\ KJ/kg$$

$$Power = \frac{\dot{m} W}{1000} = 25.149\ MW$$

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