Thermodynamics - Zak Olech - 9/10/2019

General Information

Conversion Factors

1 pascal = 1 $\frac{\text{newton}}{\text{meter}^2}$
1 kilopascal = 10^3 pa
1 megapascal = 10^6 pa
1 gigapascal = 10^9 pa

Process

1 - Assumptions
2 - Properties
3 - Analysis

Assumptions

- Typically Air is assumed to be an Ideal Gas
- Room Temperature = 300 k

Physically Meaningful Formulas

Mass Balance

$$m_{in} - m_{out} = \Delta m_{system} \tag{1}$$

Energy Balance

$$E_{in} - E_{out} = \Delta E_{system} \tag{2}$$

Entropy Balance

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \tag{3}$$

Exergy Balance

$$X_{in} - X_{out} = X_{destroyed} = \Delta X_{system} \tag{4}$$

Chapter 1 - Introduction and Basic Concepts

1-3 Importance of Dimensions and Units

$$T(K) = T(°C) + 273.15 \tag{5}$$

$$\Delta T(K) = \Delta T(°C) \tag{6}$$

$$T(R) = T(°F) + 459.67 \tag{7}$$

$$\Delta T(R) = \Delta T(°F) \tag{8}$$

1-9 Pressure

$$P_{gage} = P_{abs} - P_{atm} \tag{9}$$

$$P_{vac} = P_{atm} - P_{abs} \tag{10}$$

$$P = P_{atm} + \rho g h \tag{11}$$

$$P_{gage} = \rho g h \tag{12}$$

Chapter 2 - Energy, Energy Transfer, and General Energy Analysis

2-2 Forms of Energy

$$KE = m\frac{V^2}{2} \tag{13}$$

$$PE = mgz \tag{14}$$

$$E = U + KE + PE = U + m\frac{V^2}{2} + mgz \tag{15}$$

$$\dot{m} = \rho\dot{\vee} = \rho A_c V_{avg} \tag{16}$$

$$\dot{E} = \dot{m}e \tag{17}$$

$$\dot{E}_{mech} = \dot{m}e_{mech} = \dot{m}(\frac{P}{\rho} + \frac{V^2}{2} + gz) \tag{18}$$

2-3 Energy Transfer by Heat

$$Q = \int_{t_1}^{t_2} \dot{Q}dt \tag{19}$$

$$Q = h_2 - h_1 \tag{20}$$

2-6 First Law of Thermodynamics

$$\Delta E_{system} = E_{final} - E_{initial} = \Delta E = \Delta U + \Delta KE + \Delta PE \tag{21}$$

$$\Delta U = m(u_2 - u_1) \tag{22}$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2) \tag{23}$$

$$\Delta PE = mg(z_2 - z_1) \tag{24}$$

$$\begin{aligned} \dot{Q}_{net} - \dot{W}_{net} + \Sigma\dot{m}_{in}(h + \frac{\vec{V}^2}{2} + gz)_{in} \\ -\Sigma\dot{m}_{out}(h + \frac{\vec{V}^2}{2} + gz)_{out} = \Delta\dot{E}_{sys} \end{aligned} \tag{25}$$

Chapter 3 - Properties of Pure Substances

3-5 Property Tables

Quality

$$x = \frac{m_{vapor}}{m_{total}} \tag{26}$$

$$y = y_f + x * y_{fg} \tag{27}$$

$$y_{fg} = y_g - y_f \tag{28}$$

3-6 Ideal-Gas Equation of State

$$P\vee = RT \tag{29}$$

$$P\vee = RT \tag{30}$$

$$R = \frac{R_u}{m} \tag{31}$$

$$P\vee = ZRT \tag{32}$$

$$\frac{P_2V_2}{T_2}\frac{P_1V_1}{T_1} \tag{33}$$

$$V_1 = \frac{RT_1}{P_1} \tag{34}$$

Chapter 4 - Energy Analysis of a Closed System

4-1 Moving Boundary Work

General

$$W_b = \int_1^2 Pd\vee \tag{35}$$

Isobaric process (P1=P2)

$$W_b = P_0(\vee_2 - \vee_1) \tag{36}$$

Isothermal Process of an Ideal Gas

$$W_b = P_1 \vee_1 ln\frac{\vee_2}{\vee_1} = mRT_0 ln\frac{\vee_2}{\vee_1} \tag{37}$$

4-2 Energy Balance for Closed Systems

$$Q_{net} - W_{net} = \Delta U + \Delta KE + \Delta PE \tag{38}$$

$$W = W_{other} + W_b \tag{39}$$

$$\Delta U = m(u_2 - u_1) \tag{40}$$

$$\Delta KE = \frac{1}{2}m(V_2^2 - V_1^2) \tag{41}$$

$$\Delta PE = mg(z_2 - z_1) \tag{42}$$

Constant-Pressure Process

$$Q - W_{other} = \Delta H + \Delta KE + \Delta PE \tag{43}$$

4-3 Specific Heats

$$c_{constantvolume} = (\frac{\delta u}{\delta T}) \tag{44}$$

$$c_{constantpressure} = (\frac{\delta h}{\delta T}) \tag{45}$$

4-4 Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T)dT = c_{v,avg}(T_2 - T_1) \tag{46}$$

$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T)dT = c_{p,avg}(T_2 - T_1) \tag{47}$$

$$c_p = c_v + R \tag{48}$$

$$k = \frac{c_p}{c_v} \tag{49}$$

4-5 Internal Energy, Enthalpy, and Specific Heats of Solids and Liquids

Incompressible Substances

$$c_p = c_v = c \tag{50}$$

$$\Delta u = \int_1^2 c(T)dt = c_{avg}(T_2 - T_1) \tag{51}$$

$$\Delta h = \Delta u + \vee \Delta P \tag{52}$$

CV and CP Relationships

$$C_V = \frac{\delta u}{\delta T}_V = (\frac{du}{dT})_{I.G} \tag{53}$$

$$C_P = (\frac{\delta h}{\delta T})_P = (\frac{dh}{dT})_{I.G} \tag{54}$$

Chatper 5 - Mass and Energy analysis of Control Volumes

5-1 Conservation of Mass

$$m_{in} - m_{out} = m_{system} \tag{55}$$

$$\dot{m} = \rho V A \tag{56}$$

5-2 Flow Work and the energy of a Flowing Fluid

Total Energy of a Flowing Fluid

$$\theta = h + ke + pe = h + \frac{V^2}{2} + gz \tag{57}$$

Energy Transport by Mass

$$E_{mass} = m * \theta = m(h + \frac{V^2}{2} + gz) \tag{58}$$

5-3 Energy Analysis of Steady-Flow Systems

$$\Sigma_{in}\dot{m} = \Sigma_{out}\dot{m} \tag{59}$$

$$\dot{Q} - \dot{W} = \Sigma_{out}\dot{m}(h + \frac{V^2}{2} + gz) - \Sigma_{in}\dot{m}(h + \frac{V^2}{2} + gz) \tag{60}$$

5-5 Energy Analysis of Unsteady-Flow Processes

$$m_{in} - m_{out} = \Delta m_{system} \tag{61}$$

$$\begin{aligned} &(Q_{in} - Q_{out}) - (W_{out} - W_{in}) \\ &= \Sigma_{out} mh - \Sigma_{in} mh + (m_2 u_2 - m_1 u_1)_{system} \end{aligned} \tag{62}$$

Chapter 6 - The Second Law of Thermodynamics

Kelvin-Plank Statement, Clausius Statement

6-1 Intro to Second Law

6-2 Thermal Energy Reservoirs

6-3 Heat Engines

$$Thermalefficiency = \frac{Networkoutput}{Totalheatinput} \tag{63}$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \tag{64}$$

6-4 Refrigerators and Heat Pumps

Coefficient of Performance

$$\mathrm{COP} = \frac{\text{desired result}}{\text{required input}} \tag{65}$$

$$COP_{refrigerator} = \frac{Q_L}{Q_H - Q_L} = \frac{1}{Q_H/Q_L - 1} \tag{66}$$

$$COP_{HP} = \frac{desiredoutput}{requiredinput} = \frac{Q_h}{w_{net,in}} \tag{67}$$

$$COP_{HP} = \frac{Q_H}{Q_H - Q_L} = \frac{1}{1 - Q_L/Q_H} \tag{68}$$

$$COP_{HP} = COP_R + 1 \tag{69}$$

6-5 Perpetual-Motion Machines (PPM LN)

6-7 The Carnot Cycle

6-8 The Carnot Principles

6-9 The Thermodynamic Temperature Scale

$$(\frac{Q_H}{Q_L})_{rev} = \frac{T_H}{T_L} \tag{70}$$

6-10 The Carnot Heat Engine

$$\chi_{th,rev} = 1 - \frac{T_L}{T_H} \tag{71}$$

6-11 the Carnot Refrigerator and Heat Pump

$$COP_{R,rev} = \frac{1}{T_h/T_L - 1} \tag{72}$$

$$COP_{HP,rev} = \frac{1}{1 - T_L/T_H} \tag{73}$$

Chapter 7 - Entropy

7-1 Entropy

$$dS = (\frac{dQ}{T})_{int,rev} \tag{74}$$

Internally reversible, isothermal process

$$\Delta S = \frac{Q}{T_0} \tag{75}$$

7-2 The Increase of Entropy Principle

$$\S_{gen} \geq 0 \tag{76}$$

Entropy Generation

$$S_{heat} = \frac{q}{T} \tag{77}$$

$$S_{mass} = mS \tag{78}$$

7-3 Entropy Change

$$\Delta S = S_1 - S_2 \tag{79}$$

Pure Substance

PS - Any Process

$$\Delta S_2 - S_1 \tag{80}$$

PS - Isentropic Process

$$S_2 = S_1 \tag{81}$$

Incompressible Substance

IS - Any Process

$$S_2 - S_1 = c_{avg} ln \frac{T_2}{T_1} \tag{82}$$

IS - Isentropic Process

$$T_2 = T_1 \tag{83}$$

Ideal Gases

IG - Constant Specific Heats

IG - CSH - Any Process

$$\Delta S = C_{v,avg} ln(\frac{T_2}{T_1}) + Rln(\frac{V_2}{V_1}) \tag{84}$$

$$\Delta S = C_{p,avg} ln(\frac{T_2}{T_1}) - Rln(\frac{P_2}{P_1}) \tag{85}$$

IG - CSH - Isentropic Process

$$(\frac{T_2}{T_1})_{s=const} = (\frac{\vee_1}{\vee_2})^{k-1} \tag{86}$$

$$(\frac{T_2}{T_1})_{s=const} = (\frac{P_2}{P_1})^{(k-1)/k} \tag{87}$$

$$(\frac{P_2}{P_1})_{s=const} = (\frac{\vee_1}{\vee_2})^{k} \tag{88}$$

IG - Variable Specific Heats

IG - VSH - Any Process

$$\Delta S = S_2^{\circ} - S_1^{\circ} - Rln(\frac{P_2}{P_1}) \tag{89}$$

IG - VSH - Isentropic Process

$$S_2^{\circ} = S_1^{\circ} + Rln\frac{P_2}{P_1} \tag{90}$$

7-7 The T ds Relations

$$Tds = du + Pdv \tag{91}$$

$$Tds = dh - vdP \tag{92}$$

7-12 Isentropic Efficiencies of Steady-Flow Devices

$$\chi_T = \frac{Actualturbinework}{Isentropicturbinework} = \frac{w_a}{w_s} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \tag{93}$$

$$\chi_T = \frac{IsentropicCompressorWork}{ActualCompressorWork} = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \tag{94}$$

$$\chi_T = \frac{ActualKEatnozzleexit}{IsentropicKEAtNozzleExit} = \frac{V_{2a}^2}{V_{2s}^2} = \frac{h_1 - h_{2a}}{h_1 - h_{2s}} \tag{95}$$

7-13 Entropy Balance

$$S_{in} - S_{out} + S_{gen} = \Delta S_{system} \tag{96}$$

Steady-Flow

$$S_{gen} = \Sigma \dot{m}_e S_e - \Sigma \dot{m}_i - \Sigma \frac{\dot{Q}_K}{T_k} \tag{97}$$

Steady-Flow Work

$$w_{rev} = -\int_1^2 \vee dP - \Delta ke - \Delta pe \tag{98}$$

General

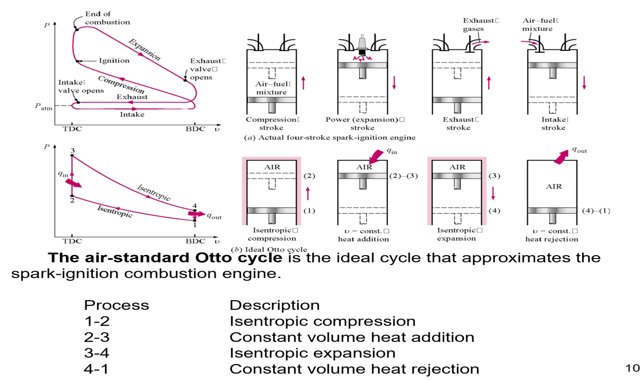
$$\text{x does not equal quality} — \int \frac{1}{x} dxln(\frac{x_2}{x_1}) \tag{99}$$

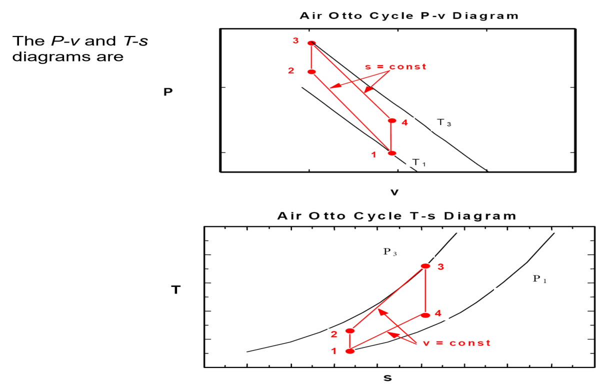
$$h = u + P * V \tag{100}$$

$$(\frac{T_2}{T_1}) = (\frac{v_1}{v_2})^{k-1} = (\frac{P_2}{P_1})^{\frac{k-1}{k}} \tag{101}$$

Chapter 9

Air-Standard Otto cycle





Compressoin Ratio

$$r = \frac{Vmax}{Vmin} = \frac{V_{BDC}}{V_{TDC}} \tag{102}$$

Mean Effective Pressure (MEP)

$$\text{MEP} = \frac{W_{net}}{V_{max} - V_{min}} \tag{103}$$

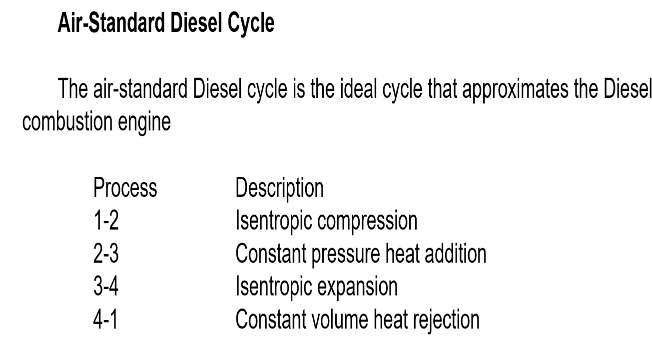
Thermal Efficiency

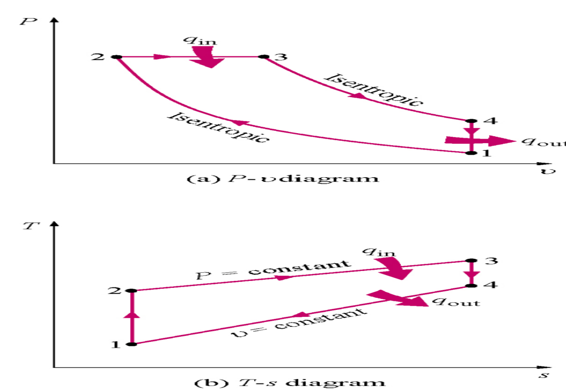
$$\eta_{th,Otto} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{mC_v(T_4 - T_1)}{mC_v(T_3 - T_2)} \tag{104}$$

Back Work Ratio

$$BWR = \frac{W_{comp}}{W_{exp}} = \frac{\delta u_{12}}{-\delta u_{34}} = \frac{C_v()T_2 - T_1}{C_v(T_3 - T_4)} = \frac{T_2 - T_1}{T_3 - T_4} \tag{105}$$

Air-Standard Diesel Cycle

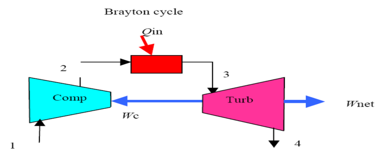




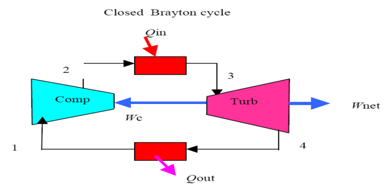
Thermal Efficiency

$$\begin{aligned}\eta_{th,Diesel} &= 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)} \\ &= 1 - \frac{1}{k}\frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)} = 1 - \frac{1}{r^{k-1}}\frac{r_c^l - 1}{k(r_c - 1)}\end{aligned} \tag{106}$$

Brayton Cycle

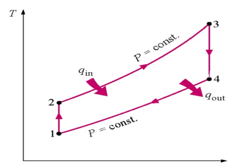


The closed cycle gas-turbine engine

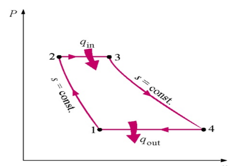


The *T-s* and *P-v* diagrams for the Closed Brayton Cycle

Process	Description
1-2	Isentropic compression (in a compressor)
2-3	Constant pressure heat addition
3-4	Isentropic expansion (in a turbine)
4-1	Constant pressure heat rejection



(a) *T-s* diagram



(b) *P-v* diagram

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Pressure Ratio

$$r_p = \frac{P_2}{P_1} \tag{107}$$

$$\eta_{th,Brayton} = \frac{W_net}{q_{in}} = 1 - \frac{1}{r_p^{(k-1)/k}} \tag{108}$$

Back Work Ratio

$$BWR = \frac{w_in}{w_out} = \frac{w_comp}{w_turb} \tag{109}$$

General Brayton Cycle Equations

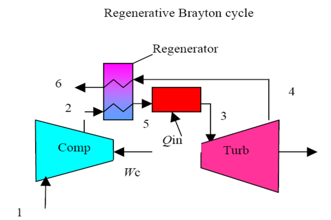
$$W_{\text{net, out}} = w_{\text{a,t,out}} - w_{\text{a,c,in}} = \nu_t - w_s T_{out} - \frac{w_{\text{s,c,in}}}{\nu_c} \tag{110}$$

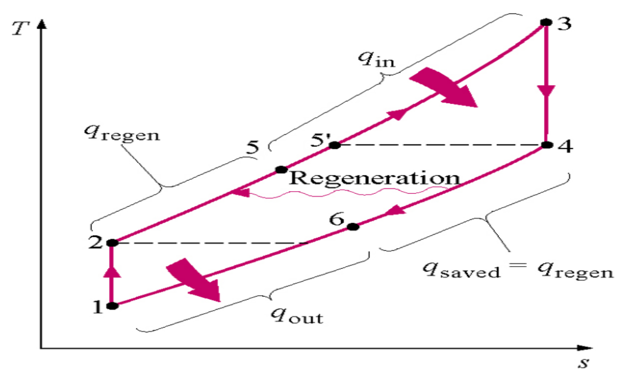
$$w_{\text{s, net, out}} = w_{\text{s, t, out}} - w_{\text{s, c, in}} \tag{111}$$

Regenerative Brayton Cycle

Regenerative Brayton Cycle

For the Brayton cycle, the turbine exhaust temperature is greater than the compressor exit temperature. Therefore, a heat exchanger can be placed between the hot gases leaving the turbine and the cooler gases leaving the compressor. This heat exchanger is called a regenerator or recuperator. The sketch of the regenerative Brayton cycle is shown below.





$$\sigma_{regen} = \frac{q_{regen,act}}{q_{regen,max}} = \frac{h_5 - h_2}{h_4 - h_2} \tag{112}$$

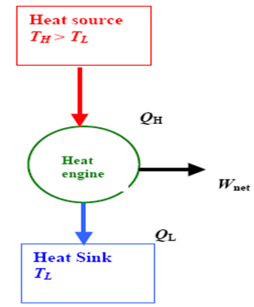
Thermal Efficiency

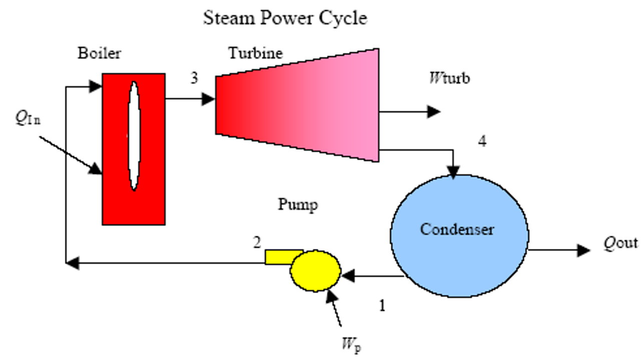
$$\eta_{th,regen} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{h_6 - h_1}{h_3 - h_5} \tag{113}$$

Chapter 10

Rainkine Cycle

Carnot Vapor Cycle





Ideal Rankine Cycle Processes

Process	Description
1-2	Isentropic compression in pump
2-3	Constant pressure heat addition in boiler
3-4	Isentropic expansion in turbine
4-1	Constant pressure heat rejection in condenser

MSC

Isentropic Compression

$$v_{r2} = \frac{V_2}{v_1} v_{r1} = \frac{1}{r} v_{r1} \tag{114}$$

Isentropic Expansion

$$v_{r2} = \frac{V_2}{v_1} v_{r1} \tag{115}$$

General

$$\dot{m}_s = \frac{\dot{w}_{\text{net,out}}}{\dot{w}_{\text{s,net,out}}} = \frac{\text{kg}}{\text{s}} \tag{116}$$

$$\dot{m} = \frac{\dot{q}_{\text{in}}}{\text{Heat Value}} \tag{117}$$

11 - Refrigeration Cycles

$$\text{COP}_R = \frac{\text{Desired output}}{\text{Required output}} = \frac{\text{Cooling Effect}}{\text{Work input}} = \frac{Q_l}{W_{\text{net, in}}} \tag{118}$$

$$\text{COP}_H P = \frac{\text{Desired output}}{\text{Required input}} = \frac{\text{Heating Effect}}{\text{Work input}} = \frac{Q_H}{W_{\text{net, in}}} \tag{119}$$

$$\text{COP}_{\text{R, Carnot}} = \frac{1}{T_h/T_L - 1} \tag{120}$$

$$\text{COP}_{\text{HP, Carnot}} = \frac{1}{1 - T_L/T_H} \tag{121}$$

$$\text{COP}_R = \frac{Q_l}{W_{\text{net, in}}} = \frac{q_L}{w_{\text{comp,in}}} - w_{\text{turb,out}} \tag{122}$$

$$\text{COP}_{\text{absorption}} = \frac{\text{Desired output}}{Requiredinput} = \frac{Q_L}{q_{\text{gen}} + W_{\text{pump}}} \approx \frac{Q_L}{Q_{\text{gen}}} \tag{123}$$

$$\text{COP}_{\text{rev,absorption}} = \nu_{\text{th,rev}} \text{COP}_{\text{R,rev}} = (1 - \frac{T_0}{T_s})(\frac{T_L}{T_0 - T_L}) \tag{124}$$