Thermodynamics - Zak Olech - October 14, 2019

Nomenclature

a	Acceleration, m/s^2
a	Specific Helmholtz function, $u - Ts$, kJ/kg
A	Area, m^2
A	Helmholtz function, $U - TS$, kJ
AF	Air–fuel ratio
c	Speed of sound, m/s
c	Specific heat, kJ/kg·K
c_p	Constant pressure specific heat, kJ/kg·K
c_v	Constant volume specific heat, kJ/kg·K
COP	Coefficient of performance
COP_{HP}	Coefficient of performance of a heat pump
COP_R	Coefficient of performance of a refrigerator
d, D	Diameter, m
e	Specific total energy, kJ/kg
E	Total energy, kJ
EER	Energy efficiency rating
F	Force, N
FA	Fuel–air ratio
g	Gravitational acceleration, m/s^2
g	Specific Gibbs function, $h - Ts$, kJ/kg
G	Total Gibbs function, $H - TS$, kJ
h	Convection heat transfer coefficient, W/m^2·K
h	Specific enthalpy, $u + Pv$, kJ/kg
H	Total enthalpy, $U + PV$, kJ
$\bar{h}_C$	Enthalpy of combustion, kJ/kmol fuel
$\bar{h}_f$	Enthalpy of formation, kJ/kmol
$\bar{h}_R$	Enthalpy of reaction, kJ/kmol
HHV	Higher heating value, kJ/kg fuel
i	Specific irreversibility, kJ/kg
I	Electric current, A
I	Total irreversibility, kJ
k	Specific heat ratio, c_p/c_v
k_s	Spring constant
k_t	Thermal conductivity
K_p	Equilibrium constant
ke	Specific kinetic energy, $V^2/2$, kJ/kg
KE	Total kinetic energy, $mV^2/2$, kJ
LHV	Lower heating value, kJ/kg fuel
m	Mass, kg
$\dot{m}$	Mass flow rate, kg/s
M	Molar mass, kg/kmol
Ma	Mach number
MEP	Mean effective pressure, kPa
mf	Mass fraction
n	Polytropic exponent
N	Number of moles, kmol
P	Pressure, kPa
P_{cr}	Critical pressure, kPa
P_i	Partial pressure, kPa
P_m	Mixture pressure, kPa
P_r	Relative pressure
P_R	Reduced pressure
P_v	Vapor pressure, kPa
P_0	Surroundings pressure, kPa
pe	Specific potential energy, gz, kJ/kg
PE	Total potential energy, mgz, kJ
q	Heat transfer per unit mass, kJ/kg
Q	Total heat transfer, kJ
$\dot{Q}$	Heat transfer rate, kW
Q_H	Heat transfer with high-temperature body, kJ
Q_L	Heat transfer with low-temperature body, kJ
r	Compression ratio
R	Gas constant, kJ/kg·K
r_c	Cutoff ratio
r_p	Pressure ratio
R_u	Universal gas constant, kJ/kmol·K
s	Specific entropy, kJ/kg·K
S	Total entropy, kJ/K
s_{gen}	Specific entropy generation, kJ/kg·K
S_{gen}	Total entropy generation, kJ/K
SG	Specific gravity or relative density
t	Time, s
T	Temperature, °C or K
T	Torque, N·m
T_{cr}	Critical temperature, K
T_{db}	Dry-bulb temperature, °C
T_{dp}	Dew-point temperature, °C
T_f	Bulk fluid temperature, °C
T_H	Temperature of high-temperature body, K
T_L	Temperature of low-temperature body, K
T_R	Reduced temperature
T_{wb}	Wet-bulb temperature, °C
T_0	Surroundings temperature, °C or K
u	Specific internal energy, kJ/kg
U	Total internal energy, kJ

v	Specific volume, m^3/kg
v_{cr}	Critical specific volume, m^3/kg
v_r	Relative specific volume
v_R	Pseudoreduced specific volume
V	Total volume, m^3
$\dot{V}$	Volume flow rate, m^3/s
$\mathbf{V}$	Voltage, V
V	Velocity, m/s
V_{avg}	Average velocity
w	Work per unit mass, kJ/kg
W	Total work, kJ
$\dot{W}$	Power, kW
W_{in}	Work input, kJ
W_{out}	Work output, kJ
W_{rev}	Reversible work, kJ
x	Quality
x	Specific exergy, kJ/kg
X	Total exergy, kJ
x_{dest}	Specific exergy destruction, kJ/kg
X_{dest}	Total exergy destruction, kJ
$\dot{X}_{dest}$	Rate of total exergy destruction, kW
y	Mole fraction
z	Elevation, m
Z	Compressibility factor
Z_h	Enthalpy departure factor
Z_s	Entropy departure factor

Greek Letters

α	Absorptivity
α	Isothermal compressibility, 1/kPa
β	Volume expansivity, 1/K
Δ	Finite change in quantity
ε	Emissivity
ϵ	Effectiveness
η_{th}	Thermal efficiency
η_{II}	Second-law efficiency
θ	Total energy of a flowing fluid, kJ/kg
μ_{JT}	Joule-Thomson coefficient, K/kPa
μ	Chemical potential, kJ/kg
ν	Stoichiometric coefficient
ρ	Density, kg/m^3
σ	Stefan–Boltzmann constant
σ_n	Normal stress, N/m^2
σ_s	Surface tension, N/m
ϕ	Relative humidity
ϕ	Specific closed system exergy, kJ/kg
Φ	Total closed system exergy, kJ
ψ	Stream exergy, kJ/kg
γ_s	Specific weight, N/m^3
ω	Specific or absolute humidity, kg H_2O/kg dry air

Subscripts

a	Air
abs	Absolute
act	Actual
atm	Atmospheric
avg	Average
c	Combustion; cross-section
cr	Critical point
CV	Control volume
e	Exit conditions
f	Saturated liquid
fg	Difference in property between saturated liquid and saturated vapor
g	Saturated vapor
gen	Generation
H	High temperature (as in T_H and Q_H)
i	Inlet conditions
i	ith component
L	Low temperature (as in T_L and Q_L)
m	Mixture
r	Relative
R	Reduced
rev	Reversible
s	Isentropic
sat	Saturated
surr	Surroundings
sys	System
v	Water vapor
0	Dead state
1	Initial or inlet state
2	Final or exit state

Superscripts

$\dot{}$ (over dot)	Quantity per unit time
$\bar{}$ (over bar)	Quantity per unit mole
° (circle)	Standard reference state
* (asterisk)	Quantity at 1 atm pressure

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

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

Energy Balance

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

Entropy Balance

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

Exergy Balance

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\dot{m} = \rho VA \tag{56}$$

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

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

$$\begin{aligned}(Q_{in} - Q_{out}) - (W_{out} - W_{in})\\ = \Sigma_{out}mh - \Sigma_{in}mh + (m_2u_2 - m_1u_1)_{system}\end{aligned} \tag{62}$$

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

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

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

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

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

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

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

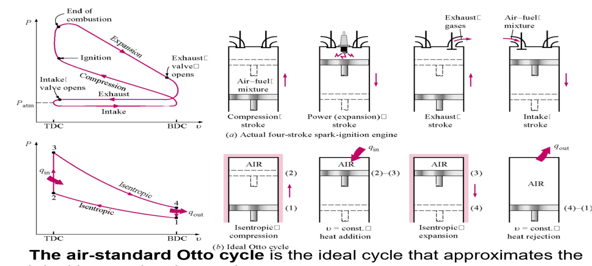
$$\text{x does not equal quality} - \int \frac{1}{x} dx ln(\frac{x_2}{x_1}) \tag{99}$$

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

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

Chapter 9

Air-Standard Otto cycle

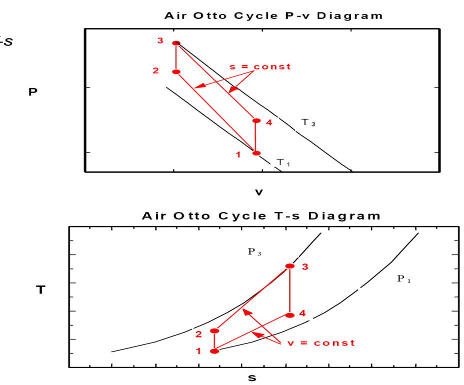


The air-standard Otto cycle is the ideal cycle that approximates the spark-ignition combustion engine.

Process	Description
1-2	Isentropic compression
2-3	Constant volume heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection

10

The P-v and T-s diagrams are



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

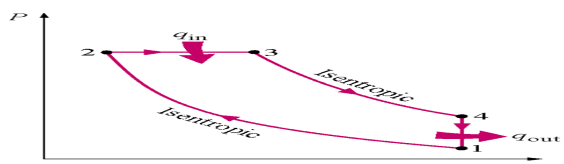
$$BWR = \frac{W_{comp}}{W_{exp}} = \frac{\delta u_{12}}{-\delta u_{34}} = \frac{C_v()T_2 - T_1}{C_v(T_3 - T_4)} = \frac{T_2 - T_1}{T_3 - T_4} \tag{105}$$

Air-Standard Diesel Cycle

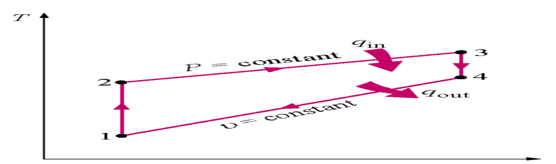
Air-Standard Diesel Cycle

The air-standard Diesel cycle is the ideal cycle that approximates the Diesel combustion engine

Process	Description
1-2	Isentropic compression
2-3	Constant pressure heat addition
3-4	Isentropic expansion
4-1	Constant volume heat rejection



(a) P-v diagram

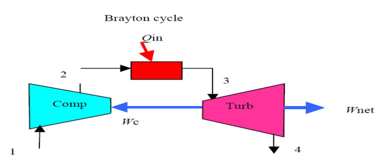


(b) T-s diagram

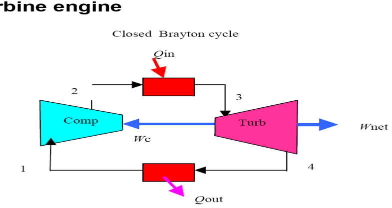
Thermal Efficiency

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

Brayton Cycle

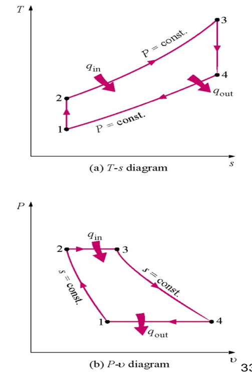


The closed cycle gas-turbine engine



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



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

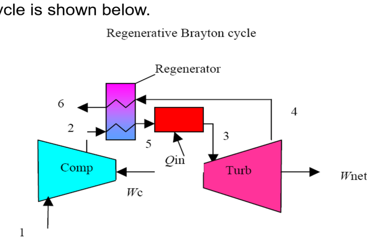
$$W_{\text{net, out}} = w_{\text{a,t,out}} - w_{\text{a,c,in}} = \nu_t - w_s T_{out} - \frac{w_{\text{s,c,in}}}{\nu_c} \tag{110}$$

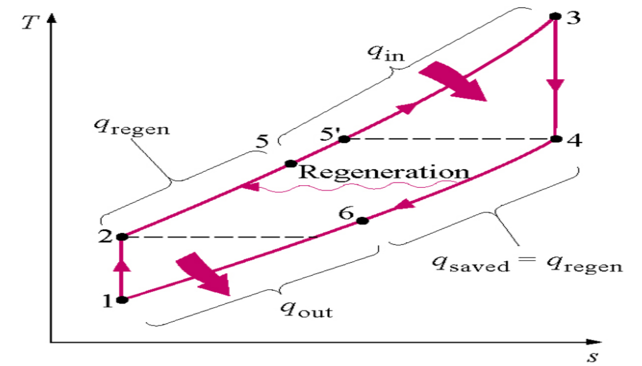
$$w_{\text{s, net, out}} = w_{\text{s, t, out}} - w_{\text{s, c, in}} \tag{111}$$

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.





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

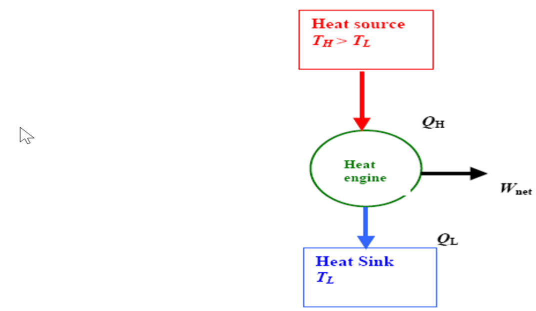
Thermal Efficiency

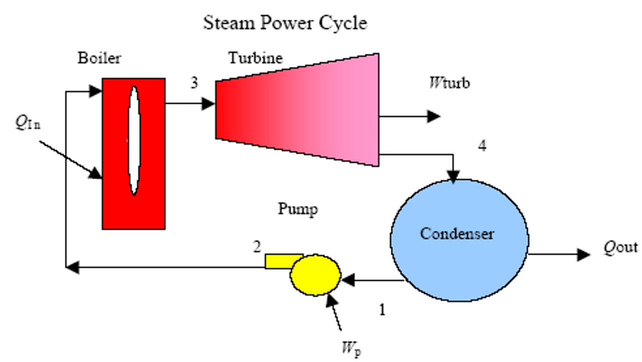
$$\eta_{th,regen} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{h_6 - h_1}{h_3 - h_5} \tag{113}$$

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

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

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

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

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

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

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

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

Chapter 14 - Gas-Vapor Mixtures and Air-Conditioning

1 - Dry and Atomspheric Air

2 - Specific and Relative Humidity of Air

Absolute or Specific Humidity (Humidity Ratio)

Dry Air $\rightarrow \omega$=0

$$\omega = \frac{m_v}{m_a} = \text{kg water vapor/kg dry air}$$
$$= \frac{P_v V M_v/(R_u T)}{P_a V M_a/(R_u T)} = \frac{P_v M_v}{P_a M_a}$$
$$= \phi \frac{P_v}{100 - P_v} \tag{125}$$

Relative Humidity

$$\phi = \frac{m_v}{m_g} = \frac{P_v \vee / R_v T}{P_g \vee / R_V T} = \frac{P_v}{P_g} \tag{126}$$

Volume of mixture per mass of dry air, V

$$v = \frac{V}{m_a} = \frac{m_m R_m T_m / P_m}{m_a} = v_a = \frac{R_a T_m}{P_a} \tag{127}$$

Mass of Mixture

$$m = m_a + m_v = m_a(1 + \frac{m_v}{m_a}) = m_a(1 + \omega) \tag{128}$$

Mass flow rate of dry air

$$\dot{m}_a = \frac{\dot{V}}{v} = \frac{kg_a}{s} \tag{129}$$

Enthalpy of mixture per mass dry air, h

$$h = \frac{H_m}{m_a} = \frac{H_a + H_v}{m_a} = \frac{m_a h_a + m_v h_v}{m_a} = h_a + \omega h_v \tag{130}$$

3 - Dew-Point Temperature

4 - Adiabatic Saturation and Wet-Bulb Temperatures

5 - The Psychrometric Chart

The enthalpy read from the psychrometric chart is the total enthalpy of the air-vapor mixture per unit mass of DRY air $h = H/m_a = h_a + \omega h_v$.

Chapter 15 - Chemical Reactions

Balancing Equations

Mole numbers are not conserved, but we have conserved the mass on a total basis as well as a specie basis.

1 - Fuels and Combustion

Air-Fuel Ratio

$$\text{AF} = \frac{m_{\text{air}}}{m_{\text{fuel}}} = \frac{\text{kmol air}}{\text{kmol fuel}} \tag{131}$$

2 - Theoretical and Actual Combustion Processes

3 - Enthalpy of Formation and Enthalpy of Combustion

General Notes:

- Reference starting slides 22 of summary ppt.
- Think about conservation of energy for a steady-flow combustion process.
- Enthalpy of elements or their stable compound is defined to be ZERO at 25°C (298 K) and 1 atm (.1 MPa)
- Enthalpy of formation tabulated in Table A-26
- Enthalpy of formation of elements found naturally as diatomic elements, is defined to be zero.

$$Q_{\text{net}} = \bar{H}^\circ{}_f \tag{132}$$

$$\bar{h} = \bar{h}^\circ{}_f + (\bar{h}_T - \bar{h}^\circ) \tag{133}$$

4 - First-Law Analysis of Reacting Systems

Steady-Flow Systems

Closed Systems

5 - Adiabatic Flame Temperature

6 - Entropy Change of Reacting Systems

7 - Second-Law Analysis of Reacting Systems