

### 1.03 UNITS

19 JULY / 2021

NOTES FOR THIS MODULE WERE MADE AFTER  
COURSE COMPLETION

#### PRESSURE

$$1 \text{ Pa} = 1 \text{ N/m}^2 = 1 \text{ kg m/s}^2 = 1 \times 10^{-5} \text{ bar}$$

$$1 \text{ bar} = 10^5 \text{ Pa} = 0.98692 \text{ atm}$$

$$1 \text{ lb/in}^2 (\text{psi}) = 144 \text{ lb/in}^2 = 0.068046 \text{ atm}$$

$$1 \text{ atm} = 101.325 \text{ kPa} = 1.0133 \text{ bar}$$

#### ENERGY DENSITY [ENERGY per Unit Mass]

or per Unit Mole or per Unit Area

#### (mass)

$$1 \text{ kJ/kg} = 0.42992 \text{ Btu/lbm} = 0.23885 \text{ kcal/kg}$$

#### (mole)

$$1 \text{ kJ/kmol}, 1 \text{ Btu/mol}$$

#### (Rate per Area)

$$1 \text{ W/m}^2 = 0.317 \text{ Btu/(hr ft}^2) = 0.85986 \text{ kcal/(hr m}^2)$$

### 1.04 DEFINING OPEN AND CLOSED SYSTEMS:

"THERMODYNAMICS is the study of energy and the interaction of energy with matter".

Transforming Energy  $\rightarrow$  From Potential to Kinetic energy.

Obtaining Energy  $\rightarrow$  Convert PE+KE to mechanical work  
to electrical work.

Generate & Apply Energy  $\rightarrow$  Charging a battery.

"HEAT TRANSFER is how energy is transferred when there is a temperature difference"

"FLUID MECHANICS is the motion of fluids (which include gases and liquids) and the transformation of energy between mechanical and thermal forms."

**SYSTEM** - the object(s) under consideration.

CLOSED SYSTEM  $\rightarrow$  CONTROL MASS

- ① Mass cannot cross System boundary
- ② There is a fixed quantity of matter in the System.

### 1.05 THERMODYNAMIC PROPERTIES:

**PROPERTIES** - describe the characteristics of the System.

**Thermodynamic Properties** - describe the thermal properties of the System.

**EXTENSIVE Properties** - depend on the extent (or amount) of material in the System; these properties are additive - e.g. mass

**INTENSIVE Properties** - do NOT depend on the extent (or amount) of material in the System. these properties are NOT additive, like temperature.

DENSITY = mass per unit volume =  $\rho = m/v$

SPECIFIC VOLUME = Volume per unit mass =  $v = 1/\rho$

PRESSURE (absolute and relative)

$$\text{TEMPERATURE } T[^\circ\text{C}] \quad T[\text{K}] \quad T[\text{K}] = T[^\circ\text{C}] + 273.15$$

$$T[^\circ\text{F}] = 1.8T[^\circ\text{C}] + 32$$

#### ENERGY

$$1 \text{ J} = 1 \text{ Nm} = 1 \text{ kg m}^2/\text{s}^2 = 1 \text{ Ws}$$

#### ENERGY RATE OR POWER

$$1 \text{ W} = 1 \text{ J/s}$$

$$1 \text{ W} = 3.4122 \text{ Btu/h}$$

#### BRICK1

#### STATE1

$m_A$	$T_A$
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$$T_B > T_A$$

$$m_A = m_B$$

$m_B$	$T_B$
-------	-------

#### STATE 2

$m_A$	$m_B$
-------	-------

At equilibrium  
 $T_A = T_B$

#### OPEN SYSTEM $\rightarrow$ CONTROL VOLUME

- ① Mass can cross the System boundary
- ② The amount of matter within the control volume can change.

**STATE** - the condition of the System as described by the System thermodynamic properties.

**STEADY STATE** means the System properties are not changing as a function of time.

**EQUILIBRIUM** - when the System is unchanging in terms of thermal, mechanical, phase and chemical characteristics.

**PROCESS** - a path between two States.

## 1.06 CONSERVATION OF ENERGY FOR CLOSED SYSTEMS:

Energy in Closed Systems :

KINETIC ENERGY = K.E.

$m = \text{constant [kg]}$

$$\text{K.E.} = \frac{1}{2} m V^2$$

$V = \text{velocity [m/s]}$

POTENTIAL ENERGY = P.E.

$$\text{P.E.} = mgZ$$

$Z = \text{height}$

$g = \text{gravitational constant}$ .

WORK - energy transfer across the System boundary

Work transfer is not a System property

" " depends on the process path

There are many types or forms of work transfer  
[Expansion and compression work, Shaft work]

$$\int_1^2 SW = \int_{V_1}^{V_2} PdV$$

Force on the piston

$$W = \int_1^2 PdV \quad \text{Need to know how } P \text{ varies as a function of } V$$



$m = \text{constant [CLOSED SYSTEM]}$

$V = \text{Volume [m}^3\text{]}$

$v = \text{Specific volume [m}^3/\text{kg}\text{]}$

$m = \text{mass [kg]}$

$$\frac{V}{m} = v$$

$dV$  positive  $\rightarrow$  expansion process  
 $\rightarrow SW > 0$

$dV$  negative  $\rightarrow$  compression process  
 $\rightarrow SW < 0$

WORK PRODUCED BY AN ENGINE

$$W = N \cdot P_{avg} (V_{max} - V_{min})$$

$N = \text{No. of cylinders.}$

Per Unit Time

$$\omega = Tw \quad T = \text{torque.}$$

## 2.01 WORK TRANSFER MECHANISMS

SHAFT WORK

$$W = \int F_t ds$$



$F_t = \text{tangential force}$

$V = R\omega = \text{Tangential velocity}$

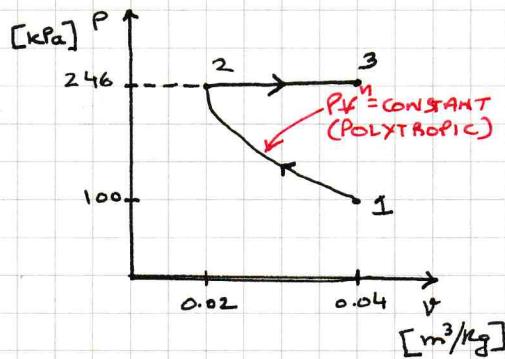
$\omega = \text{angular velocity}$

$R = \text{radius}$

SIGN CONVENTION FOR ENERGY TRANSFER:

- ① WORK out of a System  $\rightarrow$  Positive  
 $\hookrightarrow W > 0 \Rightarrow$  work done by the System
- ② WORK into a System  $\rightarrow$  Negative  
 $\hookrightarrow W < 0 \Rightarrow$  work is done on the System

## 2.02 EXAMPLE : The Work Required to Compress Air



$$2W_3 = \int_2^3 P_2 dV = P_2 (V_3 - V_2)$$

$$= 4.92 \text{ kJ/kg}$$

$> 0$  Expansion work out is positive

$$W_{TOT} = W_2 + 2W_3 = 1.84 \text{ kJ/kg NET WORK OUT}$$

$$P \cdot V^n = x$$

$$P_1 V_1^n = P_2 V_2^n$$

CLOSED SYSTEM,  $m = \text{constant}$

$$P_1 \frac{V_1^n}{m_1^n} = P_2 \frac{V_2^n}{m_2^n}$$

$$P_1 V_1^n = P_2 V_2^n$$

$$P_1 = 100 \text{ kPa}$$

$$V_1 = 0.04 \text{ m}^3/\text{kg}$$

$$V_2 = 0.02 \text{ m}^3/\text{kg} \quad n = 1.3$$

$$P_2 = ?$$

$$P_2 = \frac{m_2}{m_1} \frac{V_1^n}{V_2^n} P_1$$

$$P_2 = 246.299 \text{ kPa}$$

DETERMINE SPECIFIC WORK:

$$W = \int_1^2 \frac{PdV}{m} + \int_2^3 \frac{PdV}{m}$$

$\because P_1 V_1^n = \text{constant}$

$$P = \frac{V_1^n}{m}$$

$$W_2 = \int_1^2 \frac{\text{constant}}{V^n} dV$$

$$= -\frac{\text{const}}{0.3} \left[ \frac{1}{V_2^{0.3}} - \frac{1}{V_1^{0.3}} \right]$$

$$= -\frac{P_1 V_1^{1.3}}{0.3} \left[ \frac{1}{V_2^{0.3}} - \frac{1}{V_1^{0.3}} \right]$$

$$W_2 = -3.08 \text{ kJ/kg}$$

$< 0$  WORK IN is negative

## 2.03 THE FIRST LAW OF THERMODYNAMICS FOR A CLOSED SYSTEM.

1<sup>st</sup> LAW - relates changes in energy states to work and heat transfer  
DEFINES the conservation of Energy.

CONSERVATION OF MASS (COM)  $\rightarrow$  States that mass can never be destroyed  
CONSERVATION OF ENERGY (COE)  $\rightarrow$  States that energy " " " "  
(All you can do is change its form)

$$E_2 - E_1 = Q - W$$

An ADIABATIC PROCESS  $\rightarrow Q = 0$

$E \rightarrow$  Total Energy of the System.

$$E = KE + PE + U$$

$\leftarrow$  UPPER CASE  $\rightarrow$  Extensive Property

$U =$  Internal Energy of the System

$u =$  internal energy per mass

$\leftarrow$  INTENSIVE PROPERTY

HEAT TRANSFER "Q"

$\hookrightarrow$  is the energy transfer due to heat transfer

$\hookrightarrow$  is NOT a property.

$\hookrightarrow$  depends on the process path

$Q > 0 \rightarrow$  heat transfer into the System [+ve]

$Q < 0 \rightarrow$  heat transfer out of the System [-ve]

$\Rightarrow$  Sign convention for heat transfer is (typically) opposite of work!

## 2.04 HEAT TRANSFER

3 Types  $\rightarrow$  Conduction, Convection, Radiation.

$$Q_{\text{cond}} \propto \Delta T = T_s - T_{\text{amb}}$$

$$Q_{\text{conv}} \propto \Delta T = T_s - T_{\text{amb}}$$

$$Q_{\text{rad}} \propto (T_s^4 - T_{\text{amb}}^4)$$

COE

In - Out = Change

net heat transfer in - net work transfer out =

Change in System energy (for some time interval)

Can also write COE on a rate basis:

$$\dot{E}_2 - \dot{E}_1 = \dot{Q}_2 - \dot{W}_2$$

$$\frac{dE}{dt} = \dot{Q} - \dot{W}$$

$\leftarrow$  Overdot means rate basis

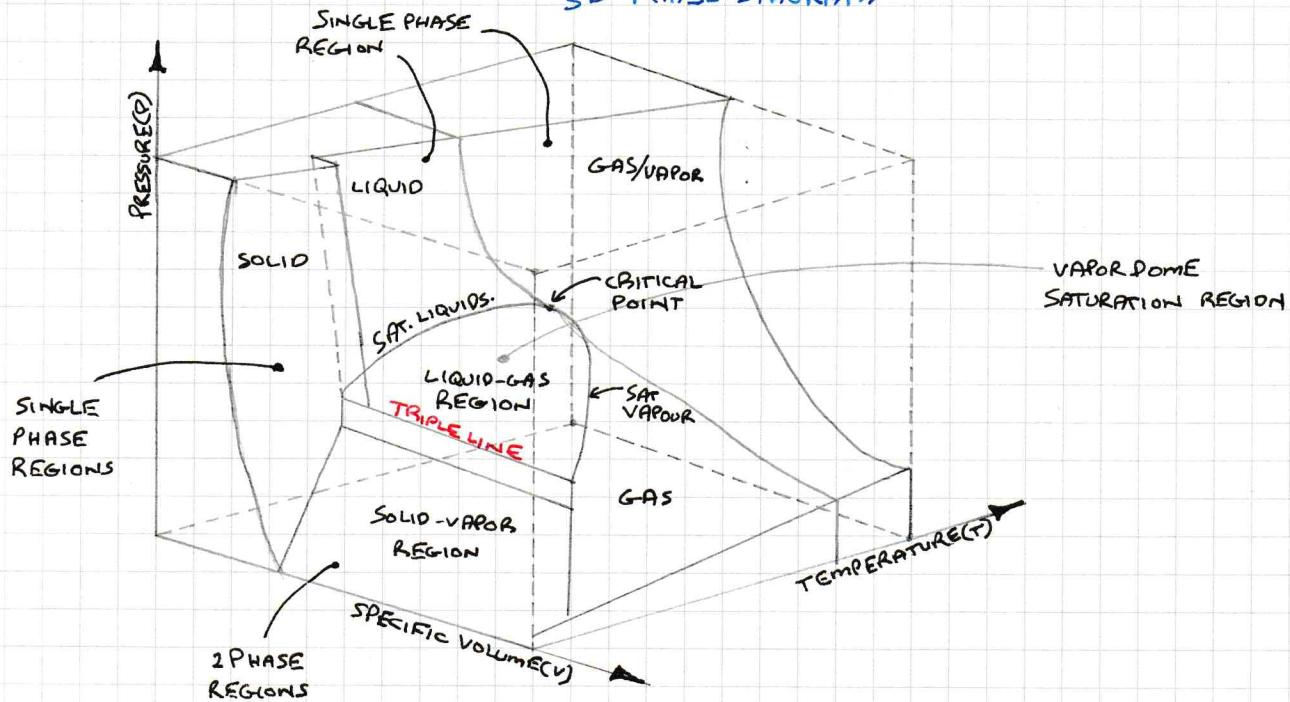
## 2.05 PHASE DIAGRAMS

26/JULY/2021

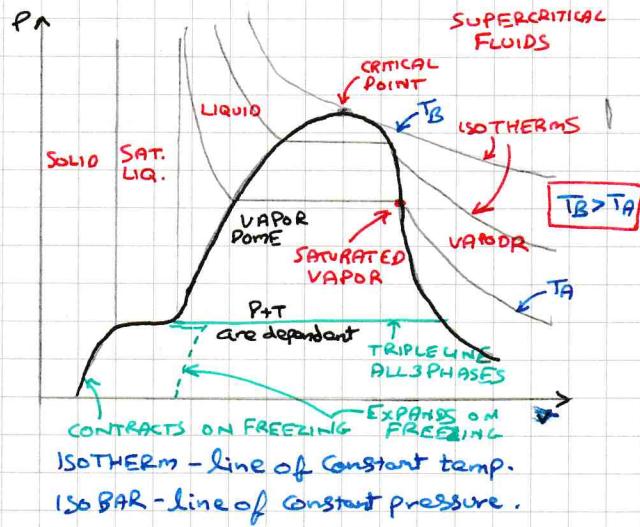
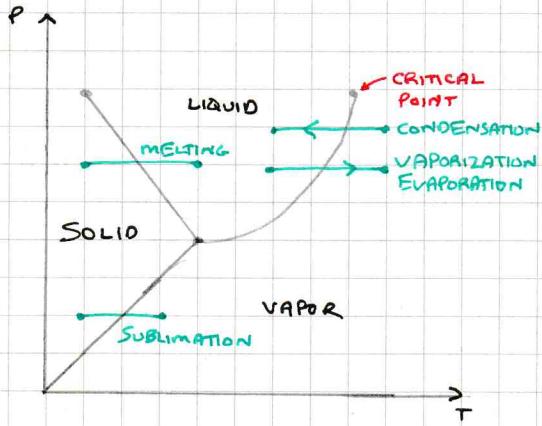
SATURATION STATE : State which begins or ends a phase change.

CRITICAL POINT : Defined by the critical temperature and is the maximum temperature where liquid and vapor phase can co-exist at equilibrium.

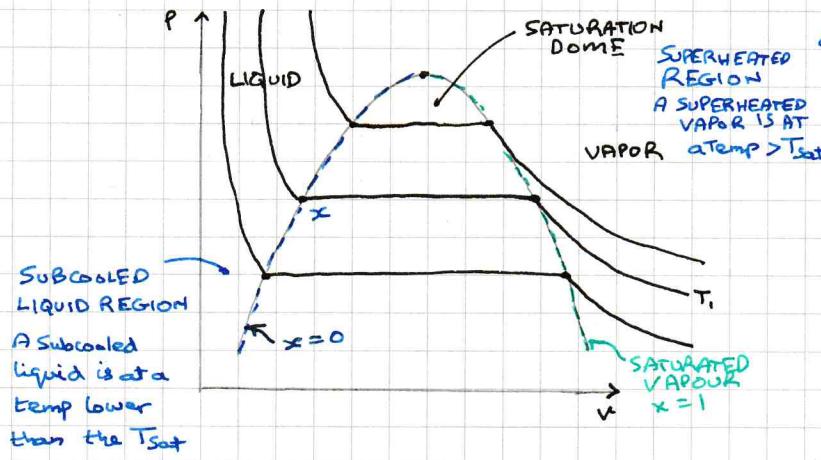
3D PHASE DIAGRAM



## 2D PHASE DIAGRAMS



## 2D PHASE DIAGRAMS : ISOBARS AND ISOTHERMS.

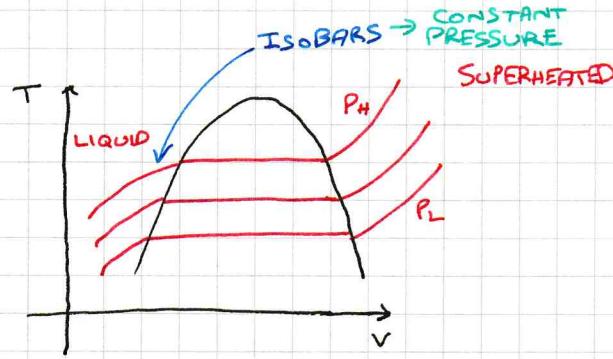
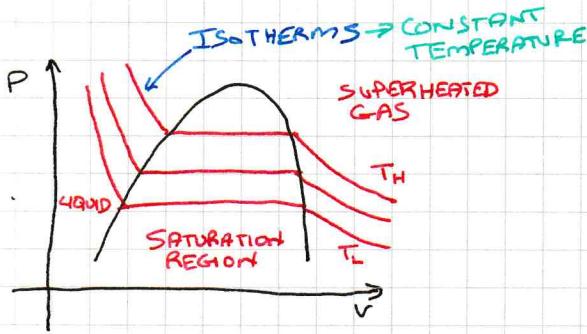


$$\text{quality} = \frac{m_{\text{vapor}}}{m_{\text{liq}} + m_{\text{vapor}}} = x [-]$$

$x = 1$  SATURATED VAPOUR

$x = 0$  SATURATED LIQUID

Quality is only defined within the Saturation region



P-v-T diagrams are Surfaces  $\rightarrow$  graphical, tabulated, relations (equations)

Common working Fluids  $\rightarrow$  water (steam), air, nitrogen, refrigerants.

SATURATION TABLES: Only includes:

Saturated liquid:  $x=0$

Saturated Vapour (gas):  $x=1$

Need to determine actual State Conditions

SPECIFIC VOLUME:

$$v_{\text{TOT}} = \frac{m_{\text{TOT}}}{m_{\text{TOT}}} = \frac{m_{\text{Liq}}}{m_{\text{TOT}}} + \frac{m_{\text{Vap}}}{m_{\text{TOT}}}$$

$$\text{but } m_{\text{Liq}} = m_{\text{Liq}} v_F \quad m_{\text{Vap}} = m_{\text{Vap}} v_g$$

$$\therefore v_{\text{TOT}} = \frac{m_{\text{Liq}}}{m_{\text{TOT}}} v_F + \frac{m_{\text{Vap}}}{m_{\text{TOT}}} v_g \Rightarrow v_{\text{TOT}} = (1-x)v_F + xv_g$$

$$v_{\text{TOT}} = v_L + x(v_g - v_L) \Rightarrow v_g \rightarrow \text{increase in Sp. Vol. on vapourisation}$$

### 3.02 : INTERNAL ENERGY, ENTHALPY AND THE SPECIFIC HEATS

Internal Energy:

$$U = \text{total internal energy} \Rightarrow u = \frac{U}{m_{\text{TOT}}} \rightarrow \text{Specific internal energy}$$

$$u = (1-x)u_f + xu_g \quad u_g = u_g - u_f$$

ONLY VALID IN SAT REGION

TRUE at all times

STATE RELATIONS

Enthalpy:

$$h = u + Pv \quad H = U + Pv$$

TRUE at all times

ONLY VALID IN SAT REGION

$$h_{fg} = h_g - h_f$$

SPECIFIC HEATS (HEAT CAPACITIES)

$$c_v \equiv \left( \frac{du}{dT} \right)_v \quad \begin{matrix} \checkmark \\ \text{INTERNAL ENERGY} \end{matrix}$$

CONSTANT VOLUME

$$c_p \equiv \left( \frac{dh}{dT} \right)_p \quad \begin{matrix} \checkmark \\ \text{ENTHALPY} \end{matrix}$$

CONSTANT PRESSURE

$$\left[ \frac{\text{kJ}}{\text{kg.K}} \right] \quad \text{(PARTIAL DERIVATIVES)}$$

T & P are independent in Superheat region  
P & T are independent in Saturated region

$$\kappa \equiv \frac{c_p}{c_v} = \text{ratio of Specific heat.}$$

STATE RELATIONS ARE ALWAYS TRUE Regardless of State or phase!

### 3.03 : THE INCOMPRESSIBLE SUBSTANCE AND THE IDEAL GAS MODELS FOR EQUATIONS OF STATE

Incompressible Substance model: (For liquids and Solids):

$$v = \text{constant} \quad \text{and} \quad u = f(T) \quad \text{only}$$

$$s = \text{constant}$$

$$c_p = \left( \frac{dh}{dT} \right)_p = \left( \frac{d(u+Pv)}{dT} \right)_p$$

CANNOT USE IN SUPERHEAT REGION

CONSTANT DENSITY | INTERNAL ENERGY

$$c_v = \left( \frac{du}{dT} \right)_v \Rightarrow c_v = \frac{du}{dT} \quad \text{FUNC OF TEMP}$$

INITIAL TO FINAL STATE

$$\Rightarrow c_p = \frac{du}{dT} = c_v \Rightarrow c_p = c_v = c$$

$$u_2 - u_1 = \int_{T_1}^{T_2} c \, dT \Rightarrow \text{if } c \neq f(T) \Rightarrow u_2 - u_1 = C(T_2 - T_1)$$

$$h = u + Pv$$

$$h_2 - h_1 = u_2 - u_1 + (P_2 v_2) - (P_1 v_1)$$

$$\Rightarrow h_2 - h_1 = C(T_2 - T_1) + v(P_2 - P_1)$$

## IDEAL GAS MODEL - For gases only:

$$\begin{aligned} P_v &= RT \text{ and } u = f(T) \\ P_v &= \bar{R} T \\ P_v &= \bar{R} \bar{T} \\ P_v &= n R T \end{aligned}$$

$$R = \text{Specific gas constant} = \frac{\bar{R}}{m_w}$$

$\underbrace{\bar{R}}$   
 $\bar{R} = \text{Universal gas constant}$   
overline means per mole basis

MOLECULAR WEIGHT

$Z = \frac{P_v}{RT}$  = Compressibility factor  $\rightarrow$  how close we are to ideal gas  
when  $Z \rightarrow 1.0 \Rightarrow$  ideal gas model is valid

as  $Z \rightarrow 0 \Rightarrow$  ideal gas no longer valid (breaks down)  
 $\hookrightarrow$  Interaction between gas molecules occur.

IDEAL GAS MODEL  $\rightarrow$  BEHAVIOUR OF  $u$  and  $h$  : IDEAL ONLY GAS

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$$P_v = RT \quad u = f(T)$$

$$\begin{aligned} C_v = \frac{du}{dT} &\rightarrow u_2 - u_1 = \int_{T_1}^{T_2} C_v(T) dT \\ &\text{INTERNAL ENERGY} \\ h_2 - h_1 &= \int_{T_1}^{T_2} (P(T) dT) \\ &\text{ENTHALPY} \end{aligned}$$

$$\begin{aligned} h &= u + P_v \Rightarrow f(T) \\ h &= u + RT \\ &\text{f(G) f(T)} \\ \frac{dh}{dT} &= \frac{du}{dT} + R(C_v) \\ g(T) &= C_v(T) + R \end{aligned}$$

## POLYTROPIC PROCESS :

$$P_v^n = \text{constant}$$

$n=0 \quad P = \text{constant} \leftarrow$  isobar

$n \rightarrow \pm \infty \quad v = \text{constant} \leftarrow$  isometric

## IDEAL GAS

$$P_v = RT$$

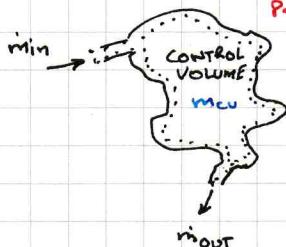
$$\frac{P_v}{T} = R \Rightarrow \frac{P_2 V_2}{T_2} = \frac{P_1 V_1}{T_1}$$

$$\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} = \left( \frac{V_1}{V_2} \right)^{n-1}$$

## CONSERVATION OF ENERGY :

MASS?

CONTROL VOLUME where mass can pass system boundaries



$m_{in}$  = instantaneous mass flow rate at inlet

$m_{out}$  = at outlet/exit

C.O.M. = Conservation of mass for a CV

$$\frac{dm_{cv}}{dt} = \sum_{i=1}^{in} m_{in} - \sum_{i=1}^{out} m_{out}$$

$$\text{Change} = In - Out \\ (\text{STORED})$$

## 3.05: CONSERVATION OF MASS FOR OPEN SYSTEM :

- Assume 1D flow

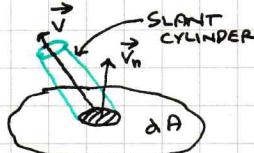
1. All flow is normal to boundaries at inlet and outlet
2. All intensive properties are uniform across inlet and outlet areas

Conservation of mass is :

$$m_{in} = \int_A \vec{V}_n dA$$

$$m_{in} = \int_A \vec{V} dA$$

$$\begin{aligned} m_{in} &= \int_A \vec{V} dA \\ &\text{ASSUME CONSTANT } \vec{V} \\ m_{in} &= \vec{V} A \end{aligned}$$



mass crossing  $dA$  for time period  $dt$  = Volume of slant cylinder

$$= \int_A \vec{V}_n dt dA$$

## 4.01 : FLOW WORK AND THE CONSERVATION OF ENERGY

### STEAM TURBINE EXAMPLE :

Steam enters turbine :

$$P_1 = 69 \text{ bar} \quad T_1 = 538^\circ\text{C} \quad V_1 = 64 \text{ m/s}$$

Turbine operating at Steady State conditions  
Steam leaves turbine as dry Saturated Vapour

$$P_2 = 10 \text{ bar} \quad x_2 = 1$$

$$\text{Turbine ID} = 0.45 \text{ m} \quad D_1 = 3.6 \text{ m}$$

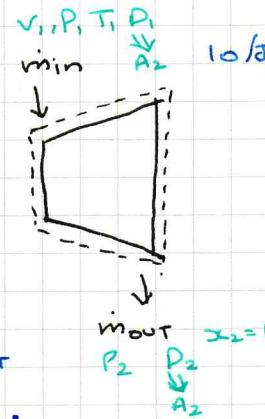
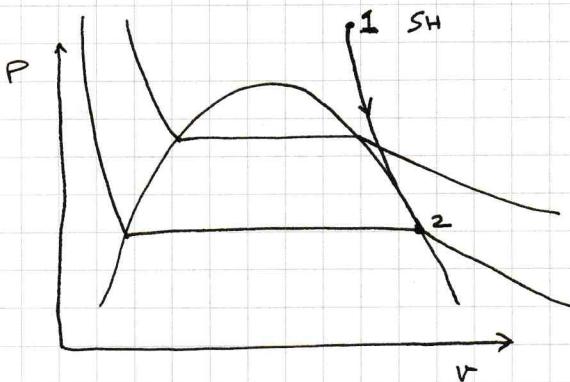
$$\text{CONSERVATION OF MASS: } \frac{dm_{cv}}{dt} = \sum m_{in} - \sum m_{out}$$

0 (STEADY STATE)

From Steam Tables:

$$(P_1, T_1): V_1 = 0.0518397 \text{ m}^3/\text{kg} \quad \text{SPECIFIC VOLUME}$$

$$(P_2, x_2): V_2 = 0.1943488 \text{ m}^3/\text{kg} \quad \text{SPECIFIC VOLUME}$$



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$$\dot{m} = (\vec{SV}A)_{in} = (\vec{SV}A)_{out}$$

$$\dot{m} = \left( \frac{\vec{V}A}{V} \right)_{in} = \frac{64 \text{ m/s} \times \frac{\pi}{4} (0.45 \text{ m})^2}{0.0518397 \frac{\text{m}^3}{\text{kg}}}$$

SPECIFIC VOLUME

$$\dot{m} = 196.35 \text{ kg/s}$$

$$\dot{m}_{in} = (\vec{SV}A)_1 = (\vec{SV}A)_2$$

$$V_2 = \frac{\dot{m}}{\dot{m}_2 A_2} = \frac{\dot{m} V_2}{A_2}$$

$$V_2 = \frac{196.35 \text{ kg/s} \times 0.1943488 \frac{\text{m}^3}{\text{kg}}}{(\frac{\pi}{4})(3.6 \text{ m})^2}$$

$$\boxed{V_2 = 3.749 \text{ m/s}}$$

### CONTROL VOLUME ANALYSIS:

CONSERVATION OF MASS States:

$$\frac{dm_{cv}}{dt} = \sum m_{in} - \sum m_{out}$$

$$\text{STORED} = \text{IN} - \text{OUT}$$

CONSERVATION OF ENERGY has exact analog to Com:

$$\text{IN} - \text{OUT} = \text{STORED}$$

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \sum \dot{m}_{in} (u_{in} + \frac{\vec{V}_{in}^2}{2} + gZ_{in}) - \sum \dot{m}_{out} (u_{out} + \frac{\vec{V}_{out}^2}{2} + gZ_{out})$$

Heat Transfer Rate    Work Transfer Rate

$$E_{cv} = (u + \frac{m_v \vec{V}^2}{2} + m_v g Z)$$

consider flow work  $\rightarrow$  work done by fluid as it is at non-zero pressure

$$\dot{w} = \dot{w}_{cv} + \dot{w}_{flow}$$

eg shaft work  
magnetic work etc.

$$\text{Recall } \int w = F dx$$

$$w_{flow} = P A dx$$

FORCE

$$\dot{w}_{flow} = P A \frac{dx}{dt} = P A \vec{V}$$

$$\dot{w} = \dot{w}_{cv} + P_e A_e \vec{V}_e - P_i A_i \vec{V}_i$$

$$\dot{m} v = A \vec{V} \quad \text{or} \quad \dot{m} = S A \vec{V}$$

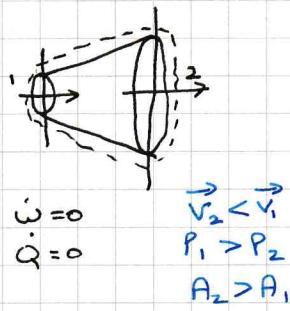
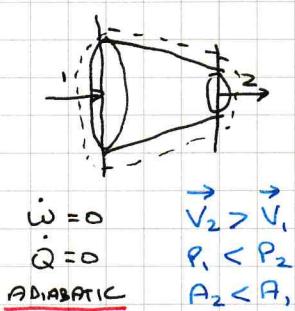
$$\dot{w}_{flow} = m_e P_e \vec{V}_e - m_i P_i \vec{V}_i$$

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{w}_{cv} - \sum \dot{m}_i P_e \vec{V}_e + \sum \dot{m}_i P_i \vec{V}_i + \sum \dot{m}_i (u_i + \frac{\vec{V}_i^2}{2} + gZ_i) - \sum \dot{m}_e (u_e + \frac{\vec{V}_e^2}{2} + gZ_e)$$

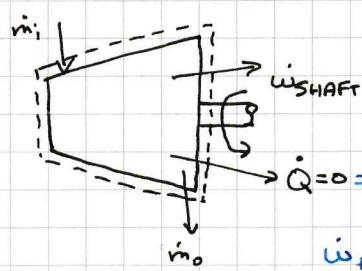
$$\boxed{\frac{dE_{cv}}{dt} = \dot{Q} - \dot{w} + \sum \dot{m}_i (h + \frac{\vec{V}^2}{2} + gZ)_{in} - \sum \dot{m}_e (h + \frac{\vec{V}^2}{2} + gZ)_{out}}$$

## 4.02 - STEADY STATE, STEADY FLOW DEVICES

### NOZZLES AND DIFFUSERS :



### TURBINES :



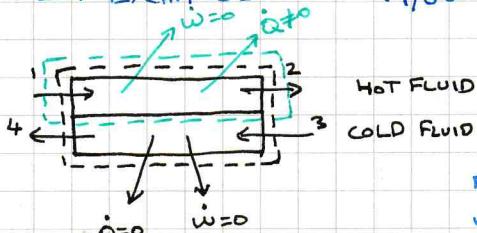
$$\frac{dm_{av}}{dt} = \sum \dot{m}_i - \sum \dot{m}_{out} = 0$$

$$\dot{m} = \dot{m}_{in} = \dot{m}_{out}$$

$$\dot{Q} = 0 \Rightarrow \text{adiabatic negligible}$$

$$\omega_t = \dot{m}(h_i - h_o)$$

### HEAT EXCHANGER:



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$$\dot{m}_1 = \dot{m}_2$$

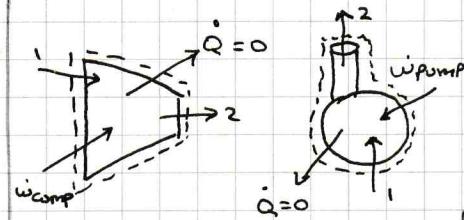
$$\text{COM: } \dot{m}_1 + \dot{m}_3 = \dot{m}_2 + \dot{m}_4$$

$$\text{COE: Negligible } \Delta E^{\text{ext}}$$

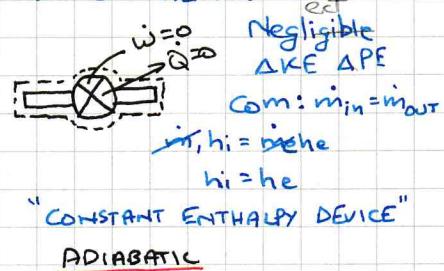
$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

ADIABATIC IF ENTIRE SYSTEM CONSIDERED

### COMPRESSORS AND PUMPS :



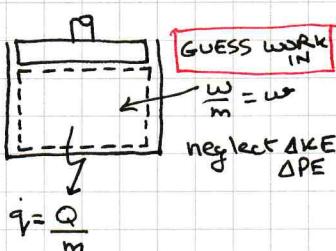
### THROTTLE/VALVES:



## 4.03 COMPRESSING WATER

### EXAMPLE PROBLEM:

#### Step 1 : DEFINE THE SYSTEM:



#### Step 2: Identify proper forms for Com and COE:

$$\dot{m} = \text{constant}$$

$$\Delta E = Q - W$$

$$\Delta U = Q - W$$

$$u_2 - u_1 = q - w$$

#### Step 3: FIND any missing and required STATE information:

$$\text{at (1) } x_1 = 1, P_1 = 200 \text{ kPa} \Rightarrow u_1 = 2582 \text{ kJ/kg}$$

$$\text{at (2) } T_2 = 250^\circ C, P_2 = 1 \text{ MPa (SUPER HEAT REGION)}$$

$$\Rightarrow u_2 = 2709.9 \text{ kJ/kg}$$

#### Step 4: FIND requested information

$$w = \frac{W}{m} = q - u_1 - u_2$$

$$W = -93 \frac{\text{kJ}}{\text{kg}} + 2587.9 - 2709.9 \frac{\text{kJ}}{\text{kg}}$$

$$W = -213 \frac{\text{kJ}}{\text{kg}}$$

WORK IN IS CORRECT ASSUMPTION

4.03: STEAM TURBINE EXAMPLE [4.01] - Part 2  
What is the power generated by the turbine? [ $\dot{W}$ ]

$$\text{COE: } \frac{dE_v}{dt} = \cancel{\dot{Q}} - \dot{W} + \sum m_{\text{in}} \left[ h + \frac{V^2}{2} + gz \right]_{\text{in}} - \sum m_{\text{out}} \left[ h + \frac{V^2}{2} + gz \right]_{\text{out}}$$

$\cancel{\dot{Q}}$

= 0      ASSUME ADIABATIC

NEGLECT PE EFFECTS

$$\dot{W} = \dot{m} \left[ \left( h + \frac{V^2}{2} \right)_{\text{in}} - \left( h + \frac{V^2}{2} \right)_{\text{out}} \right]$$

$$h_1 = 3504 \text{ kJ/kg}$$

$$h_2 = 2777 \text{ kJ/kg}$$

$$\dot{W} = \dot{m} \left[ (3504 - 2777) \frac{\text{kJ}}{\text{kg}} + \frac{(64 \text{ m})^2}{2} - \frac{(3.75 \text{ m})^2}{2} \right]$$

$$\dot{W} = \dot{m} \left[ 727 \frac{\text{kJ}}{\text{kg}} + 2.041 \frac{\text{kJ}}{\text{kg}} \right]$$

$$\frac{V_1^2 - V_2^2}{2} \left( \frac{\text{m}^2}{\text{s}^2} \right) \cdot \left[ \frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2} \right]$$

$$\therefore \dot{W} = 196.5 \frac{\text{kg}}{\text{s}} \times 729.041 \frac{\text{kJ}}{\text{kg}}$$

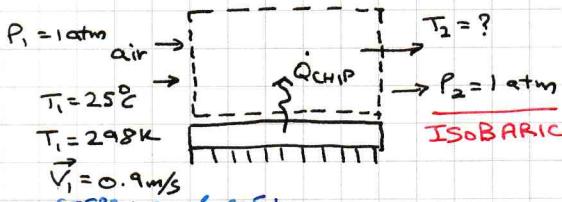
$$\therefore \boxed{\dot{W}} = 143256.6 \text{ kW} \Rightarrow \boxed{143 \text{ MW}}$$

How much  $\dot{W}$  is attributable to KE, and, Flow work + INTERNAL ENERGY?

$$\begin{aligned} \frac{\dot{W}_{KE}}{\dot{W}_{TOT}} &= \frac{2.041 \text{ kJ/kg} \times 100}{729 \text{ kJ/kg}} \\ &= 0.28\% \Rightarrow \text{Hence we neglect KE \& PE} \end{aligned}$$

4.05. EXAMPLE OF COOLING A MICROPROCESSOR

Step 1 : DEFINE THE SYSTEM



STEP 2: COME COE:  
ASSUME STEADY STATE:

$$\dot{Q} = \dot{m}(h_2 - h_1)$$

$$\dot{Q} = \dot{m}c_p(T_2 - T_1)$$

5.01 [CONTINUED] 20 JUNE 2021

ASSUME Area(A) = 1cm x 2cm = 2 cm<sup>2</sup>

$$\dot{m} = S A V = 1.1847 \frac{\text{kg}}{\text{m}^2 \cdot \text{s}} \times 0.0002 \text{ m}^2 \times 0.9 \text{ m/s}$$

$$\therefore \dot{m} = 2.1325 \times 10^{-4} \text{ kg/s}$$

SPECIFIC HEATS:  $c_p = 1.005 \text{ kJ/kg K}$

SOLVE  $\dot{Q} = \dot{m}c_p(T_2 - T_1)$

$$\therefore T_2 = \frac{\dot{Q}}{m c_p} + T_1 \Rightarrow T_2 = \frac{10 \text{ W}}{2.1325 \times 10^{-4} \frac{\text{kg}}{\text{s}} \times 1.005 \frac{\text{kJ}}{\text{kg K}}} + 298 \text{ K}$$

$$\therefore T_2 = 46.67 \text{ K} + 298 \text{ K}$$

$$\therefore T_2 = 344.66 \text{ K}$$

$\dot{m} = S A V$       STEP 3: FIND MISSING INFORMATION

FROM IDEAL GAS LAW:  $P = SRT$

$$R_{AIR} = \frac{R}{m_{WATER}}$$

$$m_{WATER} = 28.97 \text{ g/mol}$$

$$R = 8.314 \text{ J/mol K}$$

$$R_{AIR} = 8.314 \frac{\text{J}}{\text{mol K}} \times \frac{1 \text{ mol}}{0.02897 \text{ kg}}$$

$$R_{AIR} = 287 \text{ J/kg K}$$

$$P = SRT$$

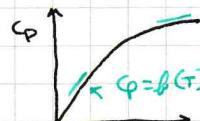
$$1 \text{ atm} = 8.287 \frac{\text{J}}{\text{kg K}} \cdot 298 \text{ K}$$

$$S = 101.325 \text{ kPa kg/K}$$

$$= 0.0011847$$

$$= 1.1847 \text{ kg/m}^3$$

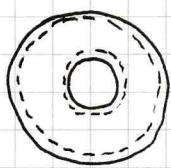
$$\begin{aligned} T &\text{ K} \\ \dot{Q} &\text{ J} \\ m &\text{ kg} \\ R &\text{ J} \\ S &\text{ J/K} \\ \rho &\text{ kg/m}^3 \end{aligned}$$



## 5.02 TRANSIENT ANALYSIS - SETTING UP THE GOVERNING EQUATIONS

STEP 1: DEFINE THE SYSTEM:

TYRE



$$V = 10 L = \text{constant}$$

$$\textcircled{1} \quad P_1 = 15 \text{ psi}$$

$$T_1 = 20^\circ\text{C}$$

$$\textcircled{2} \quad P_2 = 35 \text{ psi}$$

$$T_2 = ?$$

STEP 2: IDENTIFY PROPER FORMS OF

COM & COE:

$$\text{Com: } \frac{dm_{cv}}{dt} = \dot{m}_{in} - \dot{m}_{out}$$

$$= 0$$

NO LEAKS!

$$\frac{dm_{cv}}{dt} = \dot{m}_{in}$$

$$\int_1^2 dm_{cv} = \int_1^2 \dot{m}_{in} dt = \dot{m} \Delta t = \dot{m}_{in}$$

$$m_2 - m_1 = \dot{m}_{in}$$

$$\text{COE: } \frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \sum \dot{m}_{in} \left[ h + \frac{V^2}{2} + gz \right]_{in} - \sum \dot{m}_{out} \left[ h + \frac{V^2}{2} + gz \right]_{out}$$

NEGLECT KE+PE  
 ADIABATIC  
 NO EXP COMP

NEGLECT KE+PE  
 NEGLECT KE+PE

$$\frac{dU_{cv}}{dt} = \dot{m}_{in} h_{in} \int_1^2 dm_{cv} = \int_1^2 \dot{m}_{in} h_{in} dt$$

$$U_2 - U_1 = \dot{m}_{in} h_{in}$$

$$U_2 - U_1 = (m_2 - m_1) h_{in}$$

$$m_2 u_2 - m_1 u_1 = (m_2 - m_1) h_{in}$$

$$u_2 - u_1 = C_v (T_2 - T_1)$$

$$m_1 = \frac{P_1 V_1}{R T_1} \quad m_2 = \frac{P_2 V_2}{R T_2}$$

## 5.03 TRANSIENT ANALYSIS - REFORMULATING THE PROBLEM

27/JUNE/2021

Treat fill process as two sequential steps:

1. A quick fill to a target intermediate pressure  $1 \rightarrow 2$   $Q=0$  adiabatic Fill to  $T_2$
2. Cooling to the desired final pressure + ambient temp  $2 \rightarrow 3$   $\dot{Q}_{out} < 0$   $P_3 = 35 \text{ psi}$   
 $T_3 = 20^\circ\text{C}$

$$\text{Com: } 1-2 \quad m_2 - m_1 = \dot{m}_{in}$$

$$\text{COE: } 1-2 \quad m_2 u_2 - m_1 u_1 = \dot{m}_{in} (m_2 - m_1)$$

$$m_1 = \frac{P_1 V_1}{R T_1}$$

$$\text{Com: } 2-3 \quad \frac{dm_{cv}}{dt} = \dot{m}_{in} - \dot{m}_{out} \Rightarrow m_2 = m_3 = \frac{P_3 V}{R T_3}$$

$$\text{COE: } 2-3 \quad \frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \sum \dot{m}_{in} (\quad) + \sum \dot{m}_{out} (\quad)$$

$$u_3 - u_2 = \dot{Q}_3 \Rightarrow m_2 u_3 - m_2 u_2 = \dot{Q}_3$$

FOR IDEAL GAS:

$$u = f(T)$$

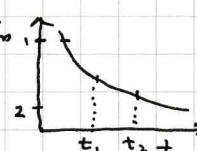
$$\text{Solve for } u_2 = f(T_2)$$

$$h = f(T)$$

$$\text{then } m_2 - m_1 = \dot{m}_{in}$$

5.04 How would our analysis change if we use a Small Compressor?

$$\text{Com: } \int_1^2 dm_{cv} = \int_{t_1}^{t_2} \dot{m}_{in} dt$$



$$\text{COE: } \frac{dU_{cv}}{dt} = \dot{m}_{in} \dot{m}_{in}$$

$$\int_1^2 dm_{cv} = \int_1^2 \dot{m}_{in} \dot{m}_{in} dt$$

## 5.04 CYCLE ANALYSIS - POWER CYCLES:

By definition, a cycle ends where it begins:

$$E_{cycle} = E_f, \text{cycle}$$

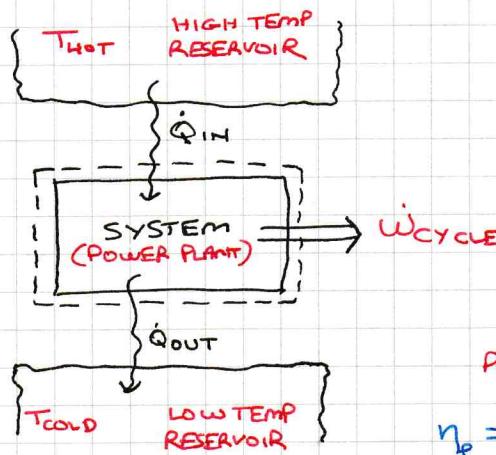
COE : Assume closed power cycle:

$$\Delta E = \Delta E_{cycle} = Q_{cycle} - W_{cycle} \Rightarrow Q_{cycle} = W_{cycle}$$

Above is general definition of a "CYCLE"

FIRST LAW OF THERMODYNAMICS

POWER CYCLES = net work transfer to the surroundings = HEAT ENGINE



POWER CYCLE EFFICIENCY:

PERFORMANCE METRIC = What you want / what did you pay for to get it  
(IN GENERAL)

$$\eta_p = \frac{W_{cycle}}{Q_{in}}$$

COE:  
 $\Delta E = Q - W$

efficiency of Power plant

$$\eta_p = \frac{\dot{Q}_{in} - \dot{Q}_{out}}{\dot{Q}_{in}}$$

$$W_{cycle} = Q_{cycle}$$

$$W_{cycle} = Q_{in} - Q_{out}$$

## 5.05 REFRIGERATION AND HEAT PUMP CYCLES:

$$|W_{cycle}| = Q_{cycle}$$

$$W_{cycle} = Q_{out} - Q_{in}$$

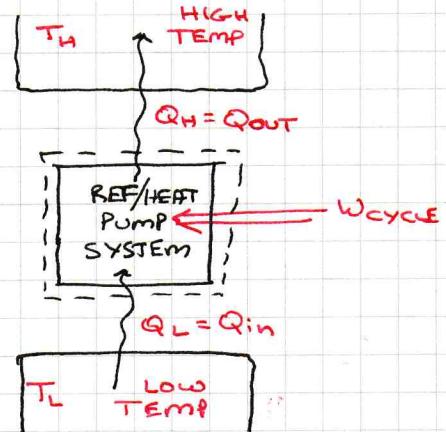
$$|Q_{out}| > |Q_{in}|$$

$$\text{Refrigeration Coeff of performance } \beta = \frac{Q_{in}}{|W_{cycle}|}$$

$$\text{Heat Pump Coeff of Performance } \gamma = \frac{Q_{out}}{|W_{cycle}|}$$

$\gamma$  can never be  $< 1$

ALWAYS WANT  $\eta_p, \beta, \gamma$  to be as high as possible.



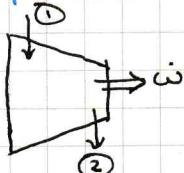
## 6.01 A CONCEPTUAL INTRODUCTION TO THE SECOND LAW OF THERMODYNAMICS

1<sup>st</sup> LAW - Tells us if process is allowed or does the process violate conservation of energy.

$$\Delta E_{\text{cm}} = Q - W \quad E_{\text{final}} > E_{\text{initial}}$$

2<sup>nd</sup> LAW - Tells us the allowed direction of a process.

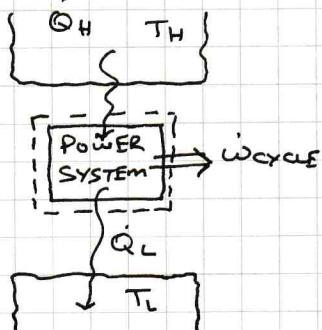
2<sup>nd</sup> LAW - Also allows us to quantify limiting behaviour. i.e. max and min values for processes.



$w_{\text{max}} \leftarrow \text{From 2}^{\text{nd}} \text{ LAW}$

2<sup>nd</sup> LAW - Also introduces a lot of other powerful and interesting concepts like the absolute temperature scale and the thermodynamic property, entropy =  $S [\text{kJ}/\text{K}]$  and Specific entropy =  $s [\text{kJ}/(\text{K kg})]$

### THE 2<sup>nd</sup> LAW OF THERMODYNAMICS AND CYCLES:



$$\eta_p = \frac{w_{\text{CYCLE}}}{Q_H}$$

$$\eta_p = \frac{Q_{\text{CYCLE}}}{Q_H}$$

$$\eta_p = \frac{Q_H - Q_L}{Q_H}$$

ALWAYS VALID  
FOR IDEAL OR NON-  
IDEAL = REAL/ACTION  
SYSTEMS

$$\text{FOR REFRIGERATION: } \beta = \frac{Q_{\text{COLD}}}{w_{\text{CYCLE}}} = \frac{Q_C}{Q_{\text{CYCLE}}}$$

$$\beta_{\text{CARNOT}} = \beta_{\text{max}} = \frac{T_L}{T_H - T_L}$$

$$\text{FOR HEAT PUMP: } \gamma = \frac{Q_H}{w_{\text{CYCLE}}}$$

$$\gamma_{\text{max}} = \gamma_{\text{CARNOT}} = \frac{T_H}{T_H - T_L}$$

### 6.02 THE CARNOT CYCLE:

05/JULY/2021

CARNOT CYCLE = 4 IDEAL PROCESSES  $\rightarrow$  4 STATES

1-2 1<sup>st</sup> ADIABATIC PROCESS,  $Q_2 = 0$

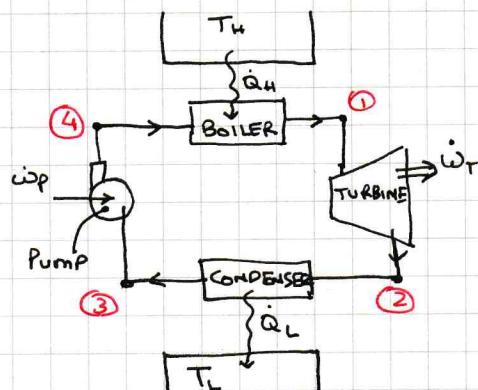
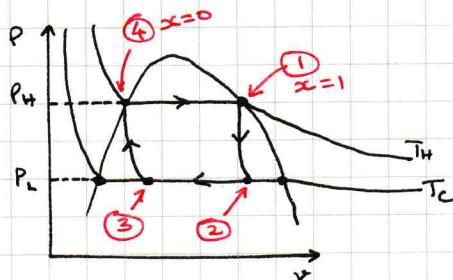
2-3 1<sup>st</sup> ISOTHERMAL PROCESS,  $T_2 = T_3$

3-4 2<sup>nd</sup> ADIABATIC PROCESS,  $Q_4 = 0$

4-1 2<sup>nd</sup> ISOTHERMAL PROCESS,  $T_4 = T_1$

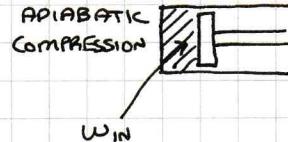
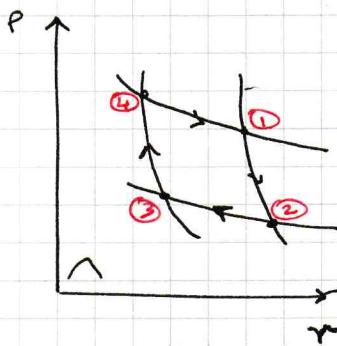
### THE CARNOT CYCLE - PART 3

The process components for a working fluid with phase change.

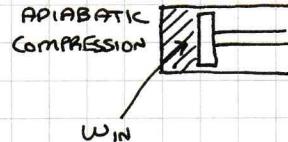
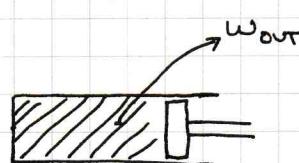


## THE CARNOT CYCLE - PART 2

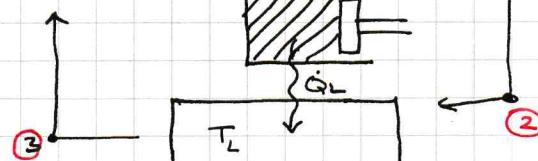
The process components for a working fluid with **NO** Phase change



ISOTHERMAL HEAT ADDITION



ADIASTATIC EXPANSION



### 6.03 THE RANKINE POWER PLANT

↳ STEAM POWER CYCLE → WORKING FLUID = WATER

THE GENERAL FEATURES: **CLOSED SYSTEM**

NEGLECT ΔE + PE CHANGES

ASSUME STEADY STATE

STEADY FLOW CONDITIONS

NO HEAT TRANSFER WITH

AMBIENT/SURROUNDINGS

COM:

$$\dot{m}_{in} = \dot{m}_{in} - \dot{m}_{out}$$

AT CONSIDER THE TURBINE **OPEN SYSTEM**

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}$$

COE:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}_{in} [h + \frac{V^2}{2} + gz]_{in}$$

$$\dot{m} = 0$$

$$-\dot{m}_{out} [h + \frac{V^2}{2} + gz]_{out}$$

TURBINE

$$\frac{\dot{W}_t}{\dot{m}} = h_1 - h_2$$

>0  
WORK OUT  
OF SYSTEM

<0  
WORK INTO  
SYSTEM

CONDENSER

$$\frac{\dot{Q}_{cond}}{\dot{m}} = \frac{\dot{Q}_{out}}{\dot{m}} = h_3 - h_2$$

<0  
HEAT OUT

BOILER:

$$\frac{\dot{Q}_{boiler}}{\dot{m}} = \frac{\dot{Q}_u}{\dot{m}} = \frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_4$$

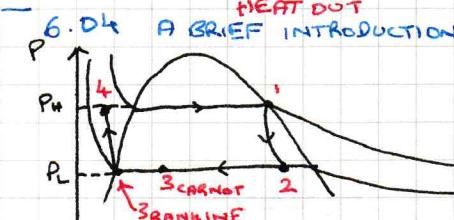
>0  
HEAT IN

These equations are valid  
for ideal and non-ideal  
components.

THE OVERALL THERMAL EFFICIENCY:

$$\eta_p = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}} = \frac{(\dot{W}_t + \dot{W}_p)/\dot{m}}{(\dot{Q}_{in})/\dot{m}}$$

$$\eta_p = \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_4)} \Rightarrow \eta_p = 1 + \frac{(h_3 - h_2)}{(h_1 - h_4)}$$



1. ADIABATIC  $\dot{Q}_{TURB} = 0$

2. IDEAL

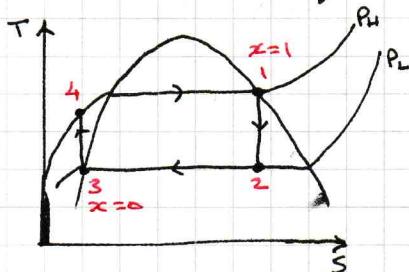
$$1. + 2. \rightarrow S = \text{constant}$$

ADIABATIC + IDEAL

PROCESSES ARE ISENTROPIC

CONSTANT ENTROPY

$$\Delta S = 0$$



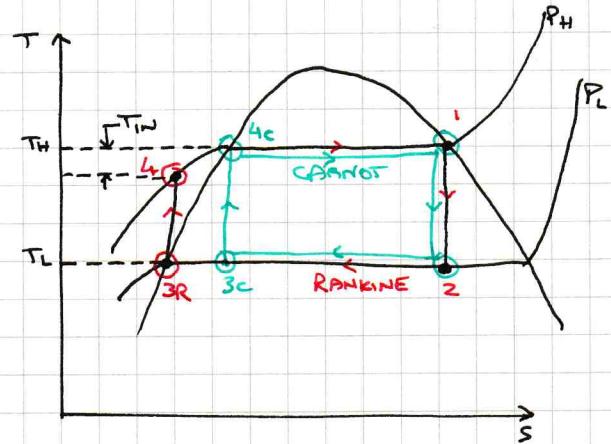
## COMPARING THE RANKINE AND CARNOT POWER CYCLES

- 1-2 ISENTROPIC EXPANSION
- 2-3 CONSTANT TEMPERATURE HEAT REJECTION
- 3-4 ISENTROPIC COMPRESSION
- 4-1 CONSTANT TEMPERATURE HEAT ADDITION

$$\eta_{\text{MAX CARNOT}} = 1 - \frac{T_L}{T_H}$$

$$\eta_{\text{RANKINE}} = 1 - \frac{T_L}{T_{in}}$$

AVG TEMP FOR HEAT ADDITION



BASIC STEPS TO INCREASE THERMAL EFFICIENCY OF RANKINE POWER PLANT

To  $\uparrow \eta_{\text{CYCLE}}$  we want  $\uparrow T_H$   $\Rightarrow T_H = T_{\text{BOILER}}$

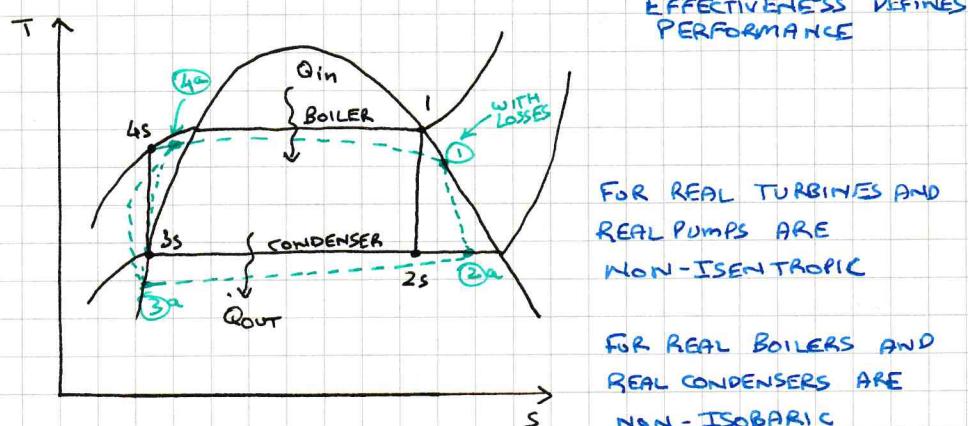
(1)  $\therefore$  we want to  $T_{PH} = T_{\text{BOILER}}$

(2) Also want to  $\downarrow P_{\text{CONDENSER}}$    
 PRACTICAL lower limit to  $P_{\text{condenser}}$   $\Rightarrow$  AMBIENT PRESSURE, i.e. 1 atm.

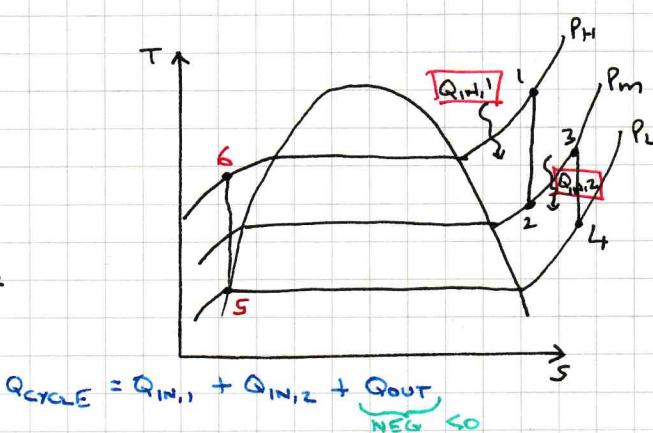
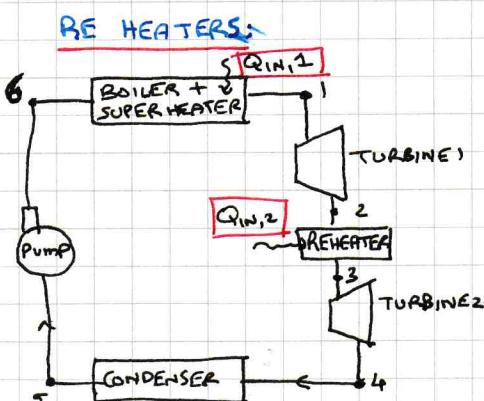
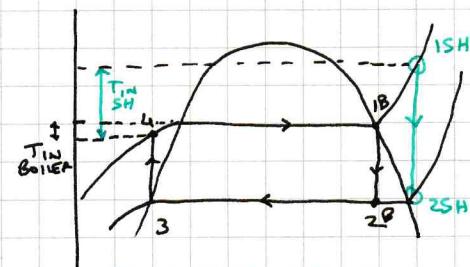
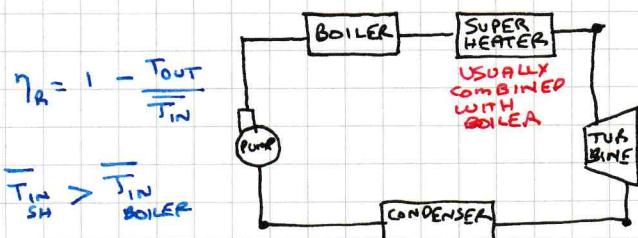
If we go below 1 atm  $\Rightarrow$  need to maintain leak tight connections  $\Rightarrow$   $\uparrow$  COSTS of Power plant.

6.05: More Advanced Methods to INCREASE the Efficiency of Rankine Power Plants

REAL POWER CYCLES - Where are the losses:



SUPER HEATERS: [JUST ANOTHER HEAT EXCHANGER]



## 6.06 CONCEPTS AND THEORY OF THE 2<sup>nd</sup> LAW OF THERMODYNAMICS

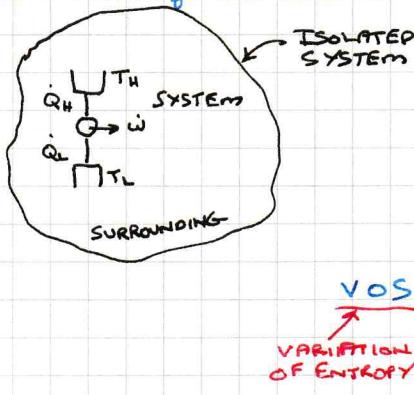
### The 2<sup>nd</sup> LAW OF THERMODYNAMICS:

- establishes entropy as a thermodynamic property
- is used to determine the ideal or best performance we can expect from a device or process
- is used to predict the direction of processes
- is used to evaluate and quantify the effects of irreversibilities.
- is used to establish conditions for equilibrium
- allows us to define reversible and irreversible processes.

PRACTICAL INTERPRETATION OF THE PROPERTY ENTROPY AND THE PROCESS TERM → GENERATION OF ENTROPY :

- ENTROPY is a measure of disorder in the system. The generation of entropy is a measure of the irreversibilities that occur during a process.
- Reversible process → Process that can occur and then be reversed and System is returned to the exact original condition without changing the surroundings of the System.
- EXAMPLE: Brakes on a bicycle or car. Braking applied → work transfer occurs, the rims of the wheels are heated by friction. This process is irreversible. Amount of friction heating is an indication of magnitude of entropy generation.

THE ENTROPY of the universe is always increasing!



ISOLATED SYSTEM = NO ENERGY TRANSFER across the isolated system boundaries

$$\text{COE} \quad \Delta E_{\text{Iso}} = Q_{\text{Iso}} - W_{\text{Iso}} \\ = 0 \qquad \qquad \qquad = 0$$

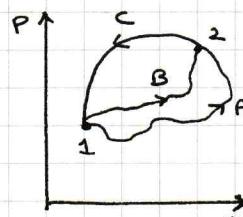
$$\Delta S_{\text{Iso}} = \left[ \left( \frac{\delta Q}{T} \right)_b \right] + S_{\text{gen}} \\ = 0$$

$$\Delta S_{\text{Iso}} = \Delta S_{\text{Sys}} + \Delta S_{\text{Sur}} = S_{\text{gen}} \geq 0$$

$$\boxed{\Delta S_{\text{Iso}} \geq 0}$$

CARUSUS INEQUALITY STATEMENT OF 2<sup>nd</sup> LAW:

$$\boxed{\int \left( \frac{\delta Q}{T} \right)_b \leq 0}$$



EQN ①

EQN ②

EQN ① - ② ⇒

$$\int_1^2 \left[ \frac{\delta Q}{T} \right]_A + \int_2^1 \left[ \frac{\delta Q}{T} \right]_C = 0$$

$$\int_1^2 \left[ \frac{\delta Q}{T} \right]_B + \int_2^1 \left[ \frac{\delta Q}{T} \right]_C = 0$$

$$\int_1^2 \left[ \frac{\delta Q}{T} \right]_A - \int_1^2 \left[ \frac{\delta Q}{T} \right]_B + 0 = 0$$

$$\therefore \int_1^2 \left[ \frac{\delta Q}{T} \right]_A = \int_1^2 \left[ \frac{\delta Q}{T} \right]_B = S_2 - S_1$$

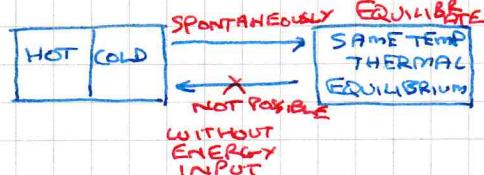
Why is water used as working fluid for Rankine Power plants?

→ Abundant, Safe, Free (For now)

Requires careful analysis to decide the location of plant with tradeoff between population centers, clean water, etc.

CONCEPTUAL INTRO TO 2<sup>nd</sup> LAW:  
→ Tells us Spontaneous change of a System will always occur from a State of lower disorder to a State of higher disorder. Consider the following observations:

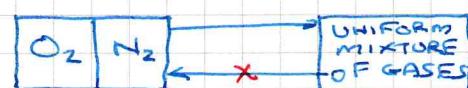
HOT AND COLD SUBSTANCES:



HIGH PRESSURE AND VACUUM SYSTEMS:



OXYGEN AND NITROGEN



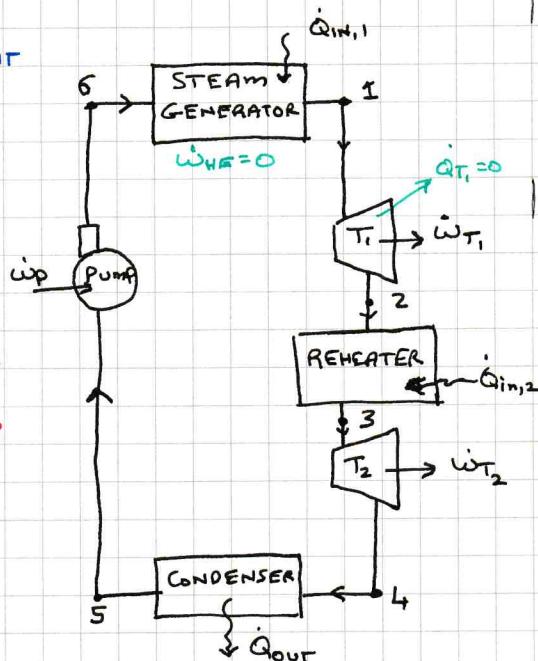
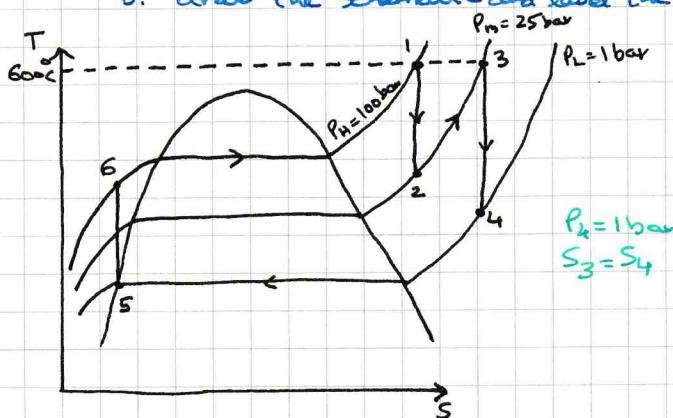
## 7.01 EXAMPLE ANALYSIS OF A RANKINE POWER PLANT

### PART 1: ASSIGNING THE STATE INFORMATION

#### PROBLEM STATEMENT:

1. Steam Power Plant  $\rightarrow$  Uses one Stage of Reheat
  2. Steam Generator  $\rightarrow$  100 bar
  3. Condenser  $\rightarrow$  1 bar
  4. Reheater Inlet Pressure  $\rightarrow$  25 bar
  5. Assume No Losses in System
  6. First Stage turbine Inlet temperature  $\rightarrow 600^\circ\text{C}$
  7. Second Stage " " "  $\rightarrow 600^\circ\text{C}$
- What is the cycle efficiency of the Power Plant?

- a. Sketch the cycle on a T-s diagram
- b. draw the Schematic and label the States



### 7.02 C. Using online Steam tables, find enthalpy at States 1 and 3

(ANSWERS MAY VARY FROM COURSERA VIDEO)

$$T_1 = 600^\circ\text{C} \quad P_1 = 100 \text{ bar} \Rightarrow h_1 = 3625.84 \text{ kJ/kg}, s_1 = 6.9045 \text{ kJ/kg-K}$$

$$T_3 = 600^\circ\text{C} \quad P_3 = 25 \text{ bar} \Rightarrow h_3 = 3686.76 \text{ kJ/kg}, s_3 = 7.5977 \text{ kJ/kg-K}$$

$$\text{d. } \because s_3 = s_4 = 7.5977 \text{ kJ/kg-K} \Rightarrow h_4 = 2769.478 \text{ kJ/kg}, \text{ & } T_4 = 146.58^\circ\text{C} \quad (\text{Refer Print})$$

e. Use water saturation tables, determine variables at State 5

$$P_5 = 1 \text{ bar} \quad T_5 = 99.63^\circ\text{C} \quad h_{f5} = 417.46 \text{ kJ/kg}, \quad s_{f5} = 1.3026 \text{ kJ/kg-K}$$

f. Use compressed liquid table and find variables at state 6 (Refer Print)

$$\begin{cases} P_6 = 100 \text{ bar} \Rightarrow T_6 = 100.3164^\circ\text{C} & h_6 = 427.7224 \text{ kJ/kg} \\ s_6 = s_5 = 1.3026 \text{ kJ/kg-K} & \end{cases}$$

### 7.03 g. Find enthalpy at exit of first stage of turbine

$\Rightarrow$  Water at exit of first stage of turbine (State 2) is in Superheat region.

$$P_2 = 25 \text{ bar}, \quad s_2 = s_1 = 6.9045 \text{ kJ/kg-K}, \quad h_2 = 3250.66 \text{ kJ/kg}, \quad T_2 = 404.79^\circ\text{C}$$

h. Find the heat into the cycle:  
ASSUME Steady State Steady Flow, Neglect ( $\Delta KE + \Delta PE$ )

$$\dot{q}_{in,1} = \frac{\dot{Q}_{in,1}}{\dot{m}} = h_1 - h_6 > 0 \quad \text{at } \dot{m}$$

$$= 3625.84 - 427.7224 \text{ kJ/kg}$$

$$= 3198.118 \text{ kJ/kg}$$

$$\dot{q}_{in,2} = \frac{\dot{Q}_{in,2}}{\dot{m}} = h_3 - h_2$$

$$= 3686.76 - 3250.66 \text{ kJ/kg}$$

$$= 436.1 \text{ kJ/kg}$$

$$\dot{Q}_{in, TOTAL} = \frac{\dot{Q}_{in,1}}{\dot{m}} + \frac{\dot{Q}_{in,2}}{\dot{m}} = 3634.218 \text{ kJ/kg}$$

### J. FIND THE CYCLE EFFICIENCY

$$\eta_{CYCLE} = \frac{\dot{Q}_{cycle/in}}{\dot{Q}_{in/in}} = \frac{1282.2}{3634.218} \frac{\text{kJ/kg}}{\text{kJ/kg}}$$

$$\boxed{\eta_{CYCLE} = 0.3528}$$

i. Find the heat out of the power plant:

$$\dot{Q}_{out} = h_5 - h_4$$

$$= 417.46 - 2769.478 \text{ kJ/kg}$$

$$\dot{Q}_{out} = -2352.02 \text{ kJ/kg}$$

$$\dot{Q}_{CYCLE} = \frac{\dot{Q}_{in, TOTAL}}{\dot{m}} + \frac{\dot{Q}_{out}}{\dot{m}} = 3634.218 - 2352.02$$

$$\dot{Q}_{CYCLE} = 1282.2 \text{ kJ/kg}$$

7.04 k. What mass flow rate of Steam is required if the power plant generates net Power of 500 MW

$$\dot{W}_{\text{CYCLE}} = 500 \text{ MW} = \left[ \frac{\dot{W}_{T_1}}{\text{min}} + \frac{\dot{W}_{T_2}}{\text{min}} + \frac{\dot{W}_P}{\text{min}} \right] \text{min} = \dot{Q}_{\text{CYCLE}}$$

$$\therefore 500 \text{ MW} = [(h_1 - h_2) + (h_3 - h_4) + (h_5 - h_6)] \text{ min}$$

$$= [375.18 + 917.282 - 10.2624] \text{ min}$$

kJ/kg      kJ/kg      kJ/kg

$$500 \times 10^6 \text{ W} = \left[ 1282.2 \frac{\text{kJ}}{\text{kg}} \right] \text{ min}$$

$$\text{min} = \frac{500 \times 10^6 \text{ W}}{1282.2 \text{ kJ/kg}}$$

$$= \frac{500 \times 10^6 \text{ kg m}^2/\text{s}^3}{1282.2 \times 1000 \text{ J/kg}}$$

$$= 389.955 \text{ kg/s}$$

$$\text{min} = 1.4038 \times 10^6 \text{ kg/hr}$$

$$1 \text{ W} = 1 \frac{\text{kg m}^2}{\text{s}^3}$$

$$1 \text{ J} = 1 \frac{\text{kg m}^2}{\text{s}^2}$$

$$\frac{\text{kg m}^2/\text{s}^3}{\text{kg m}^2/\text{s}^2}$$

$$\text{kg/s}$$

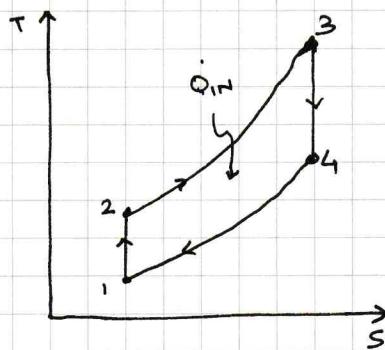
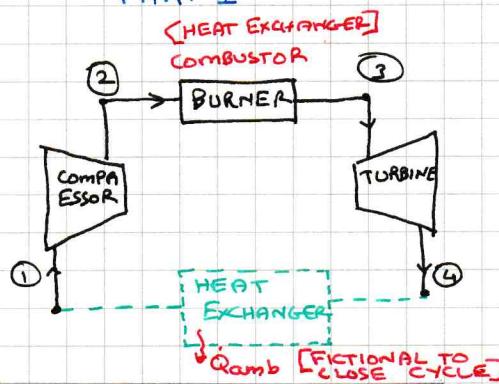
L. How much heat did we "waste" by rejecting heat to the environment?

$$\eta_{\text{waste}} = \frac{Q_{\text{out}}/\text{min}}{Q_{\text{in}}/\text{min}} = \frac{2352.02}{3634.218}$$

$$\boxed{\eta_{\text{waste}} = 0.64719}$$

## 8.01 AIR STANDARD POWER CYCLES : THE BRAYTON CYCLE

### PART 1



COMPONENT ANALYSIS  
[WORKING FLUID IS AIR]

$$\frac{\dot{W}}{m} = h_3 - h_4 \\ = c_p(T_3 - T_4)$$

$$\frac{\dot{W}}{m} = h_1 - h_2 \\ = c_p(T_1 - T_2)$$

Assume ideal gas model  
with constant specific  
heat.

COMBUSTOR :

$$\frac{Q_{in}}{m} = h_3 - h_2 \\ = c_p(T_3 - T_2)$$

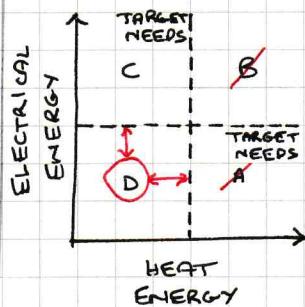
### PART 2:

- ①  $\eta \uparrow$  with ↑ burner operating pressure  $\eta$
- ② Compressor work is much higher fraction of the turbine work compared to pump work in a Rankine cycle. (Work Ratio)
- ③ Reheat and Intercooling can improve the Brayton cycle efficiency.
- ④  $T_4 > 298K$  (AMBIENT)  
There is a lot of useful heat going "out of the Stack" with the basic brayton cycle.

### CYCLE EFFICIENCY:

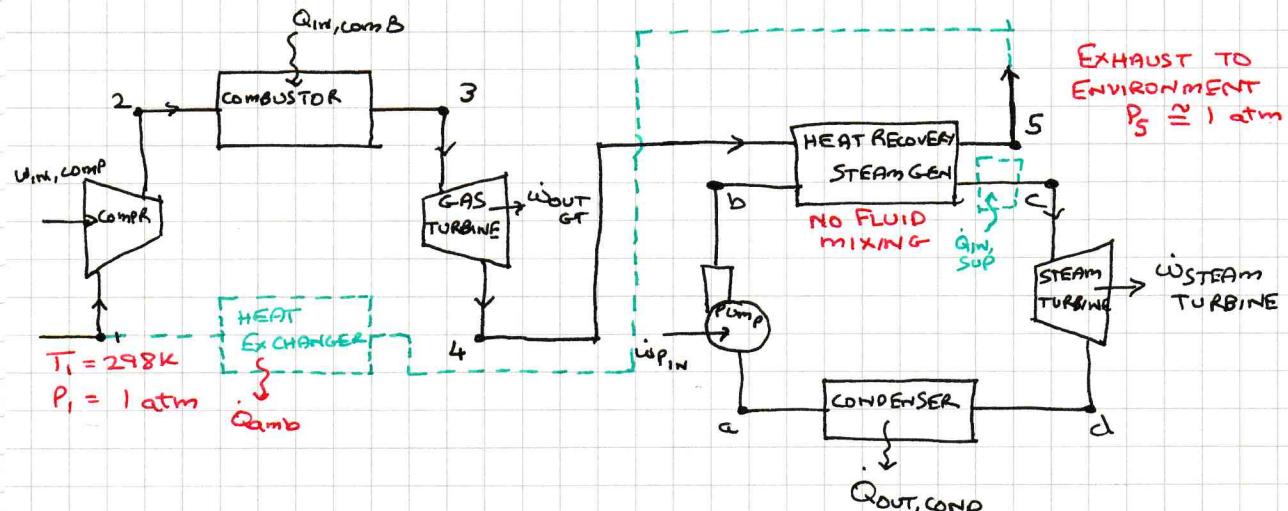
$$\eta_{cycle} = \frac{W_{cycle}}{Q_{in}} = \frac{W_{turb} + W_{comp}}{Q_{in}}$$

### operating Strategies for combined heat and power applications



A & B eliminated  $\rightarrow$  excess heat would just be wasted  
C if generated electricity exceeds  $\rightarrow$  it may be sold off if possible back to the grid.  
D is best choice. Supplement some how.

## 8.02 MORE WASTE HEAT RECOVERY : COMBINED CYCLES



$$\text{COMBINED CYCLE : } \dot{W}_{cycle} = \dot{W}_{in,comp} + \dot{W}_{out,GT} + \dot{W}_{in,pump} + \dot{W}_{out,steam\ turbine} \\ < 0 \quad > 0 \quad < 0 \quad > 0$$

$$\dot{Q}_{cycle} = \dot{Q}_{in,comb} + \dot{Q}_{out,cond} + \dot{Q}_{amb}(5,1) + \dot{Q}_{in,sup} \\ > 0 \quad < 0 \quad < 0 \quad > 0$$