COURSE WORKBOOK: Course learning objectives, notes, and examples

for

ME301
Applications of Thermodynamics

ROSE-HULMAN
INSTITUTE OF TECHNOLOGY

Learning objectives

ME301—APPLICATIONS OF THERMODYNAMICS: Learning objectives

After completing the reading assignments and the associated homework, class exercises, etc., students will be able to

1. Find information about the course via webpage.
2. Use **conservation of mass** and/or **conservation of ener**gy to analyze **open, steady-state systems**.
3. Use **conservation of mass** and/or **conservation of energy** to analyze **closed systems** changing over a **finite time**.
4. Incorporate **property relationships** for **ideal gases with constant specific hea**ts into the above analysis.
5. Find Δu and Δh for **ideal gases when *specific heats are not constant*** ((i.e., ideal gases with **variable specific heats**)
6. Work closed system energy problems incorporating ideal gas properties with variable specific heats
7. Work open system energy problems incorporating ideal gas properties with variable specific heats
8. Find Δs for ideal gases when specific heats are not constant
9. Work closed system entropy problems incorporating ideal gas properties with variable specific heats
10. Work open system entropy problems incorporating ideal gas properties with variable specific heats
11. Use the **generalized compressibility** chart to estimate properties for gases that do not behave as ideal gases
12. Find the **phase** of a substance given to independent intensive properties
    - Use the **saturation tables** to help determine the phase of a substance
    - State when (based on which phases are present) p and T are independent and when they are not
13. Define the terms
    - **Saturated liquid**
    - **Saturated vapor**
    - **Quality**
14. Given two independent intensive properties of a pure substance, find the value of any other intensive property
15. Perform a **linear interpolation** on tabulated data in order to estimate values of properties
16. Sketch a ***T-s*** **diagram** for a real substance, showing compressed liquid, superheated vapor and saturated mixture regions, as well as lines of constant pressure
17. Calculate Q and Q_{dot} for reversible processes using temperature and specific entropy
18. Use **isentropic efficiencies** to calculate power, kinetic energy changes, etc. for various devices
19. Calculate the maximum amount of work (or power) out of a system, or the minimum required work (or power) into a system

20. Calculate the **irreversibility** (or rate of irreversibility) as the lost work (or power) for a system

21. Define the terms **exergy** and **dead state**
22. Explain the interpretation of exergy
23. Calculate the exergy for a system at a known state given the temperature and pressure of the environment
24. Explain the ways in which exergy is transported and destroyed (consumed)
25. Give the interpretation of each term in the **accounting of exergy** equation
26. Calculate **exergy** and exergy changes for closed systems
27. Calculate work and **useful work** for closed systems
28. Calculate lost work (destroyed exergy) for closed systems by using both an **accounting of exergy** approach and an entropy generation approach (I.e., $T_0 S_{gen}$)
29. Calculate exergy inputs and outputs for closed and open systems due to
    - mass flow
    - heat transfer/heat transfer rates
    - work/power
30. Calculate exergy destruction/exergy destruction rates for closed and open systems by using the accounting of exergy equation
31. Create an **exergy balance sheet** to track the flow/destruction of exergy
32. List major sources of exergy destruction
33. Explain the differences between energy based efficiencies and **exergetic efficiencies**
34. Calculate exergetic efficiencies for common devices
35. Derive an expression for an exergetic efficiency for a device based on its functionality
36. Identify the components the comprise a **vapor power cycle** (e.g., a Rankine cycle)
37. Use conservation of energy and appropriate property relations to find the rate of heat transfer and/or the power in or out of each component of the cycle
38. Calculate cycle efficiency
39. Use **isentropic efficiencies** (aka **adiabatic efficiencies**) for cycle components
40. Identity trends in cycle efficiency based on T and P for heat addition and heat rejection steps
41. Explain why increasing boiler pressure and boiler temperature usually result in higher cycle efficiencies for vapor power cycles
42. Use conservation of energy and appropriate property relations to find the rate of heat transfer and/or the power in or out of each component of the cycle that includes
    - one or more **reheaters** and/or
    - a **feedwater heater**
43. Give the steps in an ideal **Brayton Cycle** and draw the corresponding T-s and P-v diagrams.

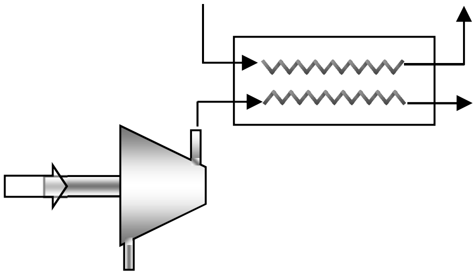
44. Draw the components (pieces of equipment) that are usually assembled to create a Brayton Cycle
45. Used conservation of energy and the appropriate property relations to calculate the heat transfer and work in/out of each step of a Brayton Cycle as well as to calculate the **cycle efficiency**
46. Give the general trends in cycle efficiency associated with changing the **pressure ratio** for a Brayton Cycle.
47. Give two methods by which an ideal **Brayton Cycle**'s efficiency can be increased.
48. Explain the functions of a **reheater**, an **intercooler** and a **regenerator**
49. Used conservation of energy and the appropriate property relations to calculate the rate of heat transfer and/or the power in/out of each step of a Brayton Cycle that includes non-ideal turbines and compressors, reheaters, intercoolers, and regeneration
50. Calculate the cycle efficiency for the above
51. Explain what is meant by **ideal regeneration** and **non-ideal regeneration**
52. State the assumptions used for the **air standard analysis** of a gas power cycle
53. State the assumptions used for the **cold air standard analysis** of a gas power cycle
54. Give the steps in an ideal **Otto Cycle** and draw the corresponding T-s and P-v diagrams
55. Used conservation of energy and the appropriate property relations to calculate the heat transfer and work in/out of each step of an Otto cycle as well as to calculate the **cycle efficiency**
56. Give the general trends in cycle efficiency associated with changing the **compression ratio** in both an Otto Cycle.
57. Given the steps of a generic, **closed-system periodic cycle**, use conservation of energy and the appropriate property relations to calculate the heat transfer and work in/out of each step, as well as to calculate the **cycle efficiency**
58. Identify the components that comprise an ideal **vapor-compression refrigeration cycle**
59. Use conservation of energy and appropriate property relations to find the rate of heat transfer and/or the power in or out of each component of the cycle
60. Calculate the **coefficient of performance** (**COP** or $\boldsymbol{\beta}$) of an ideal vapor-compression refrigeration cycle
61. Incorporate **isentropic efficiencies** (aka **adiabatic efficiencies**) for appropriate cycle components
62. Identity trends in cycle COP based on T and P for heat addition and heat rejection steps
63. Describe the composition of a mixture of gases using both a **mass analysis** and a **mole analysis**
64. Calculate the mass composition of a mixture of gases given the mole composition
65. Calculate the mole composition of a mixture of gases given the mass composition
66. Give the underlying assumptions of the **Dalton model** for gas mixtures

67. Define **partial pressure**
68. Calculate partial pressures of ideal gas mixture components
69. Given the composition of an ideal gas mixture, find average intensive properties such as specific internal energy (u), specific enthalpy (h), specific entropy (s), etc. of the mixture
70. Use the above calculated properties in conservation of energy, accounting of entropy etc.
71. Use conservation of energy, accounting of entropy, and property relations for ideal gases
    - to calculate quantities involved in the mixing of gases in closed systems, and
    - to calculate quantities involved in the mixing of gases in open systems
72. Define the following terms
    - **dew point temperature**
    - **vapor pressure**
    - **total pressure**
    - **relative humidity**
    - **humidity ratio**
    - **moist air**
    - **dry air**
    - **saturated air**
    - **mixture enthalpy**
73. For a given state of **moist air** calculate vapor pressure, dew point temperature, humidity ratio, and mixture enthalpy (per unit mass of dry air)
74. Calculate the amount of condensate for a mixture of moist air cooled below its dew point temperature
75. Define the following terms
    - **Adiabatic saturation temperature**
    - **Wet-bulb temperature**
76. Calculate humidity ratio based on dry bulb temperature, adiabatic saturation temperature, and total pressure.
77. Indicate the relative locations of T_{as}, T_{dew}, and T_{db} on a T-v (or T-s) diagram
78. For a known and constant pressure, calculate any of the following properties based on knowledge of two others: T_{dew}, T_{db}, T_{as}, ω, φ, and h
79. Sketch a **psychrometric chart** showing lines of constant T_{dew}, T_{db} T_{as}, ω, φ, h and v
80. Use a psychrometric chart to aid in the above calculations
81. Perform conservation of mass and energy calculations for various processes involving moist air including
    - **Dehumidification** (with or without reheat)
    - **Humidification**
    - **Evaporative cooling**
    - **Adiabatic mixing**
    - **Analysis of cooling towers**
82. Sketch the above processes on a psychrometric chart

83. Perform conservation of mass and energy calculations for various processes involving moist air including
    - **Dehumidification** (with or without reheat)
    - **Humidification**
    - **Evaporative cooling**
    - **Adiabatic mixing**
    - **Analysis of cooling towers**
84. Sketch the above processes on a psychrometric chart
85. Define the terms
    - **Combustion**
    - **Complete combustion**
    - **Incomplete combustion**
    - **Air-fuel ratio**
    - **Equivalence ratio**
    - **Stoichiometric air**
86. Give mole fractions of N_2 and O_2 for the most common model of dry air in combustion
87. Balance a complete combustion reaction and calculate the above quantities for the given reaction
88. Define **enthalpy of formation**
89. Calculate the rate of heat transfer to or from a steady-state steady flow system in which a combustion reaction is taking place
90. Define **adiabatic flame temperature**
91. Calculate the adiabatic flame temperature for a given combustion reaction
92. Calculate the amount of heat transfer out of a *closed system* undergoing a combustion reaction *at constant volume*
93. Define the terms
    - **enthalpy of reaction**
    - **higher heating value**
    - **lower heating value**
94. Calculate the amount of heat transfer out of a steady flow reaction chamber for a given combustion reaction given one of the above values
95. Find heating values from enthalpies of reaction or *vice versa*

Notes, examples, and activities

EXAMPLE: Open system review problem



0.016 kg/s of R-134a is compressed from 140 kPa and -10°C (h = 260 kJ/kg) to 1 MPa in a steady state compressor. The refrigerant is then passed through a heat exchanger in which it is cooled at constant pressure to 50°C. Water enters the other side of the heat exchanger at 20°C and 100 kPa and leaves at 30°C and 100 kPa. If the required compressor power is 1.2 kW,

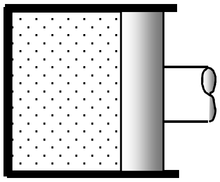
(a) Find the specific enthalpy of the refrigerant leaving the compressor. (Hint, make just the compressor your system.)

(b) Now making the *entire* heat exchanger your system, find the mass flow rate of water required. (For R-134a at 50°C and 1 MPa, h = 280.19 kJ/kg.)

(c) Could you have found the mass flow rate of water in just one step? How might you do it? Do you think I'm going to ask you to do it? Are we playing that game for *Whose Line is it Anyway*?

(d) Why did I give you the specific enthalpies of the R-134a?

EXAMPLE: Closed system review problem

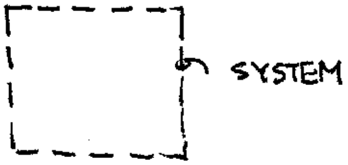


A piston-cylinder contains 1.5 kg of air. Initially, the air is at 150 kPa and 20°C. The air is compressed in an *isobaric process* (and that means...) until the volume is 1 m^3. Assume that air is an **ideal gas with constant specific heats**. If the compression is quasistatic,

(a) find the work into the system, in kJ, and
(b) the heat transfer into the system, in kJ.

DR. THOM'S CRASH COURSE IN *

FOR A GENERAL SYSTEM



Cons. of Mass:

$$\frac{dm_{sys}}{dt} = \sum_{IN} \dot{m} - \sum_{OUT} \dot{m}$$

CLOSED SYSTEM

STEADY-STATE OPEN SYS.

Cons. of Energy:

$$\frac{dE_{sys}}{dt} = \dot{Q}_{IN} + \dot{W}_{IN} + \sum_{IN} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{OUT} \dot{m}\left(h + \frac{V^2}{2} + gz\right)$$

★ NO KE or PE ⇨

CLOSED SYSTEM

STEADY-STATE, OPEN SYS

FINITE TIME

NO KE, PE

* THE COURSE FORMERLY KNOWN AS THERMO I.

PROPERTY STUFF

1. INCOMPRESSIBLE SUBSTANCE W/ CONST. C

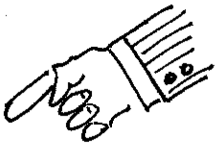
$\rho = \frac{1}{v} = \text{CONST}$

$u_2 - u_1 =$

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

$=$

$s_2 - s_1 =$



2. IDEAL GAS W/ CONST c_v, c_p

- $P\forall = N R_u T$
-
-
-

$R \equiv \frac{R_u}{\quad}$

$u_2 - u_1 =$

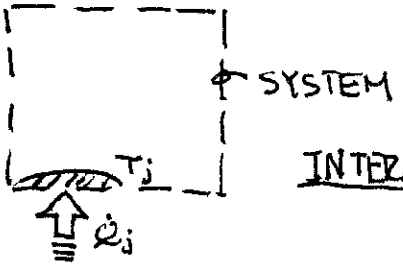
$h_2 - h_1 =$

$s_2 - s_1 =$

$=$

ENTROPY ACCT'ING & 2ND LAW STUFF

FOR A GENERAL SYSTEM:



$$\frac{dS_{SYS}}{dt} = \sum \frac{\dot{Q}_j}{T_j} + \sum_{IN} \dot{m}s - \sum_{OUT} \dot{m}s + \dot{S}_{GEN}$$

INTERALLY REVERSIBLE ⇨

CLOSED SYSTEM ⇩

OPEN, STEADY-STATE ⇩

FINITE TIME ⇩

$\dot{S}_{gen}$

OTHER USEFUL STUFF

- Boundary work for a closed system:

  $W_{1\to2} =$

- Mass flow rate across a surface

  $\dot{m} =$

- "T ds" Equations

  $T\,ds =$

  $T\,ds =$

STATE POSTULATE

The number of independent, intensive properties needed to fix the state* of a substance is equal to the number of quasistatic work modes plus one.

* State: condition of a system described by the value of its properties.

circular definition: see definition, circular

definition, circular: see circular definition

- A ________ ________ HAS ONLY ______ WORK MODE
- A ________ ________ ________ HAS ONLY ________ WORK MODE, AND ITS ________ WORK.

THE STATE POSTULATE FOR A SIMPLE COMPRESSIBLE SYSTEM SAYS THAT YOU NEED...

$\boxed{\qquad\qquad \text{PROPERTIES}}$ (TO FIX THE STATE)

EXAMPLES

$u = u(\qquad)$

$s = s(\qquad)$

$h = h(\qquad)$

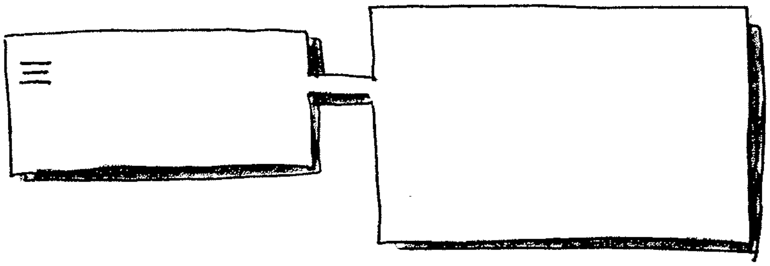
WHY IS THIS ONE SO IMPORTANT?

$p = p(\qquad)$

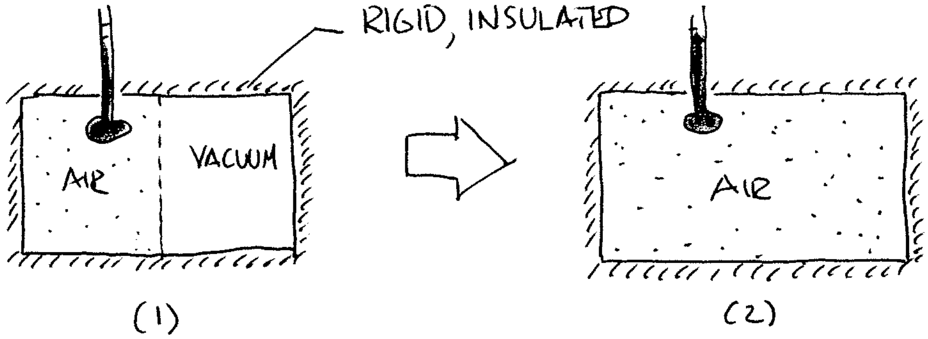
FOR ANYTHING...

$$u = u(v, T)$$

$$du = \underline{\qquad\qquad}\Bigg) \quad + \quad \underbrace{\underline{\qquad\qquad}\Bigg)}$$



JOULE'S EXPERIMENT:



FROM CONS. of ENERGY

$$U_2 = U_1 \quad \& \quad \therefore \quad \underline{\qquad\qquad\qquad}$$

$$du = \frac{\partial u}{\partial v}\Big)_T dv + \frac{\partial u}{\partial T}\Big)_v dT$$

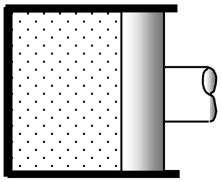
$du =$

$u_2 - u_1 =$

*

* NEVER MIX YOUR IDEAL GAS TABLES!

EXAMPLE: Isobaric process



A piston-cylinder contains 1.5 kg of air. Initially, the air is at 150 kPa and 20°C. The air is compressed in an **isobaric process** (and that means...) until the volume is 1 m^3. Assume that air is an *ideal gas, but do not assume that the specific heats are constant*. If the compression is quasistatic,

(a) find the work into the system, in kJ, and
(b) the heat transfer into the system, in kJ.

$$h = h(\quad , \quad)$$

$$dh = \frac{\quad}{\quad}\Big) + \underbrace{\frac{\quad}{\quad}\Big)}$$

≡

RECALL THE DEF'N of h:

$h \equiv$

AND SO FOR AN IDEAL GAS $h =$ *

$dh =$

$dh =$

$h_2 - h_1 =$

IFF c_v = CONST AND c_p = CONST

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

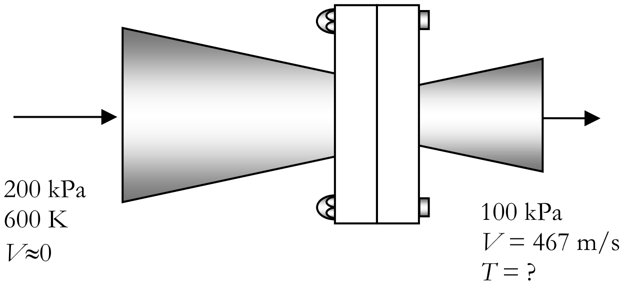
$$h_2 - h_1 = c_p(T_2 - T_1)$$

---

* CAN YOU SHOW THAT $R = c_p - c_v$?

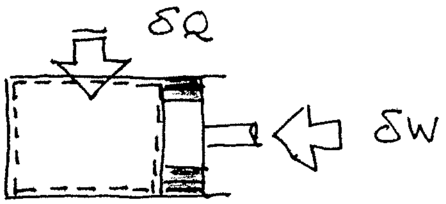
EXAMPLE: Supersonic nozzle

Air flows steadily through a supersonic nozzle. The entering air has negligible velocity. If the exiting air has a velocity of 467 m/s, find the exit temperature. Assume air is an ideal gas with variable specific heats.



CONSIDER A CLOSED SYSTEM UNDERGOING A

______________ PROCESS OVER TIME _____ .



$\delta W =$

CONSERVATION of ENERGY

$$\frac{d}{dt}(E)_{sys} = \dot{Q} + \dot{W} + \underset{\text{CLOSED}}{\angle_0} - \angle_0$$

$$d \quad = \qquad \underbrace{\qquad\qquad} \qquad \text{(NO KE OR PE)}$$

$$d \quad = \qquad\qquad\qquad (1)$$

ACCOUNTING of ENTROPY

$$\frac{d}{dt}(S)_{sys} = \Sigma \frac{\dot{Q}}{T_b} + \angle_0 - \angle_0 + \dot{S}_{GEN}$$

$$dS =$$

$$\therefore \delta Q = \qquad\qquad =$$

SUBSTITUTING INTO (1)

SOLVE FOR Tds

$$\boxed{Tds = \qquad\qquad\qquad}$$

THE 1ST Tds RELATION

FROM DEF'N of h

$$h \equiv u + pv \quad \therefore \quad dh =$$

SOLVING FOR du

$$du =$$

SUB INTO 1ST Tds RELATION

$$T\,ds = \qquad\qquad\qquad\qquad + P\,dv$$

$$\boxed{T\,ds = \qquad\qquad\qquad\qquad}$$ SECOND Tds RELATION

TRUE! BUT THESE EQN'S ARE GOOD *for any substance and any process!*

NOW FOR AN IDEAL GAS

$$ds = \frac{dh}{T} - \underbrace{\frac{v}{T}\,dP}_{}$$

$$= \qquad\qquad -$$

$$s_2 - s_1 = \qquad \underbrace{\qquad\qquad}_{}$$

$$|||$$

$$\boxed{s_2 - s_1 = \overbrace{\qquad\qquad\qquad\qquad}^{}\qquad\qquad\qquad\qquad}$$

IF YOU USE 1ST T-ds RELATION

$$s_2 - s_1 = \underbrace{\int_{T_1}^{T_2} c_v \frac{dT}{T}}_{} + R \ln\left(\frac{v_2}{v_1}\right)$$

IFF $C_v = \text{CONST}$ &
$c_p = \text{CONST}$

$$s_2 - s_1 = c_p \ln(T_2/T_1) - R \ln P_2/P_1$$
$$= c_v \ln(T_2/T_1) + R \ln(v_2/v_1)$$

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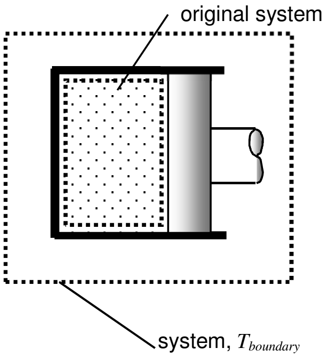
*GET IT? *Tedious?* HA!

EXAMPLE: And now, entropy!

Reconsider the piston-cylinder from the last example. The device contains 1.5 kg of air. Initially, the air is at 150 kPa and 20°C. The air is compressed in an *isobaric process* until the volume is 1 m^3. Assuming the compression to be quasistatic, you already found

(a) the work into the system, in kJ, and
(b) the heat transfer into the system, in kJ.

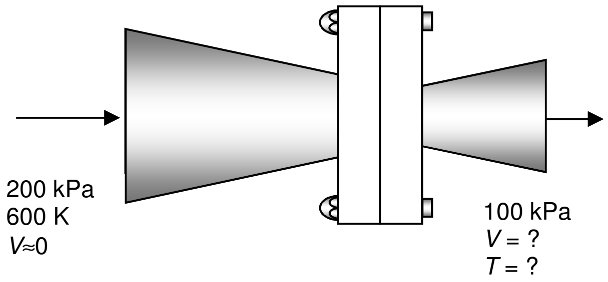


Now for something new!

(c) Find the entropy generation for the following systems:
  (1) the system shown for $T_{boundary}$ = 400 K
  (2) the system shown for $T_{boundary}$ = 300 K, and
  (3) your original system.

EXAMPLE: What's *isentropic efficiency*, I wonder?

Air flows steadily through a supersonic nozzle. The entering air has negligible velocity. If the process is **reversible and adiabatic,** (Everybody sing! That means it's also _______________!)



(a) find the exit air temperature, and
(b) the exit velocity.
(c) What do you think the **isentropic efficiency** of this nozzle is?[1]

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[1] 4

IDEALLY GASES ARE IDEAL. *What if they aren't?*

INTRODUCING . . .

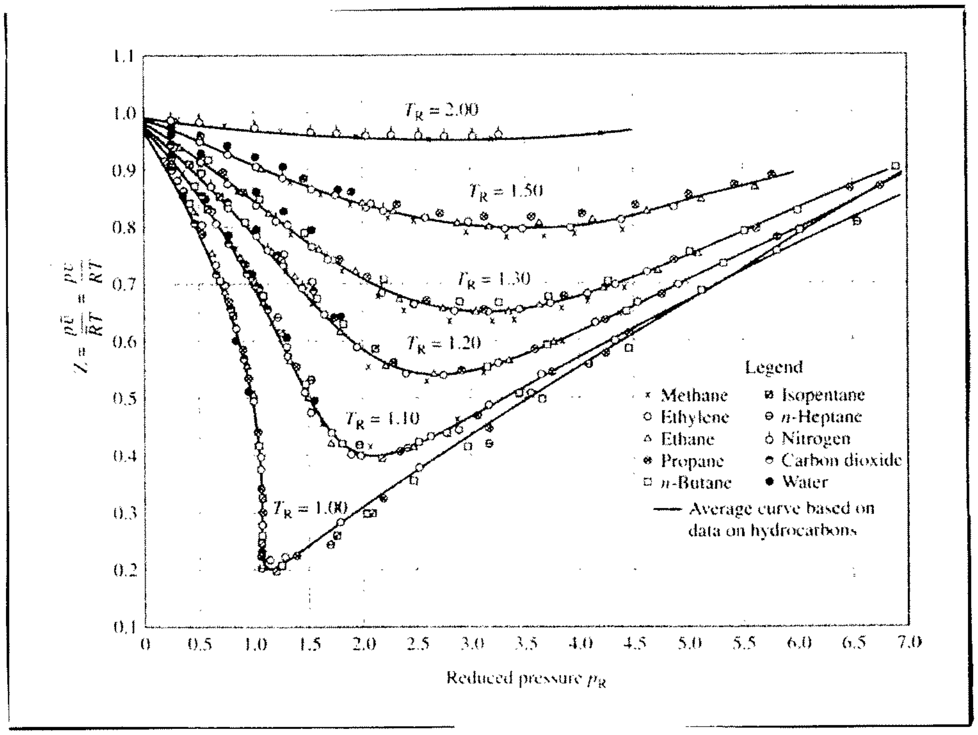
THE COMPRESSIBILITY FACTOR

$\boxed{Z \equiv \underline{\hspace{3cm}}}$

FOR AN IDEAL GAS ________

DATA FOR NON-IDEAL BEHAVIOR WELL-CORRELATED ON

Generalized Compressibility Chart



WHERE $P_R \equiv \underline{\hspace{2cm}}$ ⇦ ________ PRESSURE*

$T_R \equiv \underline{\hspace{2cm}}$ ⇦ ________ TEMPERATURE*

"REDUCED" P & T

---

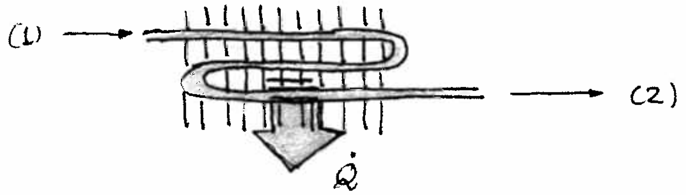
*MORE TO COME

EXAMPLE: Compressibility factor

3.40 kg of nitrogen is in a steel vessel with a volume of 0.0150 m^3. If the temperature is 400°C, find the pressure

(a) assuming ideal gas behavior, and
(b) using the generalized compressibility charts.

example *Condenser*



Given:
- $\dot{m}_{ref}$
- Steady-state
- T_1, P_1 vapor phase
- T_2, P_2 Liquid phase

Find: $\dot{Q}$ FROM REFRIGERANT TO SURROUNDING AIR

Analysis:

PROPERTIES

CHARACTERISTICS of A SYSTEM

- INDEPENDENT of ______________
- ______________ FUNCTION *NOT* A ______________ FUNCTION

★ RECALL STATE POSTULATE FOR A SIMPLE COMPRESSIBLE SUBSTANCE

> ____ ______________ PROPERTIES NEEDED TO FIX THE STATE.

FUN WITH THE P-v-T SURFACE

FIND THESE *SINGLE PHASE* REGIONS

SOLID
LIQUID
VAPOR

FIND THESE *TWO-PHASE* REGIONS

	PROCESS →	PROCESS ←
LIQUID - VAPOR		
LIQUID - SOLID		
SOLID - VAPOR		

FIND THESE THINGS

CRITICAL POINT:

TRIPLE LINE:

HINT: FOLLOW THE CONSTANT PRESSURE LINE & RELY ON EXPERIENCE.

THE P-T DIAGRAM

DRAW THE *PROJECTION* OF THE P-v-T SURFACE IN THE P-T PLANE

- *WHAT HAPPENED TO THE TWO-PHASE REGIONS?*
- *WHAT DOES THIS MEAN ABOUT P & T DURING PHASE CHANGE?*

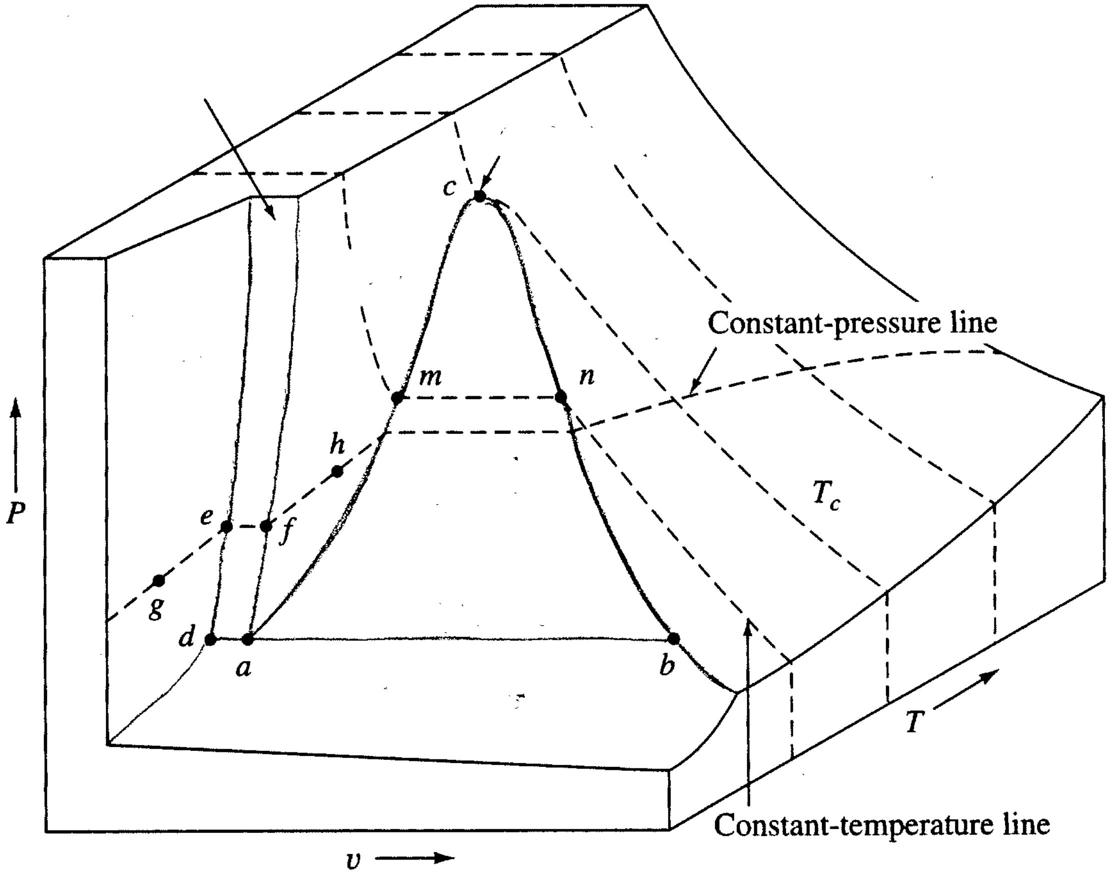
P-v DIAGRAM

DRAW THE *PROJECTION* OF THE P-v-T SURFACE IN THE P-v PLANE. INCLUDE THE CRITICAL POINT & LINES of CONSTANT TEMPERTURE

T-v DIAGRAM

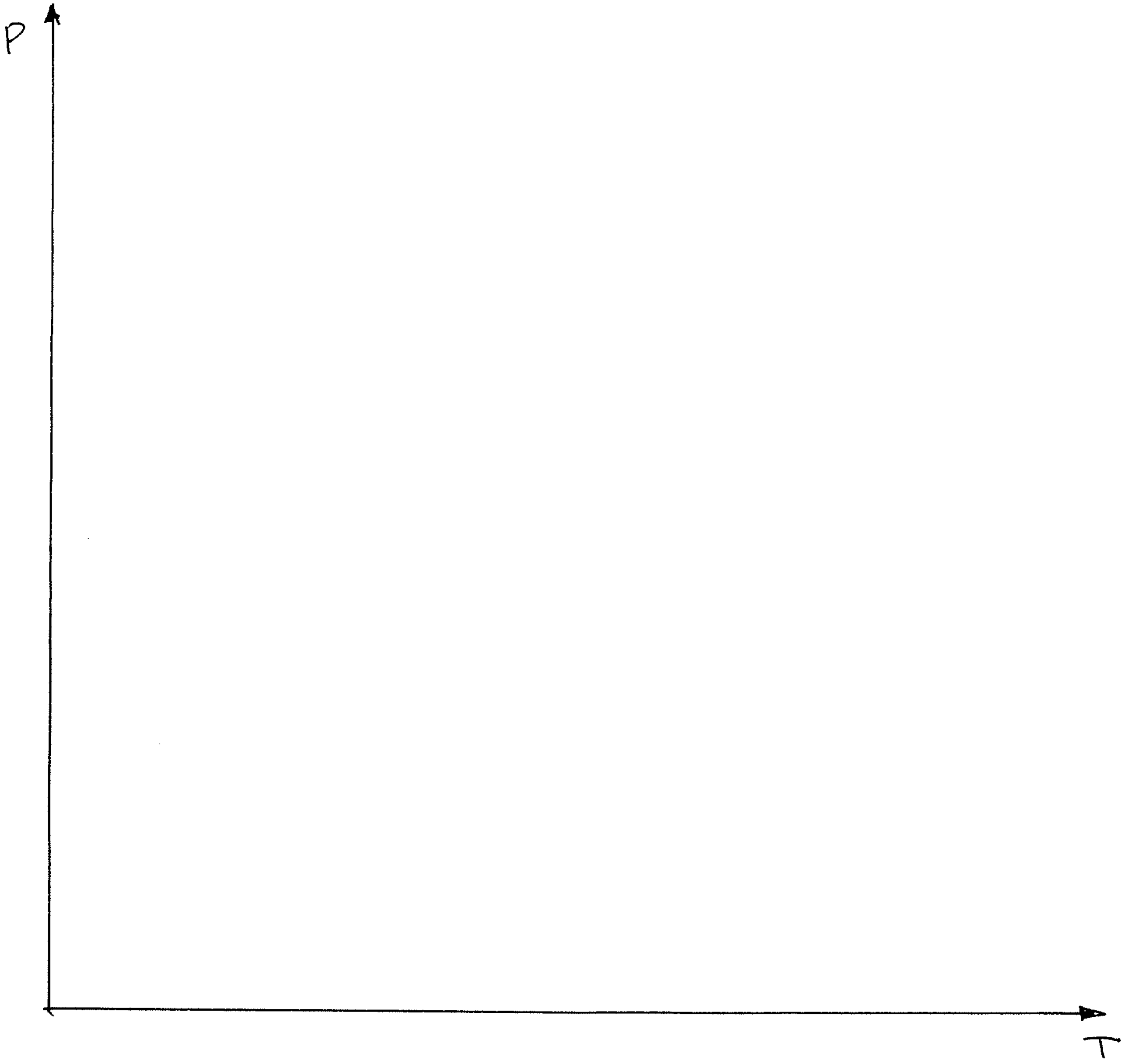
DRAW THE *PROJECTION* OF THE P-v-T SURFACE IN THE T-v PLANE. INCLUDE THE CRITICAL POINT & LINES of CONSTANT PRESSURE.

THE P-υ-T SURFACE



The *PvT* surface for a substance which contracts on freezing (not to scale).

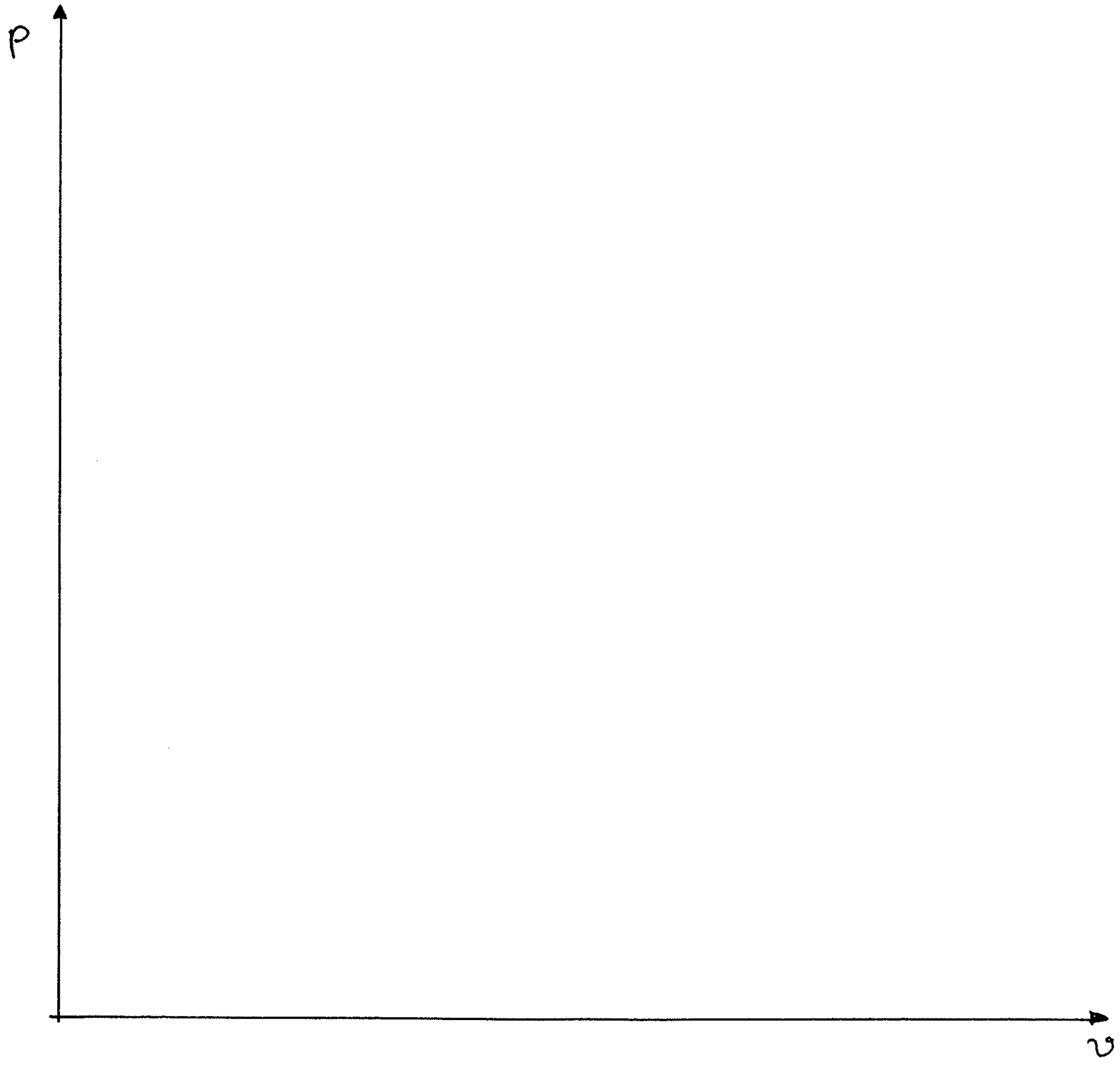
P-T DIAGRAM



INCLUDE

- CRITICAL POINT
- TRIPLE LINE
- ¿ WHAT HAPPENED TO THE TWO-PHASE REGIONS ?

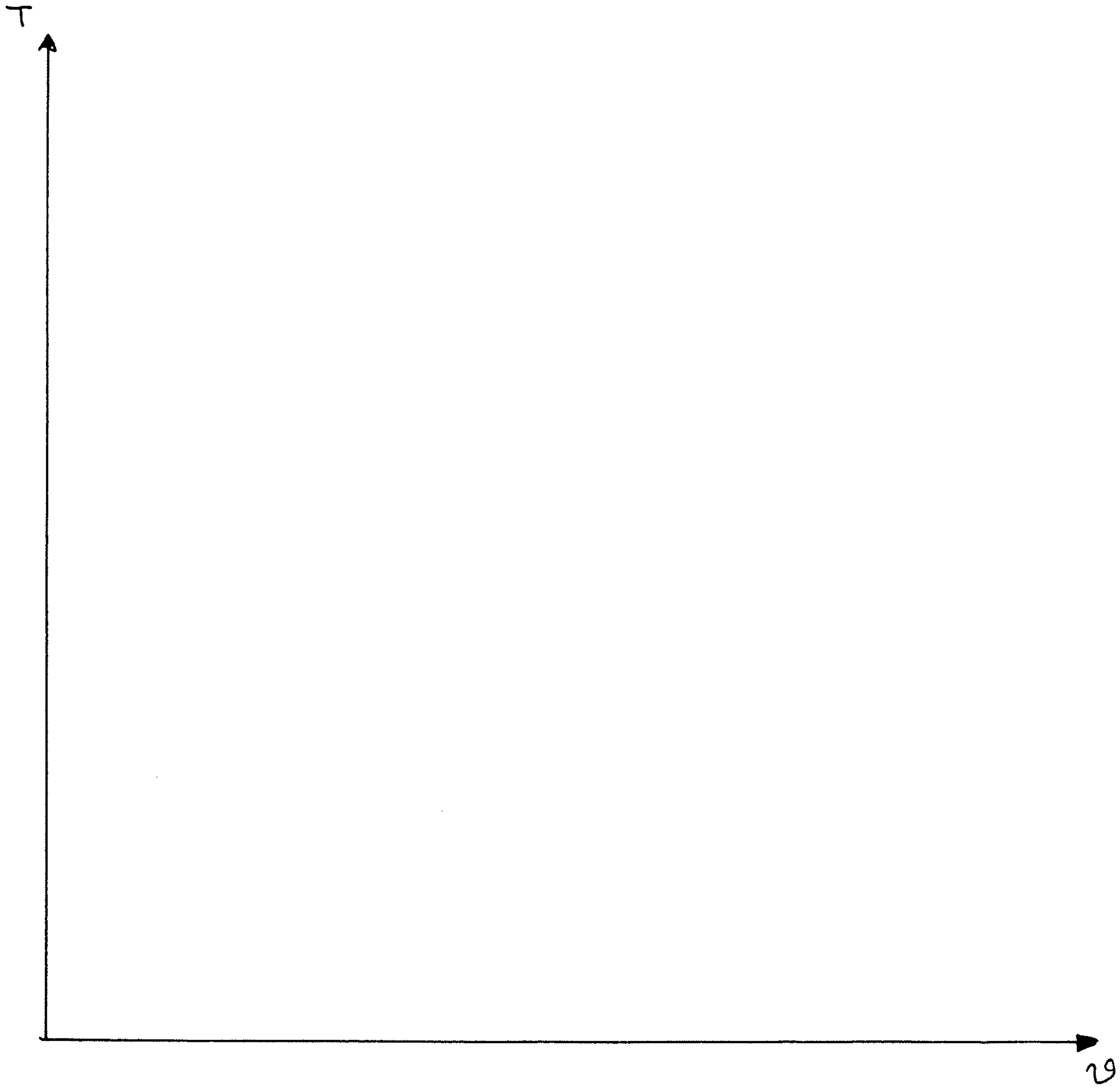
P-v DIAGRAM



<u>INCLUDE</u>

- CRITICAL POINT
- LINES of CONSTANT TEMPERATURE
- LABEL PHASES

T-v DIAGRAM



INCLUDE:

- CRITICAL POINT
- LINE(S) of CONSTANT PRESSURE
- LABEL PHASES

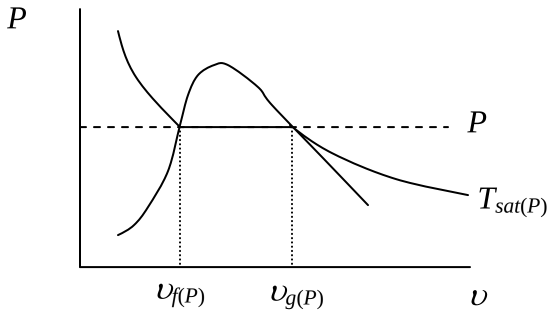
Case II: Given P (or T) and υ (or u, h, s or x)

(1) Determine the phase of the substance (and hence what set of tables you should consult).

(1a) Go to one of the liquid-vapor Saturation Tables.

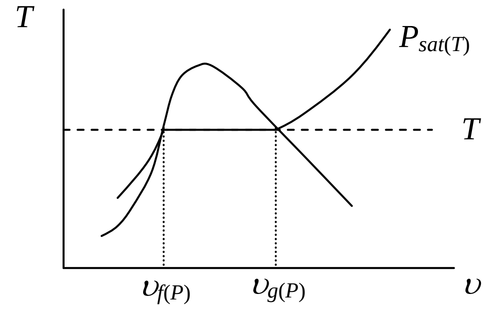
(1b) Find the saturated liquid and saturated vapor values for the specific volume : $\upsilon_{f\,(P)}$ and $\upsilon_{g\,(P)}$.

Note: If you are given quality x then you immediately know that it is either a saturated liquid, a saturated liquid-vapor mixture, or a saturated vapor and you can go directly to step (2).



(1c) Compare the given value of υ against the saturation values to find the phase (and the appropriate table):

$\upsilon < \upsilon_{f\,(P)}$	*compressed (subcooled) liquid*
$\upsilon = \upsilon_{f\,(P)}$	*saturated liquid*
$\upsilon_{f(P)} < \upsilon < \upsilon_{g(P)}$	*saturated liquid-vapor mixture*
$\upsilon = \upsilon_{g\,(P)}$	*saturated vapor*
$\upsilon > \upsilon_{g\,(P)}$	*superheated vapor*



(2) Go to the appropriate table and enter the table using the values of *P* and *υ*. Linear interpolation may be required if values do not match table entries.

Compressed Liquid: $\upsilon < \upsilon_{f\,(P)}$ [Quality is undefined.]

- If compressed-liquid approximation is used, let $\upsilon_{f\,(T)} = \upsilon$ to find temperature. Then use approximation to find other properties. (Since $\upsilon_{f(T)}$ is a *very* weak function of temperature, this approach is very inaccurate. Much more accurate to look for another property like s or u which is a strong function of temperature.)

Saturated Liquid: $\upsilon = \upsilon_{f\,(P)}$ [Quality: $x = 0$ or 0%]

- All properties equal to those for a saturated liquid.

Saturated Liquid-Vapor Mixture: $\upsilon_{f(P)} < \upsilon < \upsilon_{g\,(P)}$ [Quality: $0 < x < 1$ or $0\% < x < 100\%$]

- $T = T_{sat(P)}$, the saturation temperature at pressure P
- Calculate quality before finding any other properties: $x = (\upsilon - \upsilon_f) / (\upsilon_g - \upsilon_f)$
- Then use quality to find other intensive properties, e.g. $u = u_f + x\,(u_g - u_f)$

Saturated Vapor: $\upsilon = \upsilon_{g\,(P)}$ [Quality: $x = 1$ or 100%]

- All properties equal to those for a saturated vapor.

Superheated Vapor: $\upsilon > \upsilon_{g\,(P)}$ [Quality is undefined.]

- Enter the superheated vapor table with P and υ. Because υ often falls between the tabular values, it is often required to linearly interpolate to find the correct temperature which can then be used to find the other values. Sometimes it is necessary to do a *double linear interpolation*.

Note: If you are given temperature instead of pressure use the same process as above starting with temperature saturation table.

Finding Thermodynamic Properties for a Pure, Simple Compressible Substance — *A Simple Algorithm* for Liquid-Vapor Systems

Case I: Given P and T

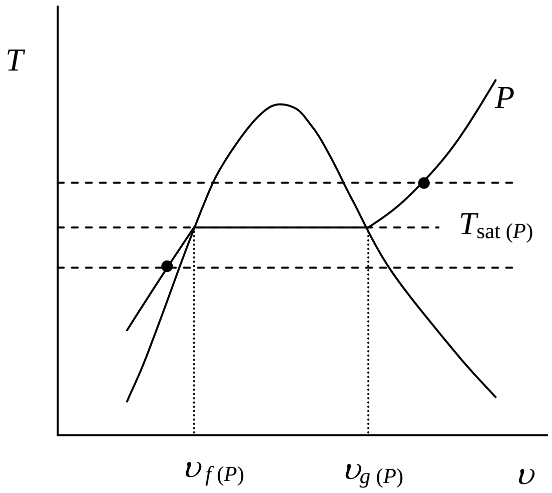
(1) Determine the phase of the substance (and hence what set of tables you should consult).

(1a) Go to one of the liquid-vapor Saturation Tables.

(1b) Compare the given P and T against the saturation values reported in the table.

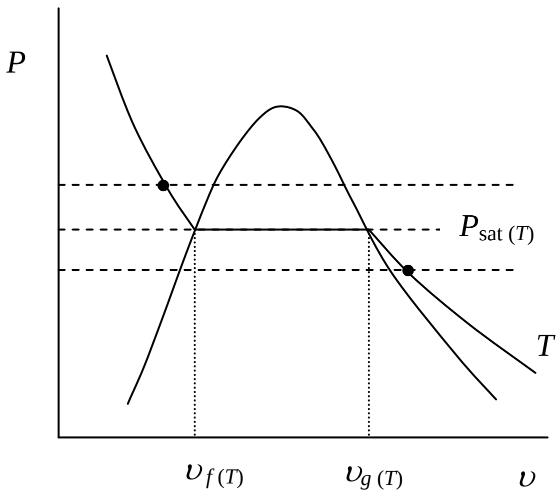
In the Pressure Saturation Table, find the saturation temperature at the given pressure, $T_{\text{sat}(P)}$.

if $T > T_{\text{sat}(P)}$ then *superheated vapor*
if $T < T_{\text{sat}(P)}$ the *compressed (subcooled) liquid*



In the Temperature Saturation Table, find the saturation pressure at the give temperature, $P_{\text{sat}(T)}$.

if $P > P_{\text{sat}(T)}$ then *compressed (subcooled) liquid*
if $P < P_{\text{sat}(T)}$ then *superheated vapor*



(2) Go to the appropriate single-phase table and enter the table using *P* and *T*. If the values of P and T do not coincide with the given values (as usually happens in *real* applications) you must *linearly interpolate* within the table to find the desired values.

Note: Compressed Liquid Approximation. If you find the substance is a *compressed (subcooled) liquid* and you do not have a compressed-liquid table or the pressure is between the saturation value and the lowest value in the compressed-liquid table, you may find it easier (and almost as accurate) to apply the **compressed-liquid approximation** to estimate the values in the compressed-liquid table using the saturation-table values as follows:

$$u_{(T,P)} \cong u_{f(T)} \quad \text{[specific internal energy]}$$

$$\upsilon_{(T,P)} \cong \upsilon_{f(T)} \quad \text{[specific volume]}$$

$$s_{(T,P)} \cong s_{f(T)} \quad \text{[specific entropy]}$$

$$h_{(T,P)} \equiv u + P\upsilon \cong u_{f(T)} + P\,\upsilon_{f(T)} = h_{f(T)} + \{P - P_{\text{sat}(T)}\}\,\upsilon_{f(T)} \quad \text{[specific enthalpy]}$$

Because $h_{(T,P)} = h_{f(T)}$ is only true if $P \cong P_{\text{sat}}$ *and* the error in using this approximation under conditions where $P \neq P_{\text{sat}}$ depends on the specific problem, *it is always more accurate to use the full approximation that includes the pressure correction!*

EXAMPLE: Property Table Practice

Given: water, $P = 10$ MPa, $T = 350°C$
Find: v (spec. vol.)

Given: water, $P = 10$ MPa, $T = 360°C$
Find: v (spec. vol.)

Given: water, $T = 360°C$, $v = 0.003\ m^3/kg$
Find: P, h

Given: water, T = 20°C, P = 10 MPa
Find: s (spec. entropy)

Given: water, T = 20°C, P = 4 kPa
Find: s (spec. entropy)

EXAMPLES: Property Table Practice

Exercise 1—Interpolation:

We have already seen that it is sometimes necessary to linearly interpolate to find values of properties in property tables. In some cases linear interpolation is even more involved, as in the case of finding properties for a superheated vapor in which neither the temperature nor pressure of interest appear as a table entry. As an example, consider the following:

Given: water, $P = 2.0$ bar, $T = 215°\text{C}$
Find: v (spec. vol.)

Here we must perform a **bi-linear interpolation**. This proceeds as follows.

Step 1

Linearly interpolate to find v at $P = 1.5$ bar and $T = 215°\text{C}$. (Ans. 1.491 m^3/kg)

Step 2

Linearly interpolate to find v at $P = 3.0$ bar and $T = 215°\text{C}$. (Ans. 0.740 m^3/kg)

Step 3

Using the results from steps 1 and 2, linearly interpolate to find v at $P = 2.0$ bar and $T = 215°\text{C}$. (Ans. 1.241 m^3/kg)

Exercise 2—Table lookup practice:

Provide the information requested in the table for *water*. Use the following abbreviations where needed:

- CL – compressed (subcooled) liquid
- SL – saturated liquid
- SM – saturated mixture
- SV – saturated vapor
- SHV – superheated vapor
- NA – not applicable
- INSUF – insufficient information given

State	Phase	Pressure, P [MPa]	Temperature, T [°C]	Specific volume, v [m^3/kg]	Specific enthalpy, h [kJ/kg]	Quality, x
1	SV		250			
2			250			0.70
3		3.0	250			
4		3.0		0.02500		
5		3.0	100			
6		3.0			3145.1	

HOMEWORK: Property Table Practice

Student : ____________________

Exercise 3—Table lookup practice:

Exercise 3 is the only deliverable part of this exercise that is to be turned in as homework.

Provide the information requested in the table for *refrigerant R134a*. Use the following abbreviations where needed:

- CL – compressed (subcooled) liquid
- SL – saturated liquid
- SM – saturated mixture
- SV – saturated vapor
- SHV – superheated vapor
- NA – not applicable
- INSUF – insufficient information given

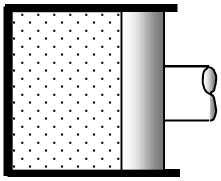
State	Phase	Pressure, *P* [kPa]	Temperature, *T* [°C]	Specific volume, *v* [m^3/kg]	Specific internal energy, *u* [kJ/kg]	Specific enthalpy, *h* [kJ/kg]	Specific entropy, *s* [kJ/(kg-K]	Quality, *x*
1		240	-12		▨	▨		
2		240			▨	266.85	▨	
3	SL	240		▨		▨		
4		240		▨		150	▨	
5	SV	240			▨		▨	▨
6			30		▨		▨	0.4
7			30	0.0188	▨	▨		
8			30	▨	90.84	▨		
9	SV		30					
10		1400	30	▨			▨	

CM ________

EXAMPLE: Piston-cylinder with water

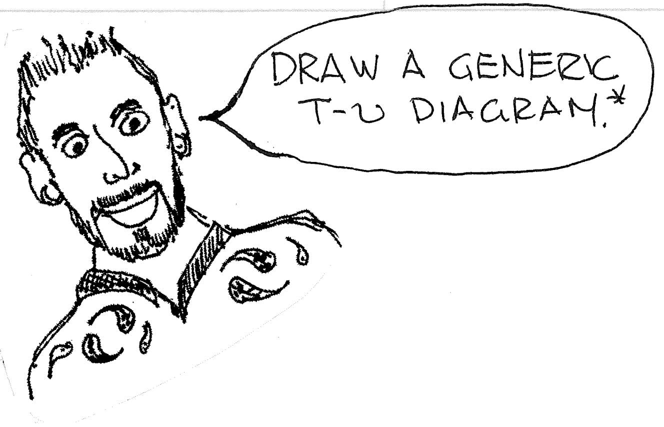
A closed system contains 0.15 kg of water. Initially the water is a saturated vapor at 205°C. The water is cooled at constant volume until the temperature is 150°C and is then compressed at constant temperature until the volume is half the original value.

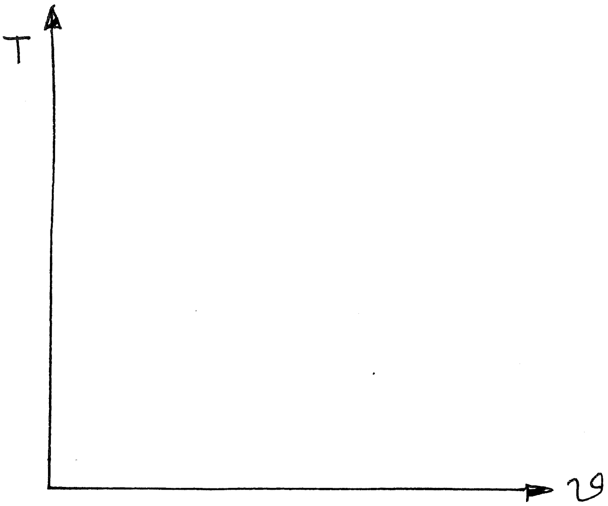
(a) Sketch the *P-v* diagram for this two-step process.
(b) Find the work in or out of the steam *for each step*.
(c) Find the heat transfer in or out of the steam *for each step*.



EXAMPLE: Mixing chamber

A steady-state mixing chamber operates at a constant pressure of 800 kPa. 4.52 kg/s of compressed liquid water enters at a temperature of 35°C, while 1 kg/s of superheated steam enters at an unknown temperature. Water leaves the device as a saturated liquid. Assuming that the process is adiabatic, determine the temperature of the superheated steam.





- NOW REPLACE ______ WITH ______.

¡ALL THE TRENDS ARE THE SAME!

¿*But why do we care?*

ENTROPY ACCOUNTING →

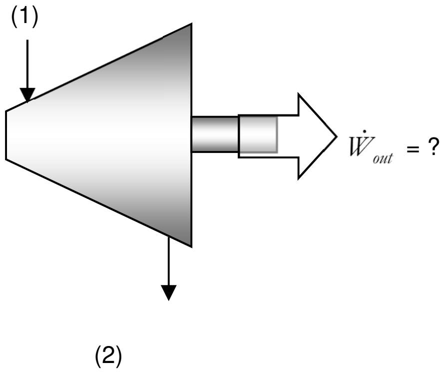
$$\frac{d}{dt}(S_{sys}) = \sum \frac{\dot{Q}_{in}}{T_b} + \sum_{in} \dot{m}s - \sum \dot{m}_{out}s + \dot{S}_{gen}$$

CLOSED SYS., FINITE TIME	OPEN, S-S SYS, 1 INLET & 1 EXIT
+ **INTERNALLY REVERSIBLE**	+ **INTERNALLY REVERSIBLE**
PICK SYSTEM SO THAT $T_b = T_{sys}$	PICK SYSTEM SO THAT $T_b = T_{sys}$

* BE SURE TO LABEL THE PHASES & SHOW LINES of CONST. P.

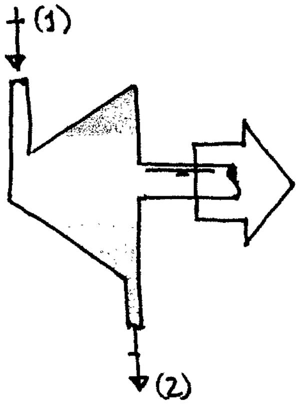
EXAMPLE: Steam turbine

1.25 kg/s of steam flows through a steady state turbine. The steam enters at 1 MPa and 300°C, and leaves at 100 kPa. If the process is adiabatic and reversible, find the power delivered by the turbine in kW.



LET'S RE-EXAMINE THE TURBINE IN THE LAST EXAMPLE.

CoE w/
•
•

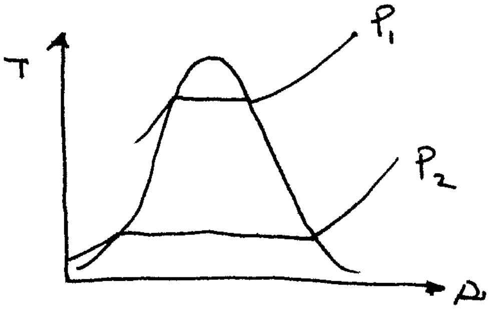


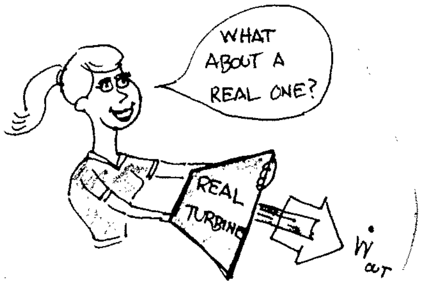
$\dot{W}_{OUT} = \dot{m}(h_1 - h_2)$

SINCE *adiabatic, reversible* ⇒ ________

BEST CASE

____





WRITE S-Acct'ing FOR A *REAL* (i.e., ADIABATIC BUT IRREVERSIBLE) TURBINE

$$\frac{dS_{sys}}{dt} = \sum \frac{\dot{Q}}{T_b} + \sum_{IN} \dot{m}s - \sum_{OUT} \dot{m}s + \dot{S}_{GEN}$$

$s_{2,ACTUAL} =$

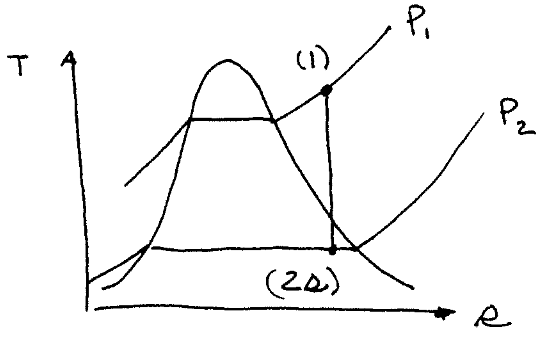
$>, <, = s_{2,IDEAL}$

∴ $h_{2,ACTUAL} = h(P_2, s_{2,ACTUAL} \quad s_{2,IDEAL})$

$>, <, = h_{2,IDEAL}$

∴ $\dot{W}_{OUT,ACT} = \dot{m}(h_1 - h_{2,ACTUAL})$

$>, <, = \dot{W}_{OUT,IDEAL}$



ACTUAL TURBINE

(2s) SIGNIFIES ______________ (IDEAL) TURBINE

(2) " ______________ "

------ WHY THE DASHED LINE FOR THE ACTUAL TURBINE?

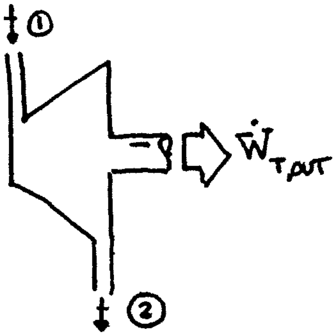
ANS:

LET US DEFINE, THEN

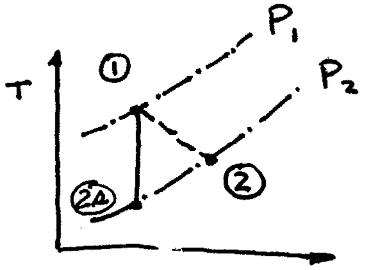
$\eta_T \equiv$ ______________

ISENTROPIC (A.K.A ADIABATIC) EFFICIENCIES

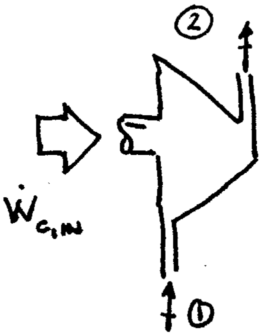
TURBINE



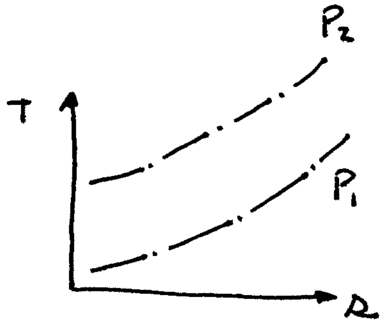
$$\eta_T \equiv \frac{\dot W_{out}}{\dot W_{out,s}} = \frac{\dot m (h_1 - h_2)}{\dot m (h_1 - h_{2s})}$$



COMPRESSOR

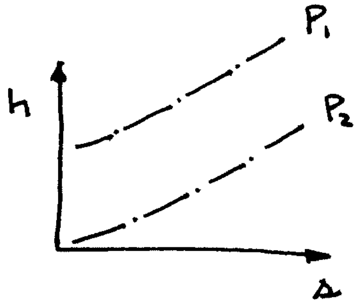


$$\eta_C \equiv \frac{\dot W}{\dot W} = \underline{\hspace{4cm}}$$

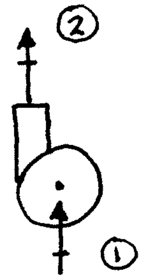


NOZZLE

$$\eta_N \equiv \frac{\Delta KE}{\Delta KE_s} = \underline{\hspace{4cm}}$$



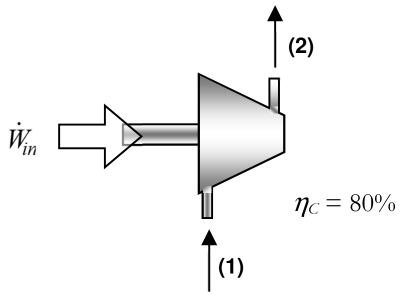
PUMP



$$\eta_P \equiv \underline{\hspace{3cm}} = \underline{\hspace{4cm}}$$

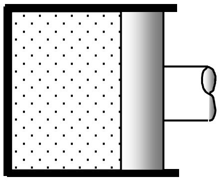
EXAMPLE: Isentropic efficiency (AKA adiabatic efficiency)

1 kg/s of steam flows through a steady-state compressor. The steam enters the compressor at 100 kPa as a saturated vapor. The exit pressure is 1.0 MPa. If the **adiabatic efficiency** (ding ding ding!) is 80%,



(a) find the power *input* to the compressor (in kW) and
(b) the temperature of the steam leaving the compressor.
(c) Sketch the process on a *T*-*s* diagram. Label the ideal and actual exit state points.

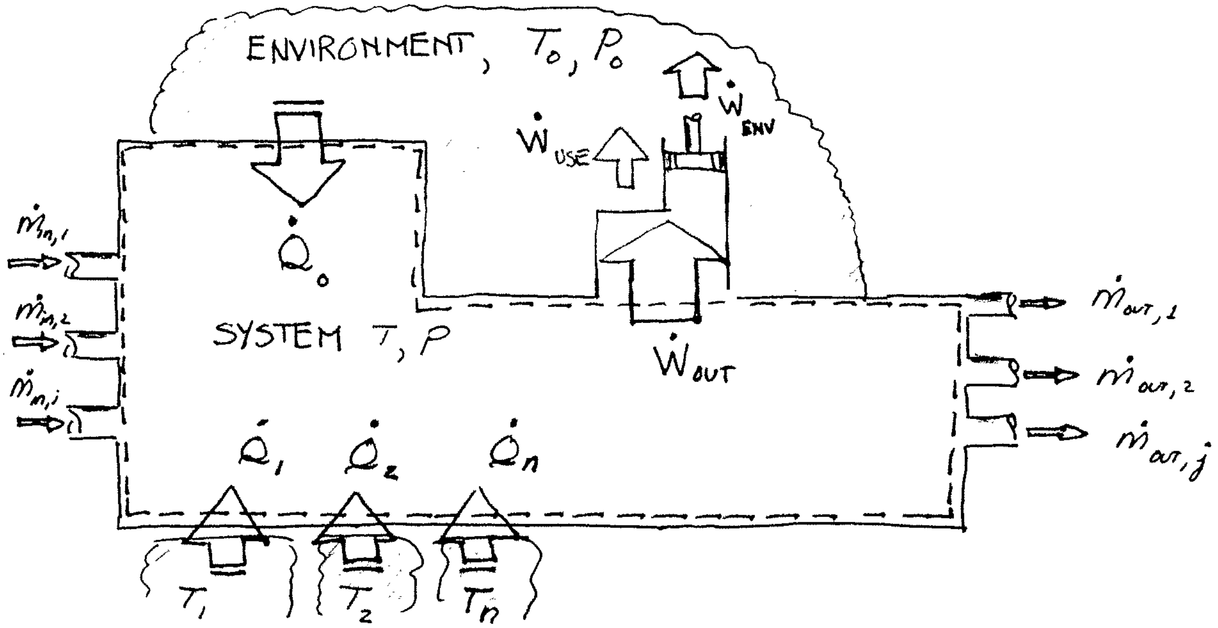
EXAMPLE: Isothermal piston-cylinder



A piston-cylinder device contains 1 kg of water. Initially, the water is at 200°C and 1000 kPa. The water is compressed in a **reversible isothermal** process until the water is a saturated liquid.

(a) Sketch the process on *P-v* and *T-s* diagrams.
(b) Find the heat transfer for the process, in kJ.
(c) Find the work for the process, in kJ.

CONSIDER A GENERAL SYSTEM EXCHANGING HEAT & POWER W/ THE ENVIRONMENT AS WELL AS HEAT TRANSFER W/ n RESERVOIRS.



THE BIG QUESTION

¿ HOW BIG CAN WE GET $\dot{W}_{OUT}$ TO BE KEEPING THE HEAT TRANSFER TO/FROM RESERVOIRS THE SAME AS THE SYSTEM GOES THROUGH THE SAME STATE POINTS?

Cons. of Energy →

Acct. of Entropy →

SOLVE ACCT. of ENTROPY FOR $\dot{Q}_0$ & SUB INTO ENERGY:

$$\dot{Q}_0 =$$

ENERGY BECOMES

SOLVE FOR $\dot{W}_{out}$

$$\dot{W}_{out} = -\frac{d}{dt}\left(E_{sys} - T_0 S_{sys}\right) + \sum_{i=1}^{n}\left(1 - \frac{T_0}{T_i}\right)\dot{Q}_i + \sum_{in}\dot{m}\left(h + \frac{V^2}{2} + gz - T_0 s\right)$$

$$- \sum_{out}\dot{m}\left(h + \frac{V^2}{2} + gz - T_0 s\right) - \underbrace{\qquad\qquad}$$

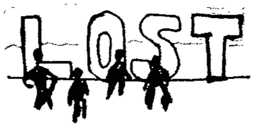
≡ (rate of)

$\dot{W}_{out,MAX}$ OCCURS WHEN

$$\therefore \quad \dot{W}_{out,MAX} = \dot{W}_{out,}$$

AND

$$\boxed{\dot{W}_{out} = \dot{W}_{out,} \quad -}$$

RATE of IRREVERSIBILITY = 

____

EXAMPLE: Isentropic efficiency of a turbine

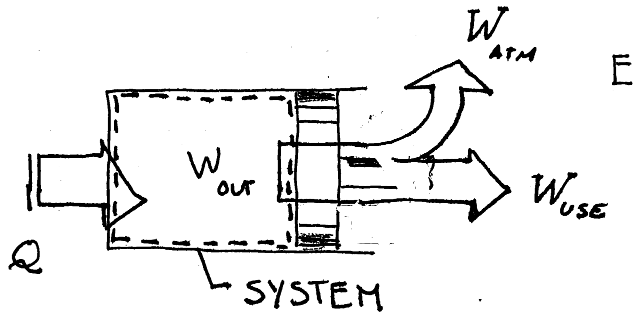
A turbine with an adiabatic efficiency of $\eta_T = 0.9$ operates between 8 MPa and 100 kPa with an inlet temperature of 700°C. The mass flow rate of steam through the turbine is 1.25 kg/s and the environment is at $T_0 = 300$ K and $P_0 = 100$ kPa.

a) Sketch the process on a T-s diagram.
b) Calculate:
    1) the power out of the turbine,
    2) the rate of irreversibility in the turbine, and
    3) the lost power from the turbine.
c) Calculate the quantity

$$\varepsilon = \frac{\dot{W}_{out}}{\dot{W}_{out} + \dot{W}_{lost}}$$

How does this compare to η_T? Explain.

WHAT IS THE MAXIMUM AMOUNT of *USEFUL* WORK OUT of A CLOSED SYSTEM AS IT GOES TO EQUILIBRIUM W/ THE ENVIRONMENT, EXCHANGING HEAT ONLY WITH THE ENVIRONMENT?



ENVIRONMENT T_o, P_o

STATE (1) T_1, P_1

STATE (2) $T_2 = T_o$
$P_2 = P_o$

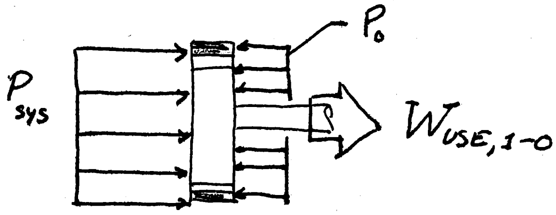
FROM LAST TIME:

$\dot{W}_{OUT} =$

NEED FINITE TIME

$W_{1\to 0} =$

NOT ALL WORK IS USEFUL. SOME IS WORK DONE THE ATMOSPHERE:



$W_{ATM} = \int$

$\therefore \; W_{ATM} =$

SO

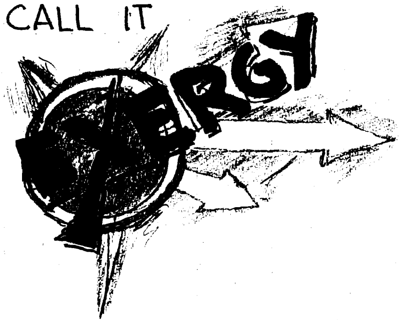
$W_{1-0,MAX} =$

$=$


HOLY MACARONI

Holy Macaroni! THAT'S A ______________!

LET'S CALL IT

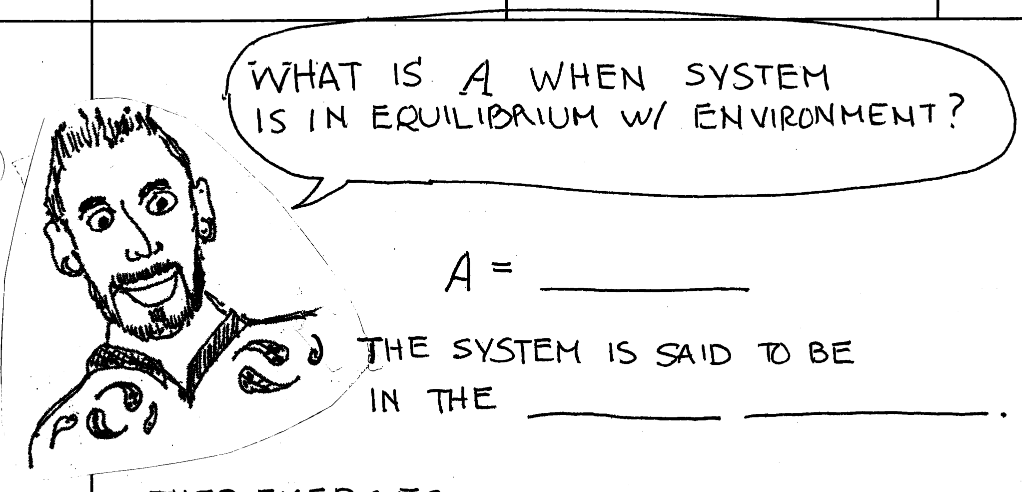


$\equiv$

INTERPRETATION

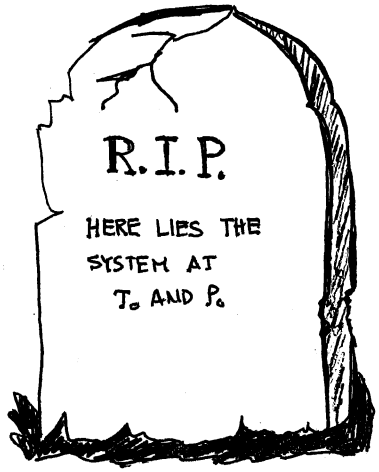
$$\left.\begin{matrix}U_0\\S_0\\V_0\end{matrix}\right\}$$

PROPERTIES of ______________
EVALUATED @ T_0, P_0



$A =$ ______

THE SYSTEM IS SAID TO BE IN THE ______ ______.



OTHER EXERGIES

$a =$ ______ ______ $=$ [/]

$a_f =$ ______ ______ ______ $=$

BOOK	US	QUANTITY
$\mathcal{E}$		
e		
E		
e		
e_f		

REWRITE THE LONG EQN. FROM LAST TIME USING EXERGY NOTATION.

(HINT: SUBTRACT $P_0 \frac{d\forall_{sys}}{dt}$ FROM BOTH SIDES)

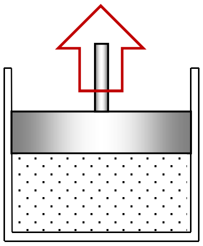
REARRANGING

$$\underbrace{\frac{d}{dt}(A_{SYS})} = \underbrace{\sum_{i=1}^{n}\left(1-\frac{T_o}{T_i}\right)\dot{Q}_i} - \underbrace{\dot{W}_{OUT,USE}} + \underbrace{\sum_{IN}\dot{m}(a_f) - \sum_{OUT}\dot{m}\,a_f}$$

$$- T_o\dot{S}_{gen} \;\}$$

THE

EXAMPLE: Useful work and such

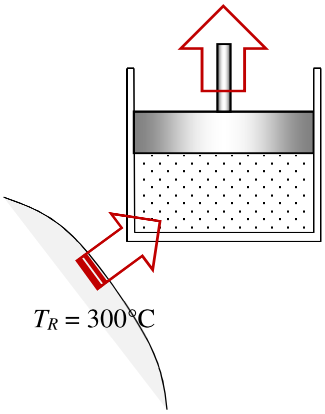


Two kg of saturated steam vapor is contained in a piston cylinder at 200 kPa. It undergoes a constant temperature process until the quality is 0.5. The surroundings are at 101 kPa and 300 K.

(a) Find the work *out* of the steam for this process.
(b) Find the *useful* work out of the steam for this process.
(c) What is the *maximum* amount of useful work that can be extracted from the steam
    1. at its initial state?
    2. at its final state?
    3. between the two states?
(d) How do your answers to (b) and (c) compare? What does that mean?
(e) Calculate the heat transfer in or out of the system and the entropy generation using a good ole ConApps approach. How does $T_0 S_{gen}$ compare to part (d)?

EXAMPLE: Closed system finite time exergy analysis

A mass of 0.25 kg of air (c_p = 1.005 kJ/kg·K, c_v = 0.718 kJ/kg·K) is contained in a piston cylinder initially at P_1 = 200 kPa and T_1 = 35°C. The air undergoes a two-step process consisting of a constant pressure process until the temperature reaches 175°C followed by a constant volume process until the temperature reaches 250°C. All heat transfer to the air occurs from contact with a thermal reservoir at T_R = 300°C. The surroundings are at 100 kPa and 300 K.



(a) Sketch the two-step process on *T*-*s* and *P*-*v* diagrams.

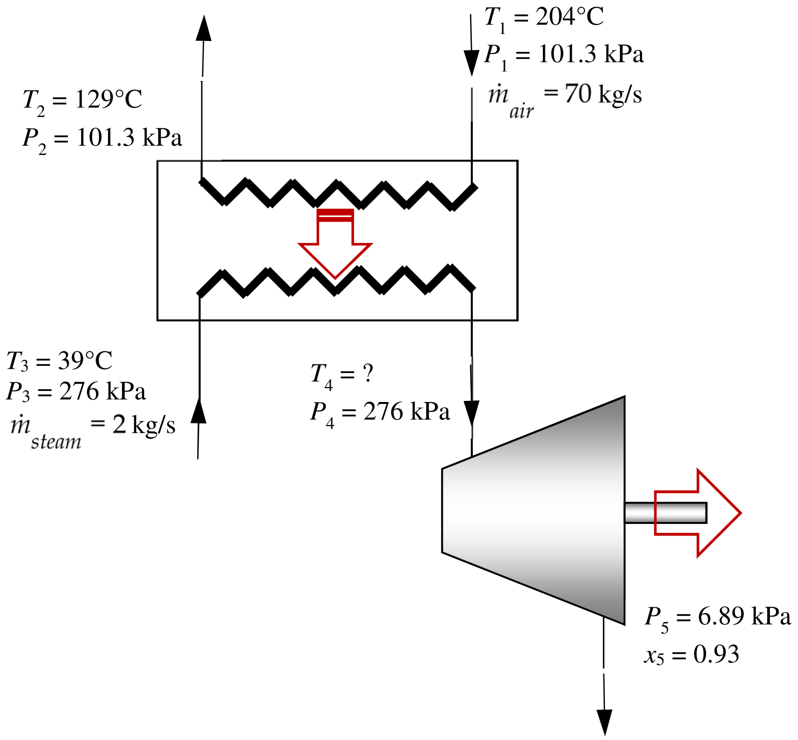
(b) Using an energy conservation/entropy accounting approach, find

  1. the total useful work *out* of the air and
  2. the maximum possible useful work out of the air.

(c) Repeat (b) using an accounting of exergy approach.

EXAMPLE: Oh where does the exergy go?

Consider a heat exchanger and a steam turbine used as a waste heat recovery system. The heat exchanger takes hot combustion gases and uses them to heat steam, which in turn passes through a turbine. The gases can be modeled as air treated as an ideal gas with variable specific heats. The surroundings are at T_0 = 25°C and P_0 = 101 kPa.



(a) Find the power (in kW) delivered by the turbine.

(b) Find the isentropic (adiabatic efficiency) of the turbine.

(c) For the heat recovery system (heat exchanger and turbine combined) identify

1. where inflows of exergy occur

   ____________________, ____________________

2. outflows of exergy occur

   ____________________, ____________________, ____________________

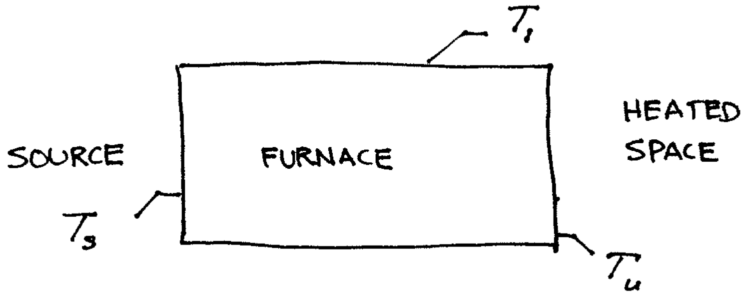
3. destruction of exergy occur

   ____________________, ____________________

(d) Using an exergy accounting approach, calculate the necessary information to fill in the following **exergy balance sheet**

Net rate of exergy in:		(100%)
Disposition of exergy: - Rate of exergy out		
Power developed		(%)
Water stream		(%)
- Rate of exergy destruction		
Heat exchanger		(%)
Turbine		(%)
		(100%)

CONSIDER A FURNACE THAT UTILIZES THERMAL ENERGY FROM A SOURCE AT TEMPERATURE T_s AND DELIVERS IT TO A HEATED SAPCE AT T_u. THERMAL ENERGY IS LOST AT T_l.

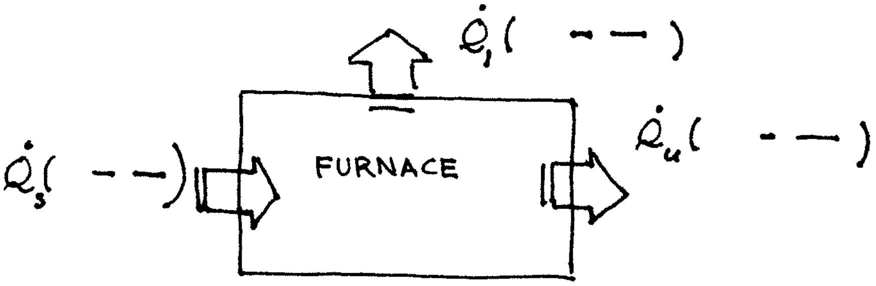


WRITE CONSERVATION OF ENERGY FOR THE FURNACE:

USING YOUR RESULTS, DEFINE A FURNACE EFFICIENCY

$\eta \equiv$ ____________________

NOW WRITE THE ACCOUNTING OF EXERGY FOR THE FURNACE:



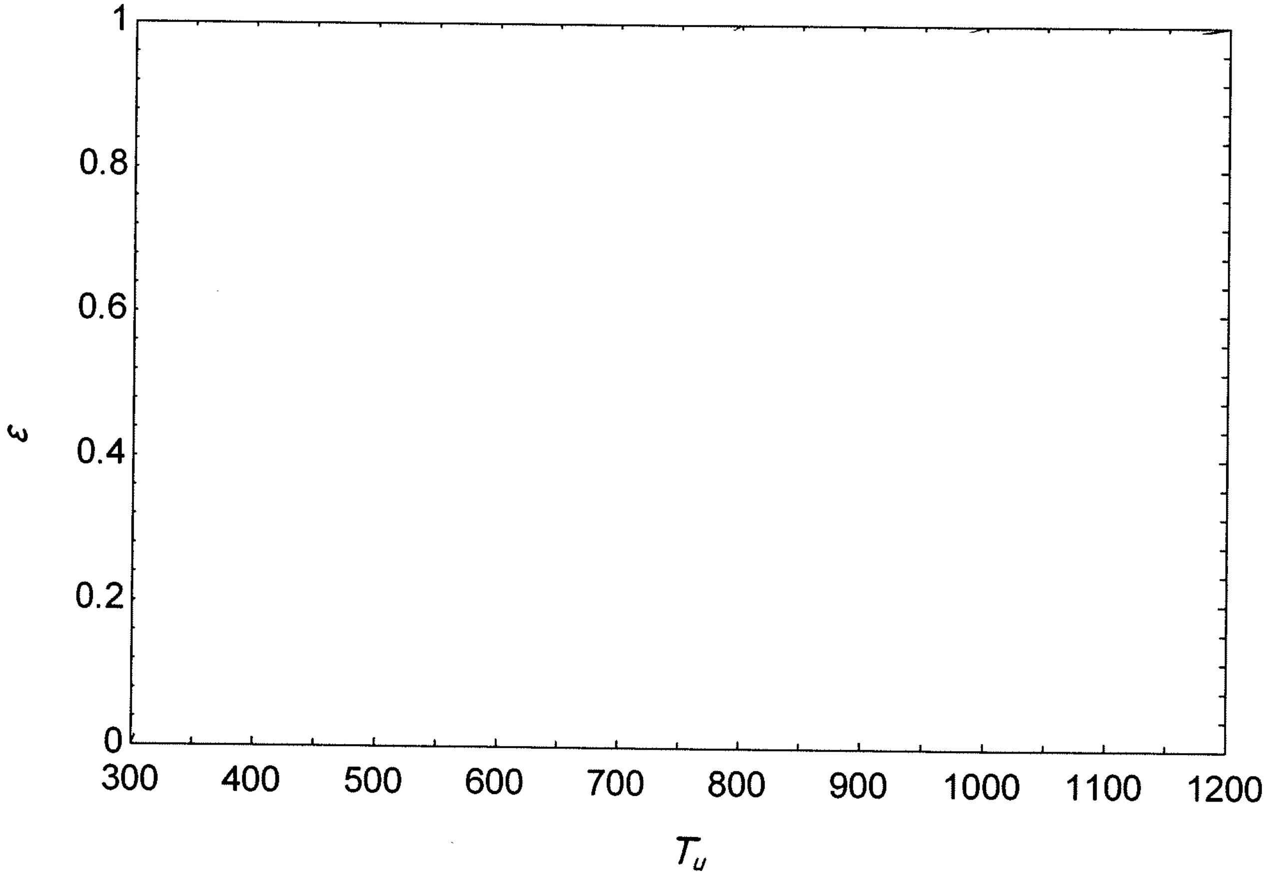
USING YOUR RESULTS, DEFINE AN ***EXERGETIC EFFICIENCY*** FOR THE FURNACE EFFICIENCY

$\varepsilon \equiv$ ____________________

NOW EXPRESS YOUR EXERGETIC EFFICIENCY IN TERMS OF THE FURNACE EFFICIENCY, η

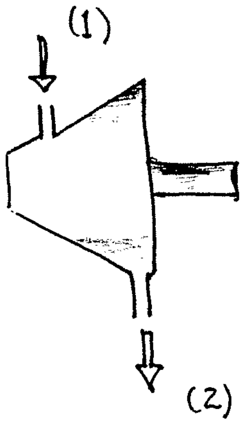
$\mathcal{E} =$ ______________________

PLOT EXERGETIC EFFICIENCY AS A FUNCION OF T_u FOR T_s = 1200 K, 1000 K AND 800 K. ASSUME $\eta = 1$ AND T_0 = 300 K.

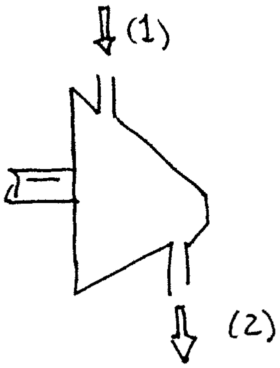


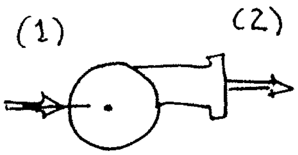
USING THIS SAME APPROACH, FIND EXPRESSIONS FOR THE EXERGETIC EFFICIENCIES OF THE FOLLOWING COMPONENTS:

TURBINE:

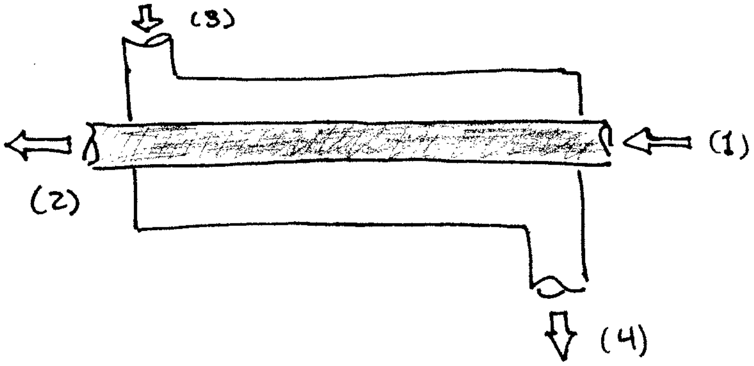


COMPRESSORS/PUMPS:

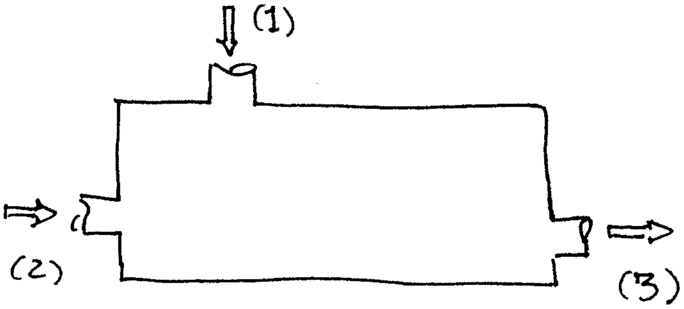




HEAT EXCHANGERS:

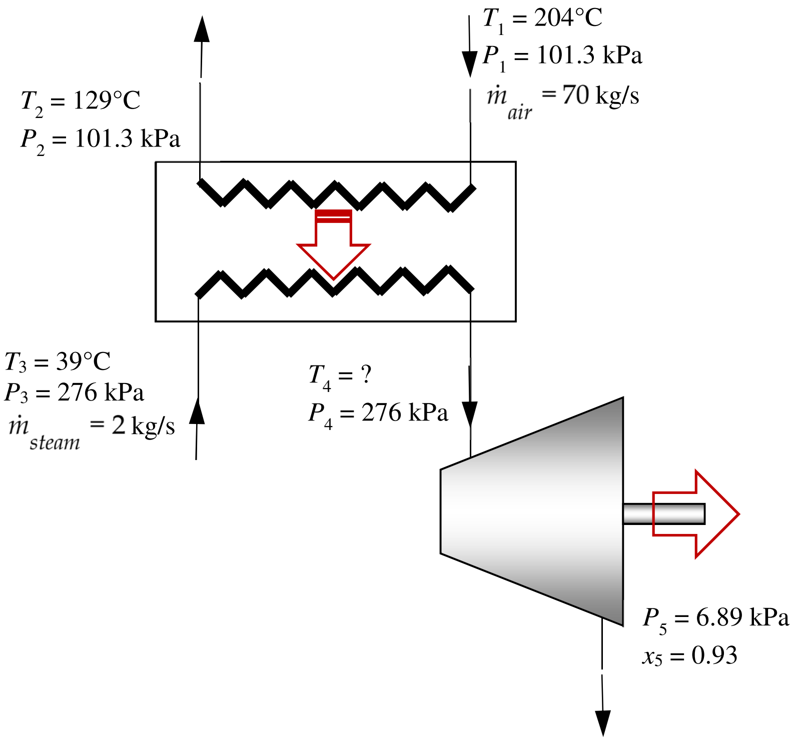


HEAT EXCHANGERS WITH MIXING:



EXAMPLE: More exergetic efficiencies

Reconsider the waste heat recovery system from a previous example. The heat exchanger takes hot combustion gases and uses them to heat steam, which in turn passes through a turbine. The gases can be modeled as air treated as an ideal gas with variable specific heats. The surroundings are at T_0 = 25°C and T_0 = 25°C and P_0 = 101 kPa.



Based on your previous results,

(a) find the exergetic efficiency of the turbine, ε_T.
(b) How does the answer to part (a) compare to η_T? Explain?
(c) find the exergetic efficiency of the heat exchanger, ε_{HXR}.
(d) find the exergetic efficiency of the entire waster heat recovery system, ε.
(e) Does $\varepsilon = \varepsilon_{HXR} \cdot \varepsilon_T$? Explain.

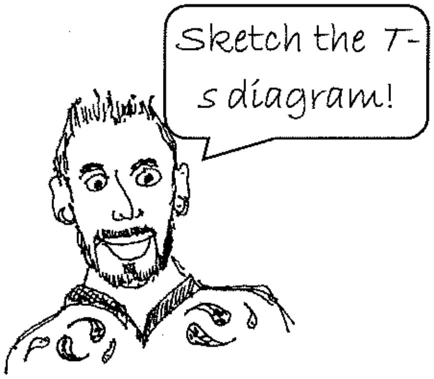
Ideal Rankine cycle

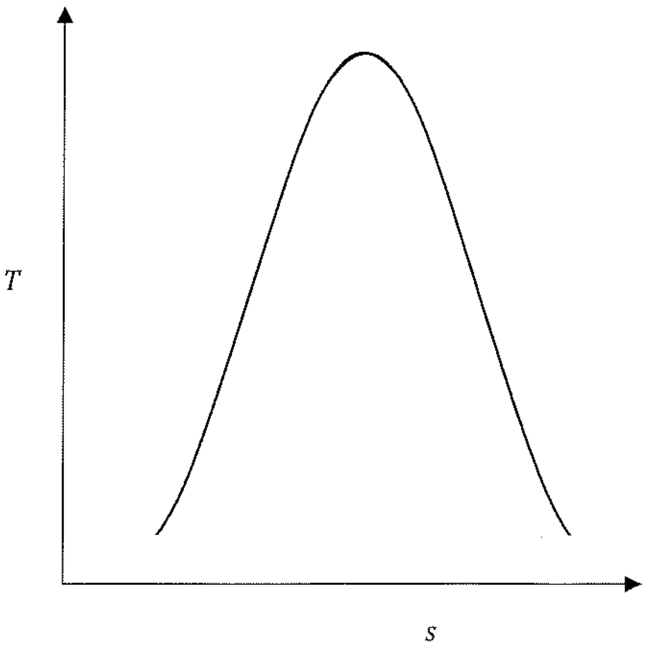
Ideal Rankine cycle is an example of a ____________

____

Four steps

1. Reversible, adiabatic pumping of a saturated liquid from low to high pressure.
2. Constant pressure heat addition until liquid becomes a _____________________ ___________________.
3. Reversible, adiabatic expansion through a turbine.
4. Constant pressure heat rejection back to state (1).

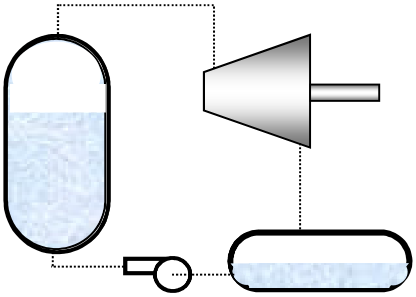




EXAMPLE: (Almost) ideal Rankine cycle

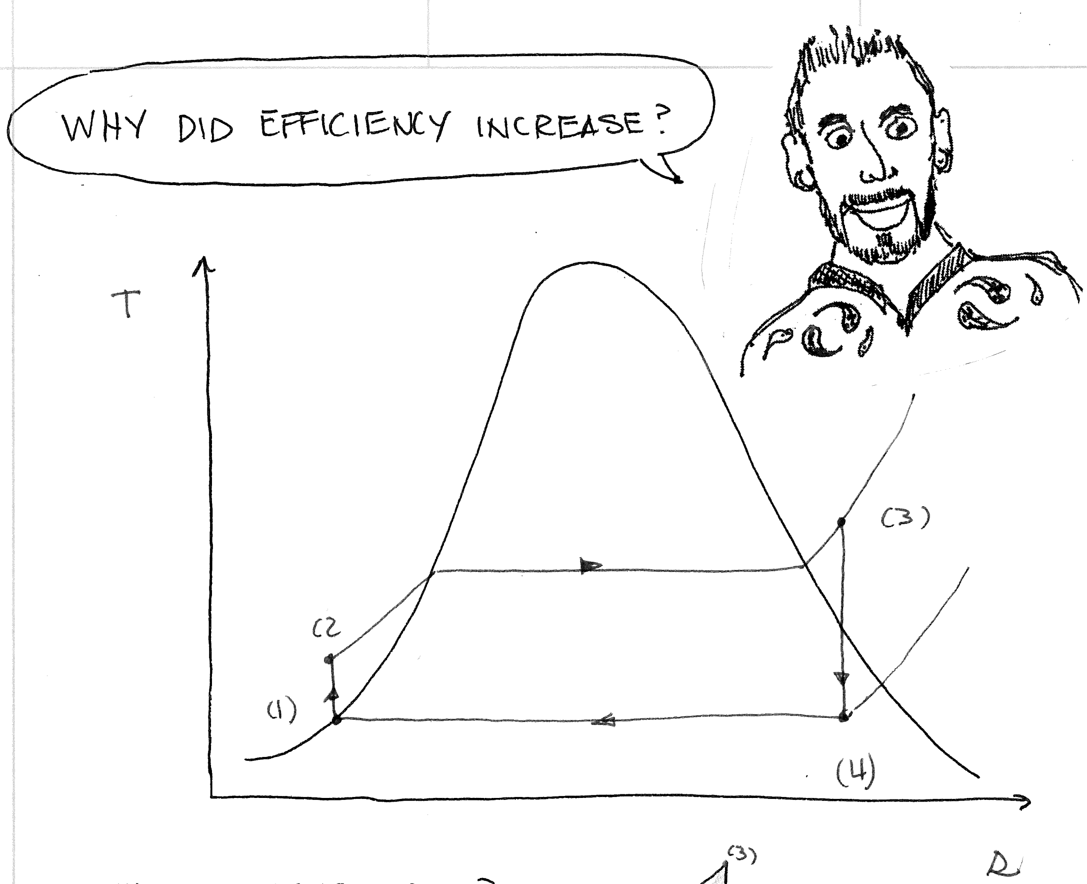
A Rankine cycle operates with a boiler pressure of 8 MPa and a condenser pressure of 10 kPa. Otherwise the cycle is ideal. The liquid entering the pump is saturated, and the vapor entering the turbine has a temperature of 700°C. The mass flow rate of steam through the cycle is 1 kg/s.

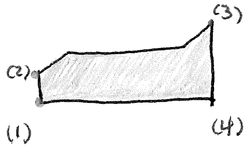
a) Sketch the cycle on a *T*-*s* diagram.
b) Calculate:
   1) the power into the pump,
   2) the heat transfer into the boiler,
   3) the power out of the turbine, and
   4) the heat transfer rejected by the condenser.
c) Find the efficiency of the cycle.

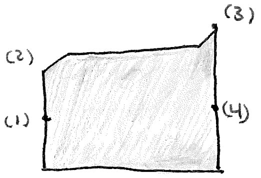


EXAMPLE: (Almost) ideal Rankine cycle

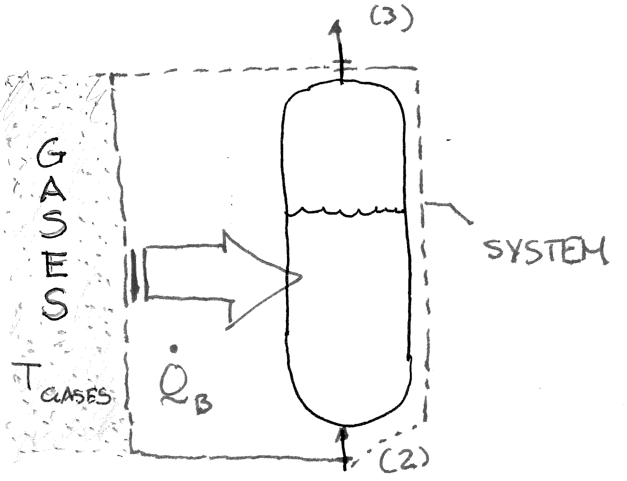
Repeat the last problem, but increase the boiler pressure to 10 MPa.



WHAT IS THIS AREA? 

WHAT IS THIS AREA? 

LET US NOW CONSIDER THE *ENTROPY ACCT'ING EQN* APPLIED TO THE BOILER. ASSUME THE HEAT ADDITION COMES FROM COMBUSTION GASES @ $T_{GASES} = 800°C$.



FOR THE SYSTEM SHOWN, FIND

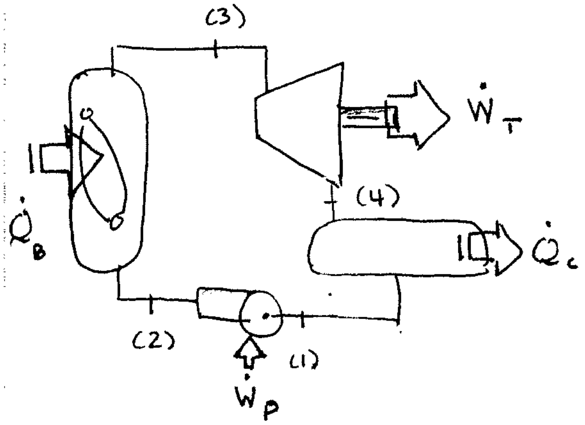
a) $\dot{S}_{gen}$ ($\dot{\sigma}$) FOR $P_2 = 8$ MPa

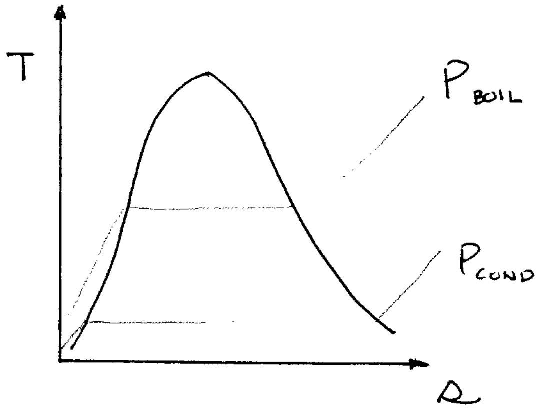
b) $\dot{S}_{gen}$ FOR $P_2 = 10$ MPa

EXAMPLE: (Almost) ideal Rankine cycle

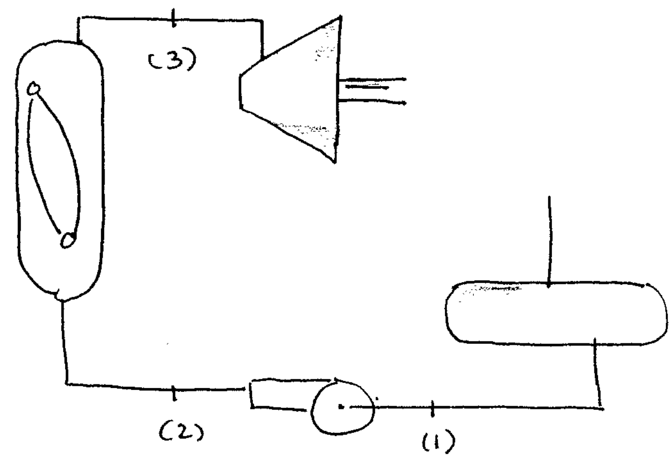
Repeat the problem again, but this time let the adiabatic efficiencies of the pump and the turbine be 70% and 90%, respectively.

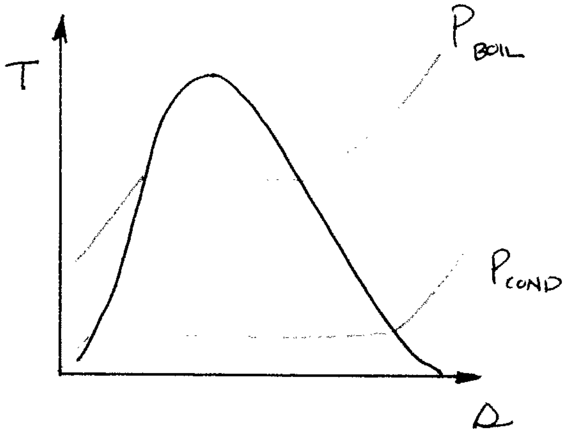
BASIC CYCLE



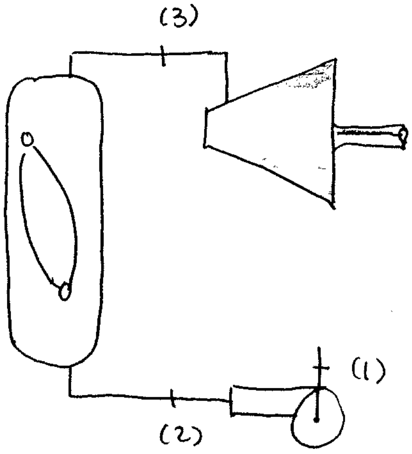


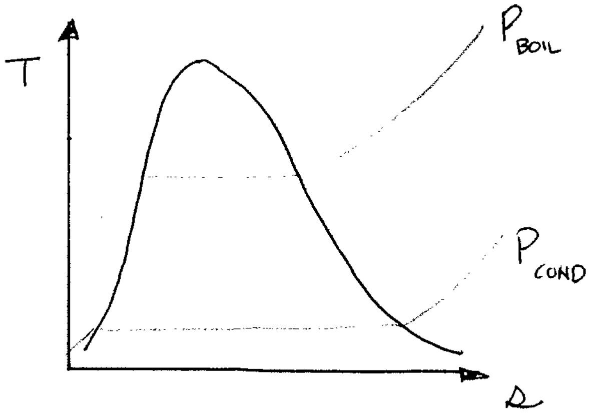
REHEAT

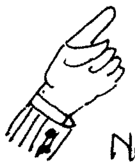




REGENERATION

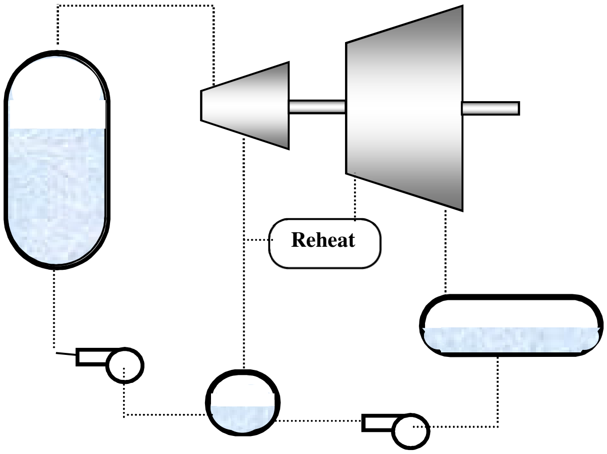






NOTE!

EXAMPLE: (Almost) ideal Rankine cycle with bells and whistles



An (almost) ideal Rankine cycle is modified to include reheat and regeneration using an open feedwater heater. The mass flow rate of steam through the boiler is 1.25 kg/s. The boiler operates at 10 MPa, the open feedwater heater operates at 6 MPa, and the condenser operates at 10 kPa. The water enters both pumps as a saturated liquid. The temperature of the steam entering both turbines is 700°C.

(a) Sketch the cycle on a *T*-*s* diagram.

(b) Find the power or heat transfer rate in/out of each device.
(Hint: Start with an analysis of the open feedwater heater.)

(c) Find the cycle efficiency. (Hint: Careful with W_{dot} and Q_{dot} vs. w_{dot} and q_{dot}.)

THE IDEAL RANKINE CYCLE IS AN EXAMPLE of

________ POWER CYCLE BECAUSE THE

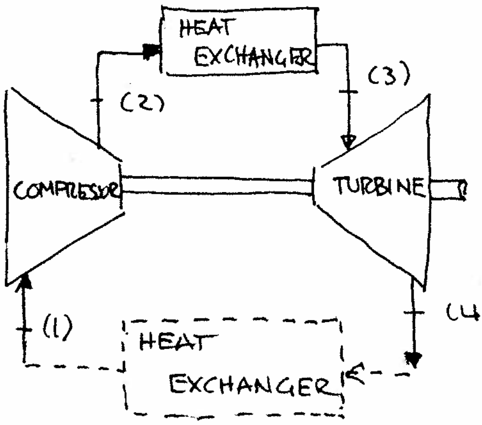
WORKING FLUID ________ ________.

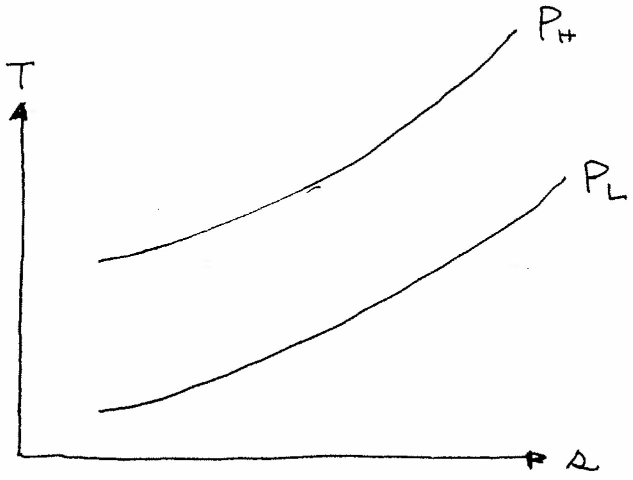
POWER CYCLES IN WHICH THE WORKING FLUID REMAINS A GAS THE ENTIRE TIME ARE CALLED

POWER CYCLES

EXAMPLES

IDEAL BRAYTON CYCLE





(1) → (2)

(2) → (3)

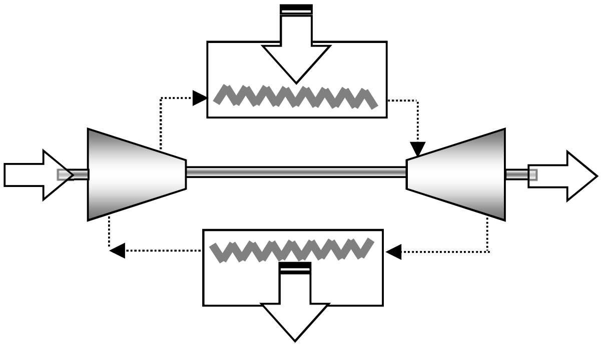
(3) → (4)

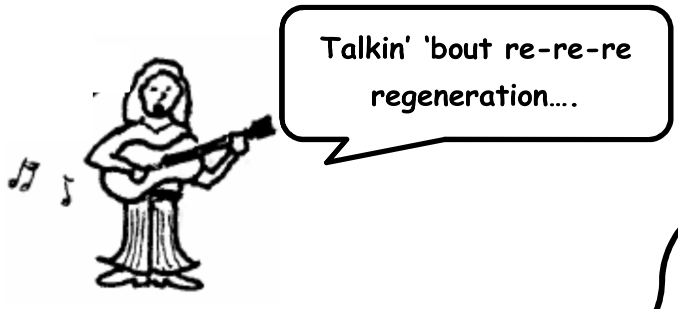
(4) ⇢ (1)

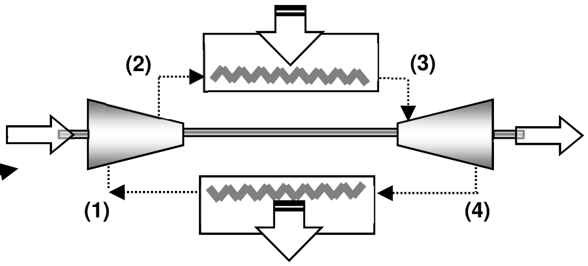
EXAMPLE: Air-standard Brayton cycle

An **air-standard** Brayton cycle operates under the following conditions: compressor inlet: 100 kPa, 300 K; turbine inlet, 1 MPa, 1300 K.

(a) Find the heat transfer rate and power (per unit mass flow rate) for each device in the cycle.
(b) Find the cycle efficiency.
(c) What is the pressure ratio for the cycle?



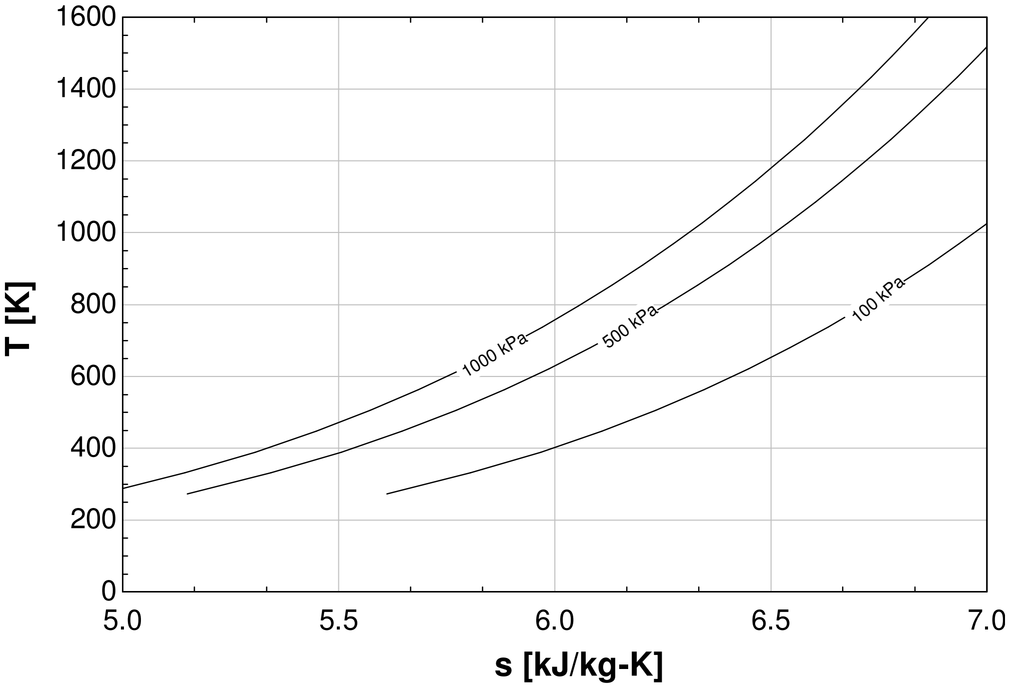




Reconsider the example from last time. Here are some relevant properties:

(1) T = 300 K, P = 100 kPa
(2) T = 573 K, P = 1000 kPa
(3) T = 1300 K, P = 1000 kPa
(4) T = 726 K, P = 100 kPa

Below is a to-scale T-s diagram. Show the cycle on the diagram.

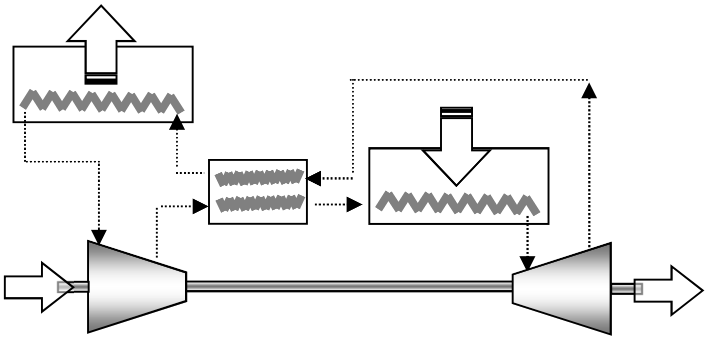


Using the diagram above, suggest a way you could improve the efficiency of the cycle. (**Hints**: Write an expression for efficiency, and consider the relative temperatures of the various state points.)

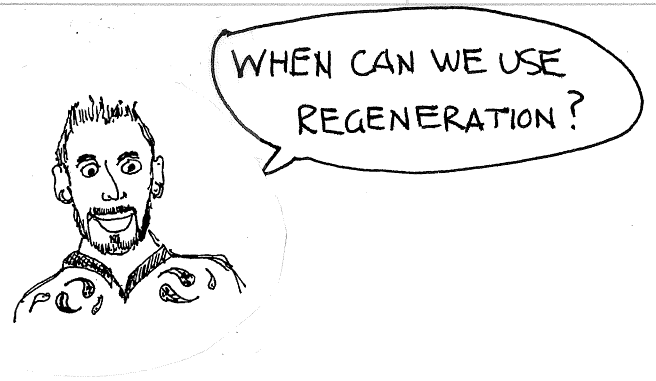
Now draw a number of *open steady-state devices* connected end-to-end that could accomplish this increase in efficiency. (**Hint**: You will need one extra open system device not included in the standard Brayton cycle.)

EXAMPLE: Brayton cycle with regeneration

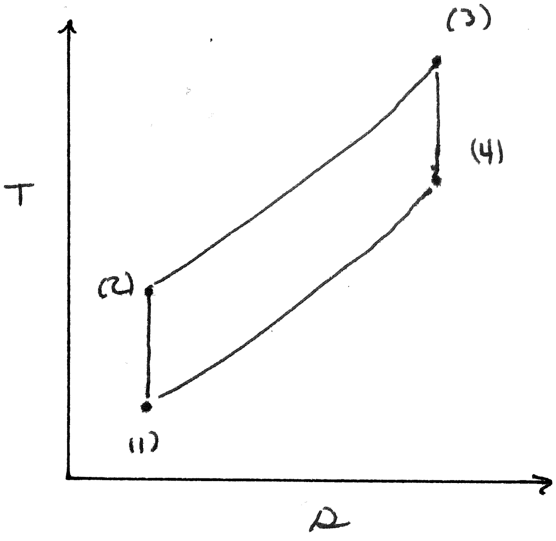
Reconsider the **air-standard** Brayton cycle from the last example. The following conditions still apply: compressor inlet: 100 kPa, 300 K; turbine inlet: 1 MPa, 1300 K. Now add an **ideal regenerator** to the system.

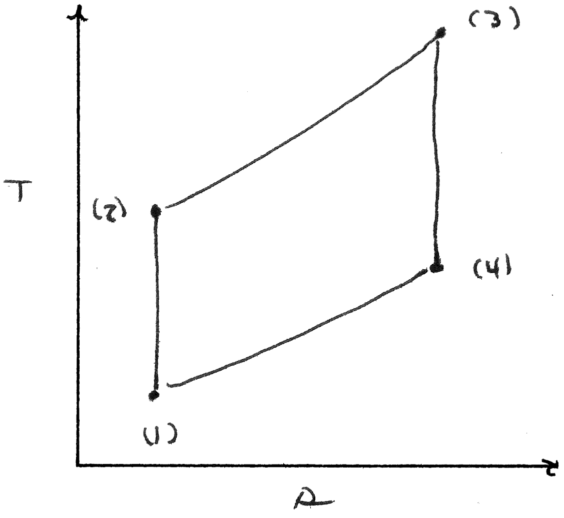


(a) Find the new heat transfer rate (per unit mass flow rate) into the high pressure heat exchanger and the new cycle efficiency.
(b) Find the rate of entropy generation for the regenerator.
(c) Repeat (a) and (b) if $\eta_{\text{regen}} = 0.85$.



COMPARE THE TWO BRAYTON CYCLES BELOW.





η_p = (LOW) OR (HIGH)

η = (LOW) OR (HIGH)

w_{out} = (LOW) OR (HIGH)

T_4 >, <, = T_2

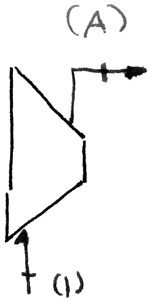
η_p = (LOW) OR (HIGH)

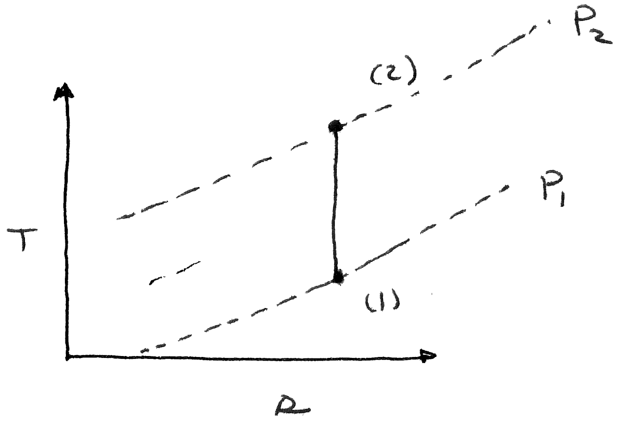
η = (LOW) OR (HIGH)

w_{out} = (LOW) OR (HIGH)

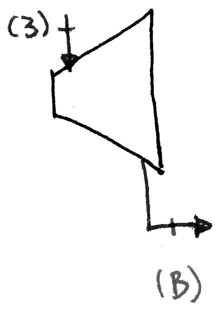
T_4 >, <, = T_2

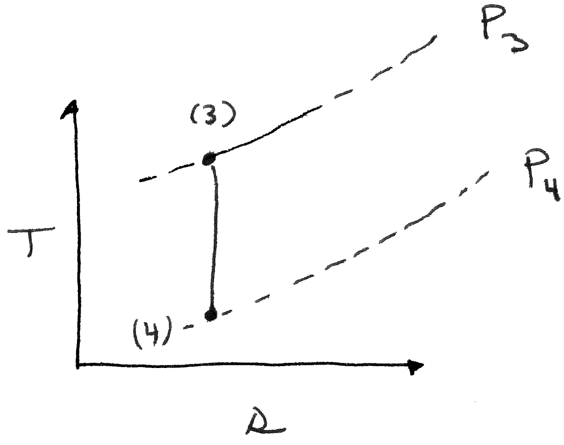
INTERCOOLING

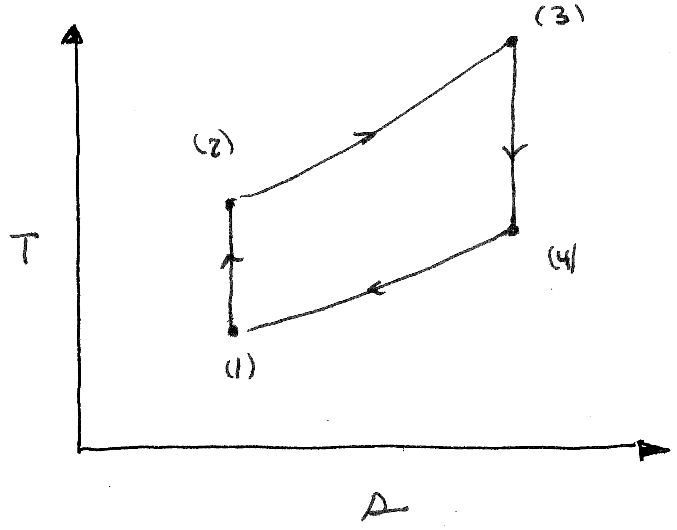




REHEAT







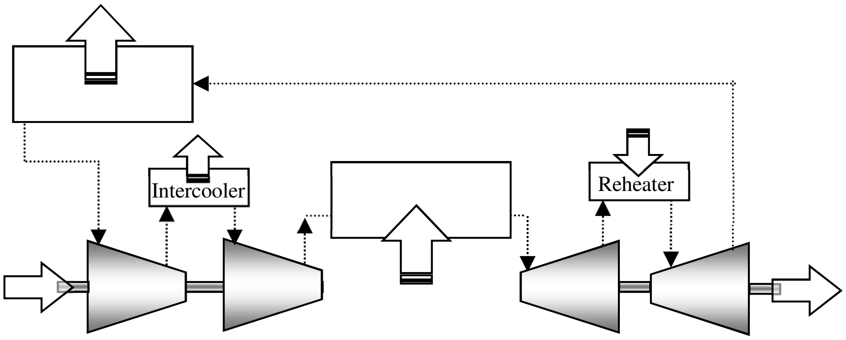
EXAMPLE: Careful with those modifications!

Let's look at that **air-standard** Brayton cycle again. The following conditions still apply: compressor inlet: 100 kPa, 300 K; turbine inlet: 1 MPa, 1300 K. Now add an ideal intercooler and an ideal regenerator. (I.e., $T_B = T_1$ and $T_E = T_3$.)

(a) Sketch the *T*-*s* diagram.

(b) Find the power (per unit mass flow rate) to the two compressors and the heat transfer rate (per unit mass flow rate) from the intercooler.

(c) Find the power (per unit mass flow rate) from the two turbines and the heat transfer rate (per unit mass flow rate) to the reheater.



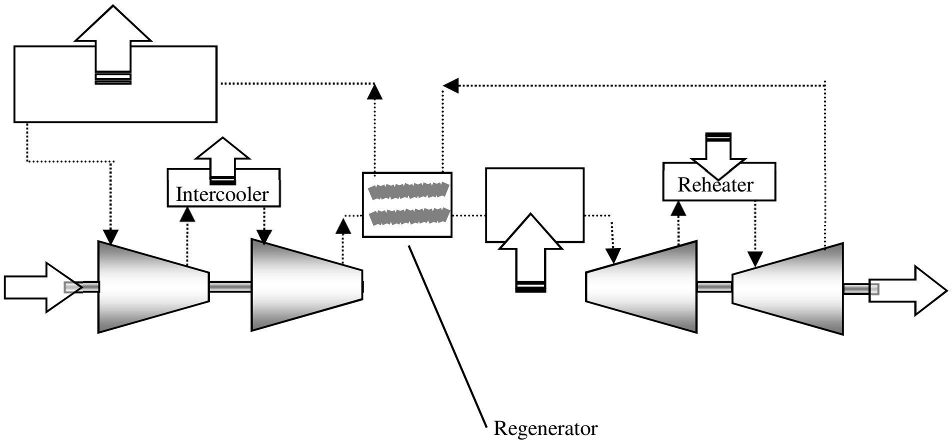
(d) Find the cycle efficiency. What the heck?

EXAMPLE: Ah-hah! Now we fixed it!

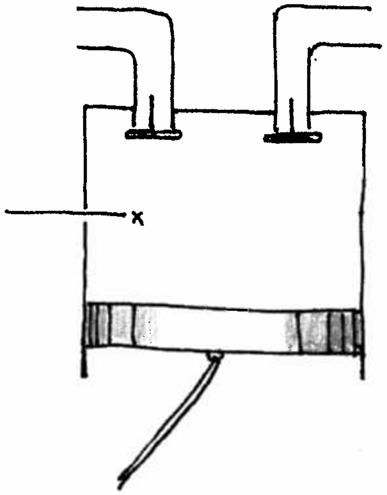
OK, so the efficiency went down. Well, now add an ideal regenerator to the system and let's see what happens!

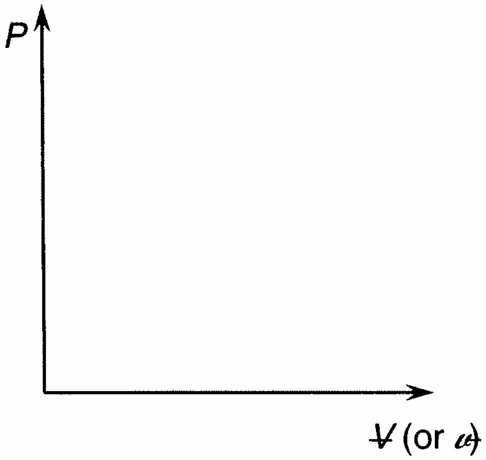
(a) Sketch the *T*-*s* diagram.

(b) Calculate the new heat transfer rate (per unit mass flow rate) into the high-pressure heat exchanger and the new efficiency. Holy cow!



Consider the piston cylinder in your car. Let's consider what *really* happens as it is operating.





Let's analyze it! But first, some assumptions…

Air Standard Assumptions

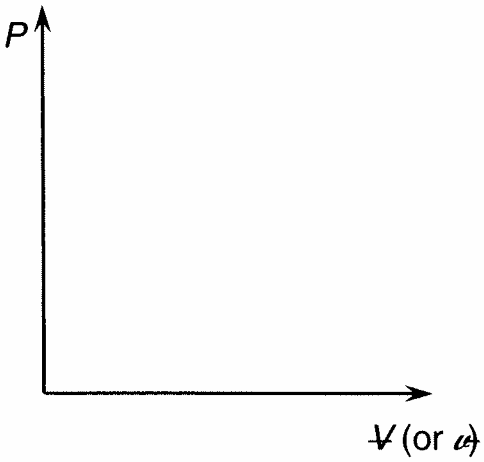
1. Working fluid is ______________
2. and it behaves as an ______________ ______________.
3. The system is ______________. (We are ignoring intake and exhaust strokes.)
4. Combustion is modeled as an ______________ ____________ ______________.
5. All processes are ______________ ______________.

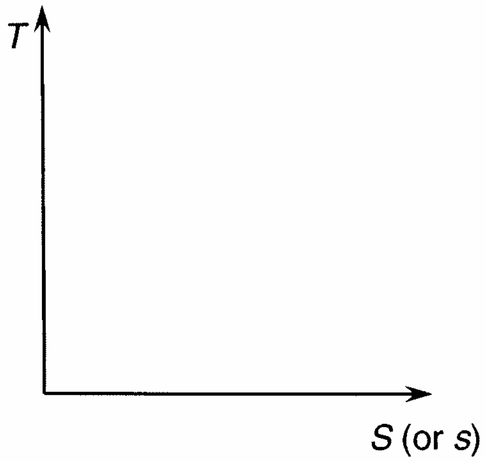
Cold Air Standard Assumptions

Same as air standard assumptions with

Our best first guess at this cycle using these assumptions is the

Otto Cycle





Some other definitions:

r_c = / = ______________ ______________

$\Delta\forall$ = ______________

$\forall_{min}$ = ______________

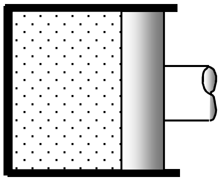
(MEP)·$\Delta\forall$ =

Cold air standard	Air standard

EXAMPLE: Cold air-standard Otto cycle

A reciprocating device operating at 6000 rpm is modeled as a **cold-air-standard** Otto cycle with a compression ratio of 8.5 and a displacement of 0.005 m^3. Before the adiabatic compression, the air is at 120 kPa and 40°C. After the constant volume heat addition, the air is at 950°C. Use c_v = 0.713 kJ/kg-K and c_p = 1.001 kJ/kg-K.

(a) Sketch the cycle on *P*-*v* and *T*-*s* diagrams.
(b) Find the heat transfer and work (per unit mass) for each process in kJ/kg.
(c) Find the net work (per unit mass) and the efficiency of the cycle.
(d) Find the power delivered by the device in kW.



And now the

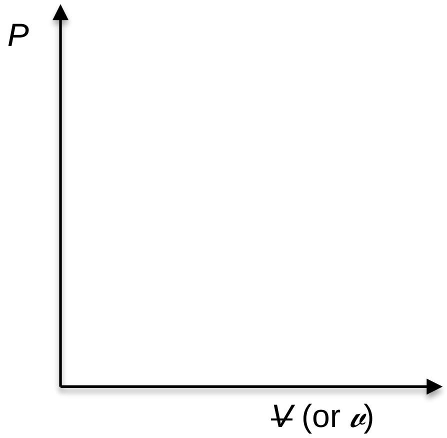
Diesel Cycle

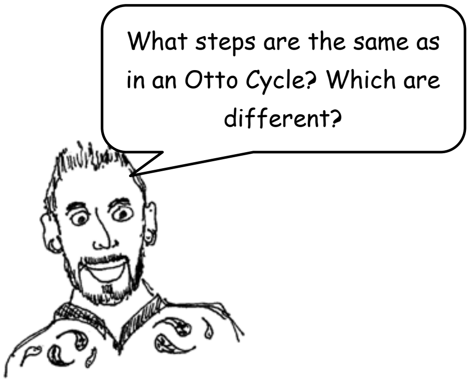
(1) → (2) ____________________________

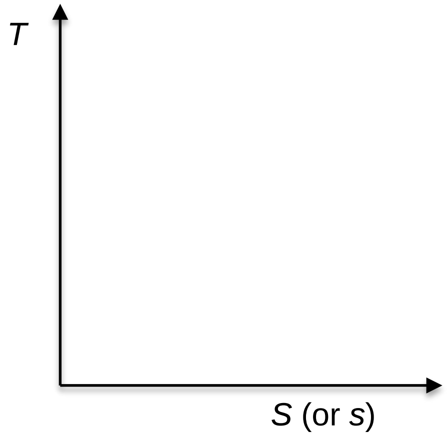
(2) → (3) ____________________________

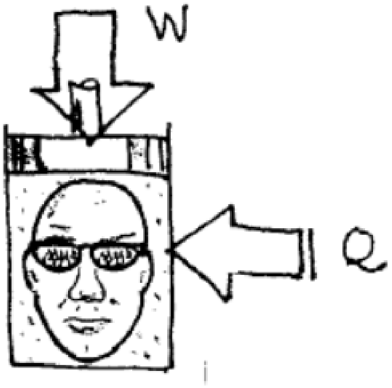
(3) → (4) ____________________________

(4) → (1) ____________________________









Vin Diesel Cycle

(1) → (2) ____________________________

(2) → (1) ____________________________

Draw four piston cylinders representing the four different states of the Diesel Cycle. Leave some space between each drawing. Be sure that you represent the volumes accurately, at least relative to the other volumes.

(1)

(2)

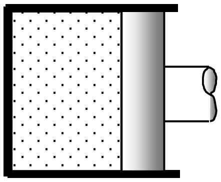
(3)

(4)

Now draw arrows representing the heat transfer and/or work into or out of the system *between* each state.

EXAMPLE: Air-standard Diesel cycle

An **air-standard** Diesel cycle has a compression ratio of 15. Before the adiabatic compression, the air is at 100 kPa and 20°C. 1600 kJ/kg of thermal energy is added during the constant pressure heat addition.



(a) Sketch the cycle on P-v and T-s diagrams.

(b) Find the heat transfer and work (per unit mass) for each process in kJ/kg.

(c) Find cut-off ratio for the cycle.

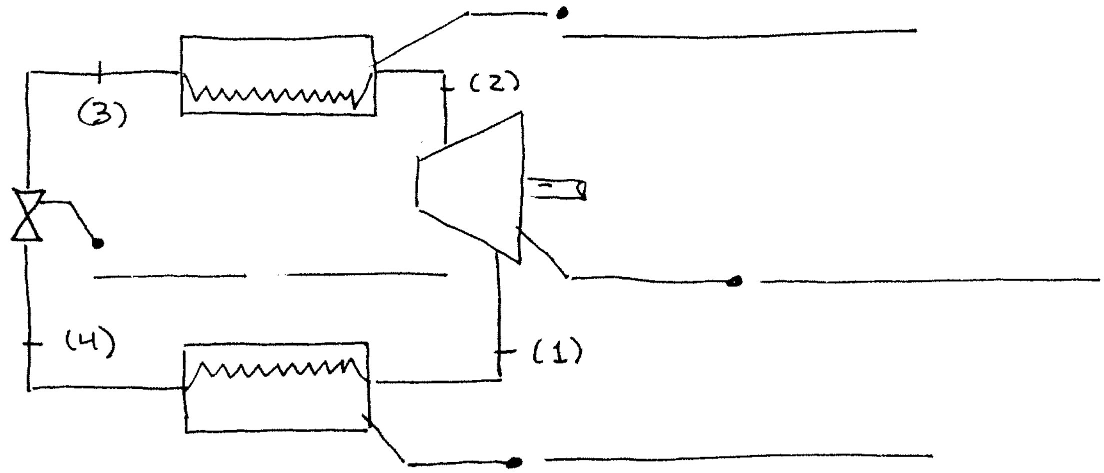
(d) Find the cycle efficiency. For a **cold**-air-standard, the cycle efficiency is given by

$$\eta_{cold-air} = 1 - r^{1-k}\,\frac{r_c^{\,k} - 1}{k(r_c - 1)}.$$

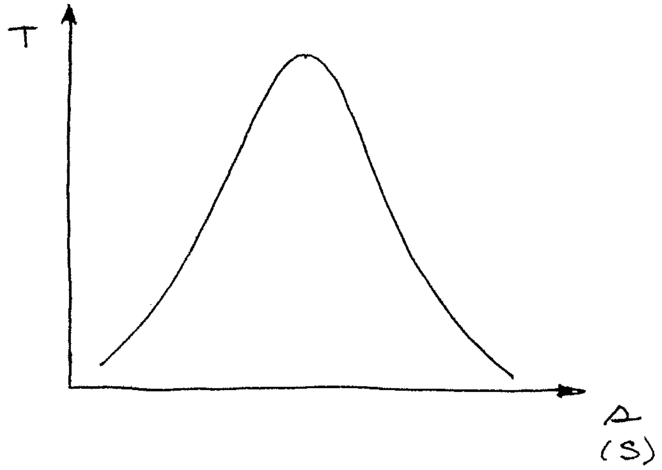
How does your value compare to this?

IDEAL VAPOR-COMPRESSION REFRIGERATION CYCLES

COMPONENTS



SKETCH THE T-s DIAGRAM



JOULE-THOMPSON COEFFICIENT

$$\mu_{JT} \equiv \left(\frac{\quad}{\quad} \right)_{-\,\text{CONST}}$$

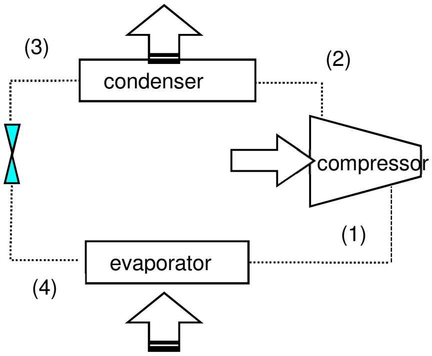
FOR A REFRIGERANT

$$\mu_{JT} \begin{array}{l} \overset{?}{>} 0 \\ \overset{?}{<} 0 \\ \overset{?}{=} 0 \end{array}$$

¿CAN YOU USE AN IDEAL GAS AS A REFRIGERANT?

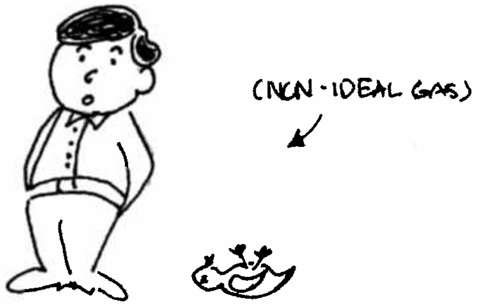
EXAMPLE: Ideal vapor-compression refrigeration cycle

An ideal vapor-compression refrigeration cycle uses R-134a as a working fluid in an air-conditioning system. The refrigerant enters the compressor as a saturated vapor at 40°F and leaves the condenser as a saturated liquid at 130°F. The mass flow rate of the refrigerant is 1.5 lbm/s.



(a) Find the power into the compressor, in B/s.
(b) Find the heat transfer rate out of the condenser, in B/s.
(c) Find the heat transfer rate into the evaporator, in B/s.
(d) Find the COP for the cycle.
(e) Find the quality of the refrigerant at the exit of the valve.
(f) Repeat with an isentropic efficiency for the compressor of η_C=0.85.

IDEAL GASES



OBEY

(1)

¿HOW DO YOU FIND m IF n IS KNOWN?

- DIVIDE EQ. 1 BY M IN $\frac{g}{mol}$ OR $\frac{kg}{k\text{-}mol}$ OR ________
- MULTIPLY " " " "

⇒ ⇒

WRITE AS MANY OTHER VERSIONS of THE IDEAL GAS EQUATION AS YOU CAN:

-
-
-
-

MIXTURES of GASES

TWO DIFFERENT WAYS TO INDICATE Composition

ANALYSIS	ANALYSIS
mf_i = ________	y_i = ________

$mf_i =$

$y_i =$

$\sum mf_i =$ ______ $\sum y_i =$ ______

¿HOW DO YOU FIND m_i IF YOU KNOW N_i ?

NOW FOR THE *MIXTURE*...

-OR- $\boxed{\quad = \underline{\qquad\qquad}}$

↳ DEFINES THE

SIMILARLY

$\boxed{\quad = \underline{\qquad\qquad}}$

APPARENT (AVERAGE)
IDEAL GAS CONSTANT
FOR MIXTURE
(MASS BASIS)

DALTON'S MODEL | ASSUMES

- WRITE EQ. 1 FOR A MIXTURE
  SOLVE IT FOR P_{MIX}

$P_{MIX} =$ (2)

- NOW WRITE EQ. 1 FOR *COMPONENT* i & SOLVE IT FOR P_i
  USING DALTON'S MODEL.

$P_i =$ (3)

↑ ______

______ ______

WRITE A SENTENCE DEFINING PARTIAL PRESSURE!

PARTIAL PRESSURE IS

COMPARE EQ. 3 TO EQ. 2. HOW DOES P_i COMPARE TO P_{MIX}?

$P_i =$

AND $\therefore$

$\sum P_i =$

EXAMPLE: Moles to masses

Combustion air is mixed with methane gas before it is ignited. The following *mole* analysis of the entering gas is known.

CH_4 - 8 %
O_2 - 16%
N_2 - 76%

(a) Determine the mass analysis of the gas mixture (mass fractions).
(b) Determine the mass flow rate of the gas mixture if the *molar* flow rate is 2000 kmol/min.
(c) Determine the apparent molar mass and the apparent ideal gas constant for the gas.
(d) If the temperature and the pressure of the mix are 25°C and 100 kPa, respectively, find the **partial pressure** of each component.
(e) Redo (a) through (d) if the analysis given were a *mass* analysis.

(a) Assume you have _______________ of mixture.

i				
CH_4				
O_2				
N_2				

EXAMPLE: Properties o' mixtures

Dry atmospheric air is actually a mixture of gases including oxygen, nitrogen, argon and trace amounts of other gases. Consider 1 m^3 of air for which the **volumetric composition** is 21% O_2, 78% N_2 and 1% Ar. Initially the air is at 27°C and 100 kPa. It is then heated to 227°C at constant volume.

(a) Find the apparent molar mass and the ideal gas constant for the air.
(b) Find the mass of the air.
(c) Assuming variable specific heats,
  i. find the heat transfer added to the air during the process, and
  ii. calculate the entropy generated during the process, in kJ/K.
(d) Repeat (c) by using the air tables instead of using the given mixture composition.

(a) Assume you have _______________ of mixture.

i				
O_2				
N_2				
Ar				

EXAMPLE: Open system mixing

Air at T_a = 77°C, P_a = 1 bar and *molar* flow rate of $\dot{n}_a$ =0.1 kmol/s enters an insulated mixing chamber. It mixes with water vapor at T_w = 277°C, P_w = 1 bar and *molar* flow rate of $\dot{n}_w$ =0.3 kmol/s, with the mixture exiting at P_{mix}= 1 bar. If both air and water can be modeled as ideal gases with variable specific heats,

(a) find the temperature of the exiting mixture T_{mix} and
(b) the rate of entropy generation in the mixture.
(c) What is the source of entropy generation?

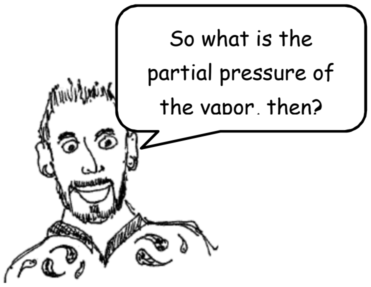
Psychrometrics

Psychrometrics is

The gas-vapor combination at which we'll look is ___________ and ___________.

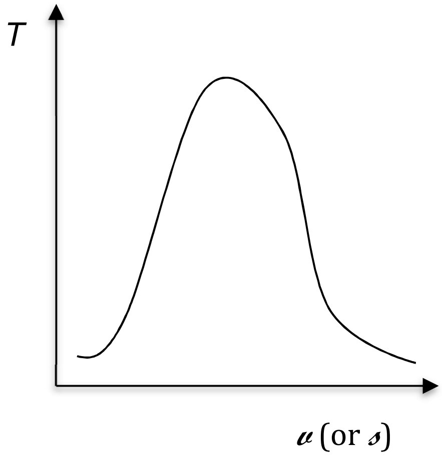
In water-air mixtures, the water might ___________. (Water is the *vapor* in our gas-vapor mixture.)

Both the air and the water behave as if they existed at _____ and _____. They obey ___________'s model.



P_v =

Sketch a line of constant P_v on the *T*-*v* diagram below for the water. Then cool it at constant pressure. What happens eventually?



Relative humidity:

Humidity ratio:

Mixture enthalpy:

Mixture specific volume:

EXAMPLE: You must be Psychro!

A moist-air mixture has a dry-bulb temperature of 85°F and a relative humidity of φ = 60%. The total pressure of the mix is 14.7 psia.

(a) If the water vapor existed alone at T_{mix} and $\cancel{V}_{mix}$, what would its pressure be? I.e., determine the

_______________ _______________

(b) For every lbm of dry air, how much water vapor is there? I.e., determine the

_______________ _______________

(c) If you cooled this mix at constant pressure, at what temperature would the water start condensing? I.e., determine the

_______________ _______________

(d) Determine the enthalpy of the mixture **per unit mass of dry air.** Is this the same as H_{mix}/m_{mix}?

EXAMPLE: Now throw in conservation of mass

A moist-air mixture has a dry-bulb temperature of 85°F and a relative humidity of $\varphi = 60\%$. The total pressure of the mix is 14.7 psia.

~~(a) If the water vapor existed alone at T_{mix} and V_{mix}, what would its pressure be? I.e., determine the~~

Partial pressure (or vapor pressure)

~~(b) For every lbm of dry air, how much water vapor is there? I.e., determine the~~

Humidity ratio

~~(c) If you cooled this mix at constant pressure, at what temperature would the water start condensing? I.e., determine the~~

Dew point temperature

~~(d) Determine the enthalpy of the mixture **per unit mass of dry air.** Is this the same as H_{mix}/m_{mix}?~~

(e) If the mixture is cooled to T= 60°F, how much liquid condenses per lbm of dry air?

NEW!

Adiabatic Saturation Temperature

The **adiabatic saturation temperature** is a useful property of moist air that is solely a function of humidity ratio, total pressure, and dry-bulb temperature. That is

$$T_{as} = T_{as}(\_\_\_\_, \_\_\_\_, \_\_\_\_)$$

or if you solve for ω,

$$\omega = \omega(\_\_\_\_, \_\_\_\_, \_\_\_\_)$$

Its utility comes from the fact that adiabatic saturation temperature is well-approximated by ___ ____ ____________. That is

$$T_{as} \approx \_\_\_\_\_\_$$

Let's find $\omega = \omega(T_{db}, T_{as}, P)$.

Write *Conservation of Mass* for the system.

For the *air (dry air) only*

(1)

And now for the *water only*

In terms of ω

(2)

Write *Conservation of Energy* for the system.

In terms of ω

(3)

Substitute (1) and (2) into (3)

Solve for ω_1.

Assume that the (dry) air is an ideal gas with _______ ________ _____.

> The adiabatic saturation temperature of state (1) is the unique temperature for which ___ = ___ = ______ with φ_2 = ____%.

Write a sentence that defines adiabatic saturation temperature:

For these conditions

$h_{v,2}$ = _____

$h_{w,3}$ = _____ = _____

$h_{v,1} \approx$ _____

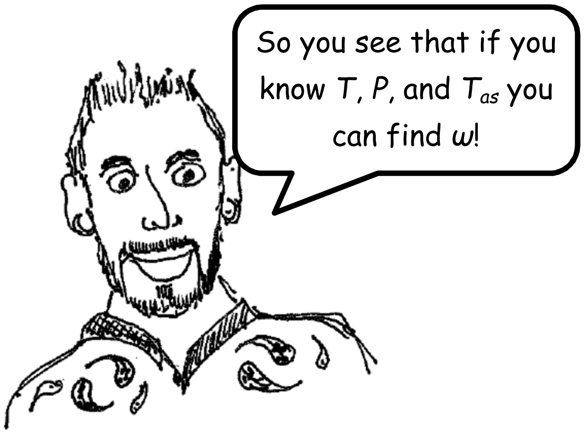
so

ω_1 = ____

ω_1 = ____

where

ω_2 = __________________ = __________________



EXAMPLE: Yet more psych properties

A moist air mixture has the following measured properties

- T = 86°F
- T_{wb} = 78°F
- P = 14.7 psia

(a) Find the humidity ratio.
(b) Find the relative humidity.
(c) Find the mixture specific enthalpy (per lbm dry air)
(d) Find the mixture specific volume (per lbm dry air)

EXAMPLE: This one is harder than it looks

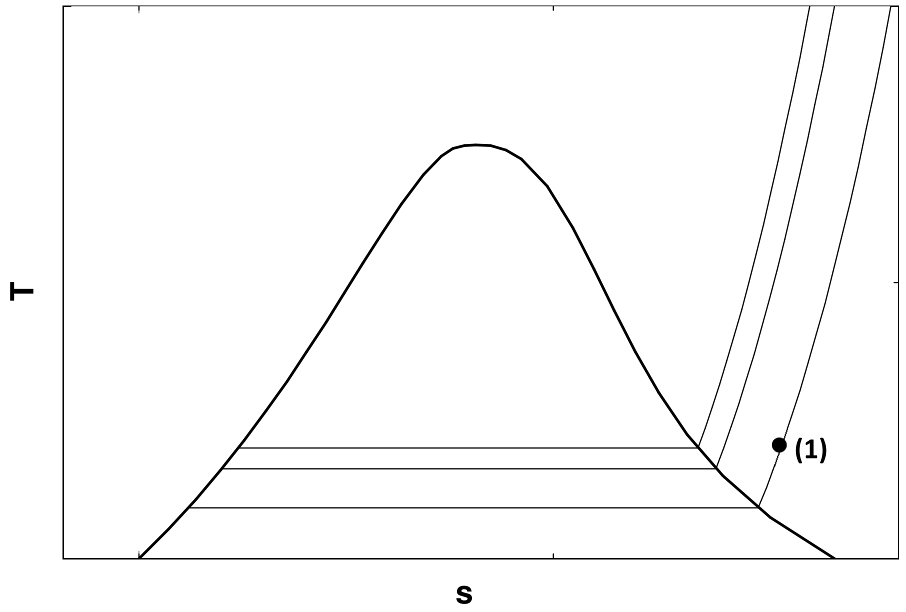
Moist air at 14.7 psia has the following properties:

- ω = 0.0031 (What are the units?)
- T = 70°F

Find the adiabatic saturation temperature.

Fun with Psychrometrics

Consider the T-s (or T-v) diagram for the water in a moist air mixture. The moist air has a temperature T_1 and relative humidity $\varphi_1 < 100\%$



Label these points on the diagram:

1. Line of constant P_v
2. P_g (if $\varphi = 100\%$)
3. $T_{dew\ point}$
4. The adiabatic saturation point. Show T_{as} and the corresponding vapor pressure

How do T (or T_{db}), T_{as} (or T_{wb}) and T_{dew} compare when $\varphi = 100\%$?

When $\varphi = 100\%$? ________________________

Psychrometrics Calculations Comment Card[1]

How would you rate calculating ω if you know T_{db} and T_{wb}?

☐ Easy as pie ☐ Messy but doable ☐ Not a chance!

How would you rate calculating T_{db} if you know ω and T_{wb}?

☐ Easy as pie ☐ Messy but doable ☐ Not a chance!

How would you rate calculating h if you know φ and T_{db}?

☐ Easy as pie ☐ Messy but doable ☐ Not a chance!

How would you rate calculating h if you know ω and T_{db}?

☐ Easy as pie ☐ Messy but doable ☐ Not a chance!

How would you rate calculating T_{wb} if you know φ and T_{db}?

☐ Easy as pie ☐ Messy but doable ☐ Not a chance!

How did you hear about these calculations? ____

____

Would you recommend these calculations to a friend? ______________________________

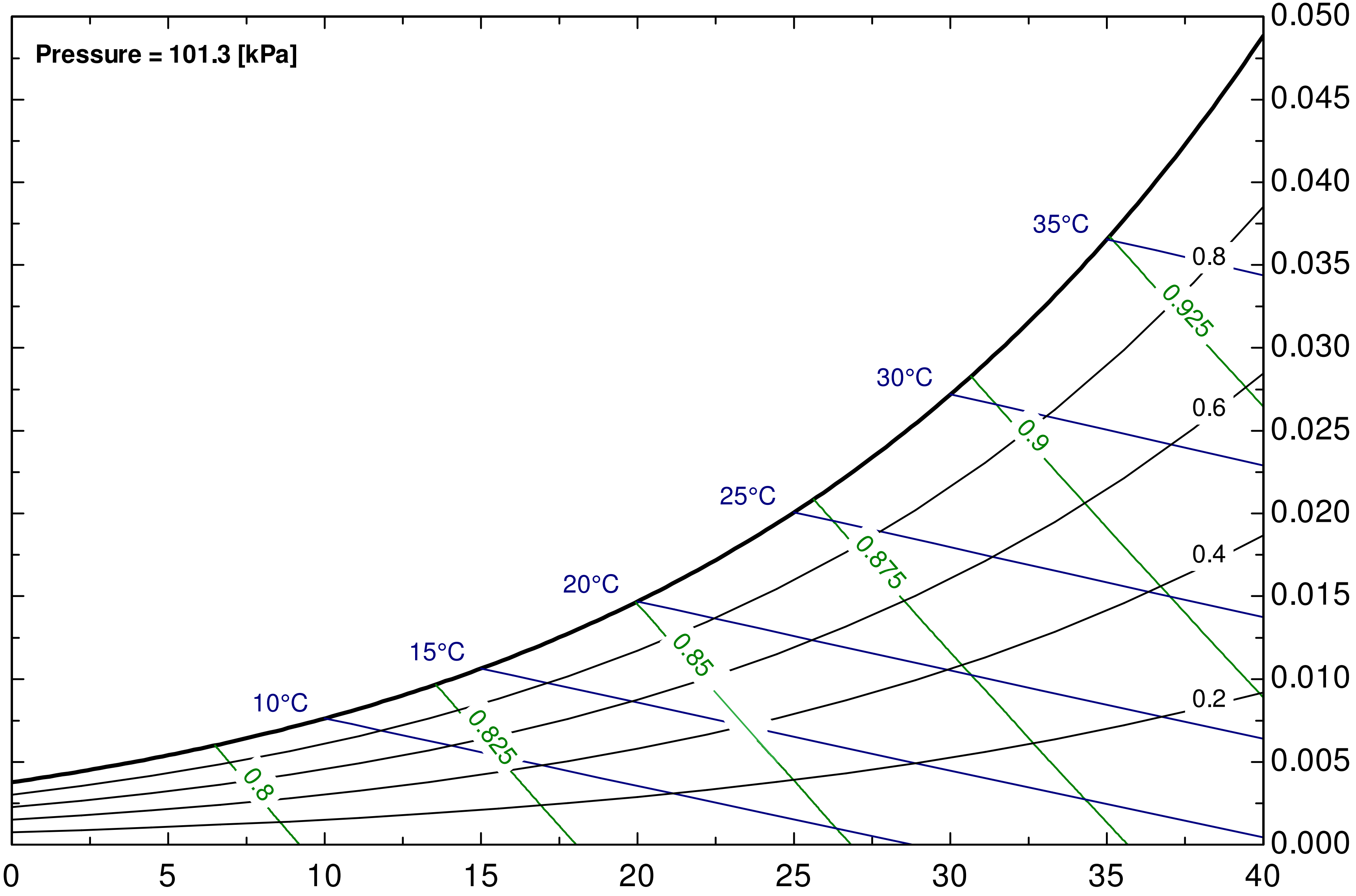
____

(If you are interested in learning how to avoid these calculations, please pay attention during the rest of class!)

---

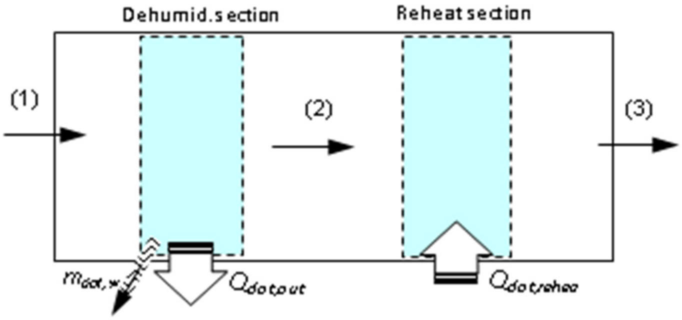
[1] When filling out your comment card, please assume that the moist air total pressure is known and constant. ME301 will hold your responses in strict confidence and will not share your identity with any third party.

Psych Chart to the rescue!



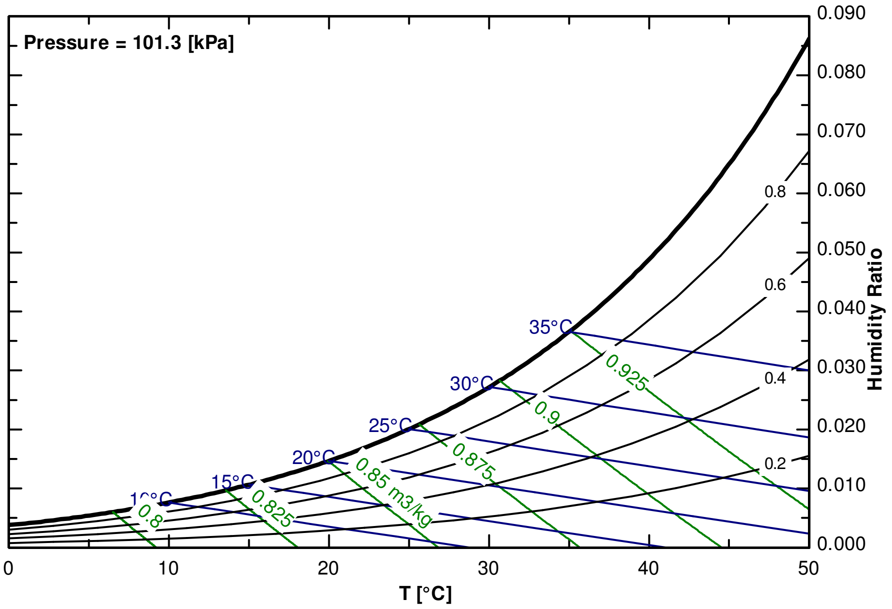
EXAMPLE: Cooling with dehumidification

A steady-flow cooling and dehumidification process with a reheat section delivers moist air at a dry-bulb temperature of 25°C and a relative humidity of ϕ = 50%. Air enters the cooling section at a dry bulb temperature of 40°C and ϕ = 40% with a flow rate of 75 m^3/min.



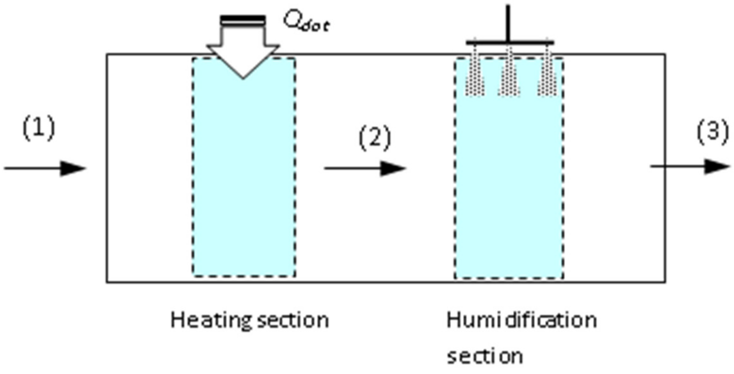
(a) Draw the process on a psychrometric chart.
(b) Determine the mass flow rate of the dry air in kg/min.
(c) Determine the amount of liquid water extracted in the process, in kg/min.
(d) Determine the rate of heat transfer out of the air in the cooling section.
(e) Determine the rate of heat transfer into the air in the reheat section.

(a)



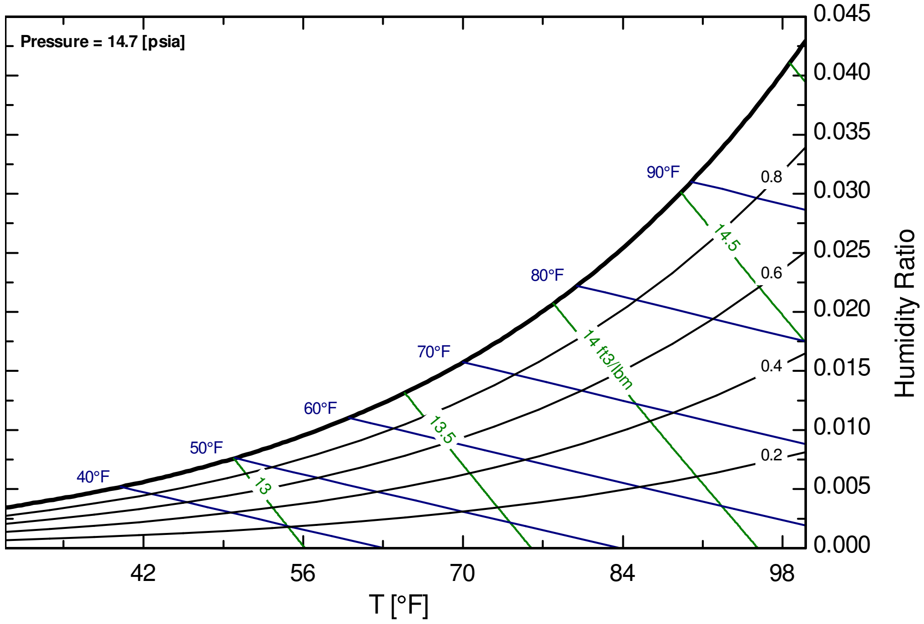
EXAMPLE: Heating with humidification

A steady-flow heating and humidification process is used to provide moist air at a dry bulb temperature of 77°F with a relative humidity $\phi = 45\%$. Outdoor air at $T_{DB} = 40°\text{F}$ and $\phi = 90\%$ enters the heating section at a rate of 2100 ft^3/min where the temperature is increased to 75°F. The air then enters the humidifier section so that the desired exit conditions are achieved. The entire device operates at a constant total pressure of 1 bar.



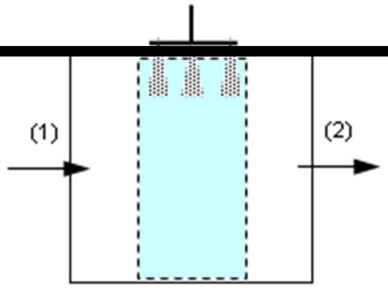
(a) Draw the two-step process on a psychrometric diagram.
(b) Determine the mass flow rate of dry air through the device.
(c) Determine the heat transfer rate to the heating section.
(d) Determine the mass flow rate of steam in the humidifying section.
(e) Determine the temperature of the steam if it has a pressure of 1.01325 bar.

(a)



EXAMPLE: Evaporative cooling

Air at a total pressure of 1 atm has a dry bulb temperature of 35°C and $\phi = 15\%$ is passed through an evaporative cooler.

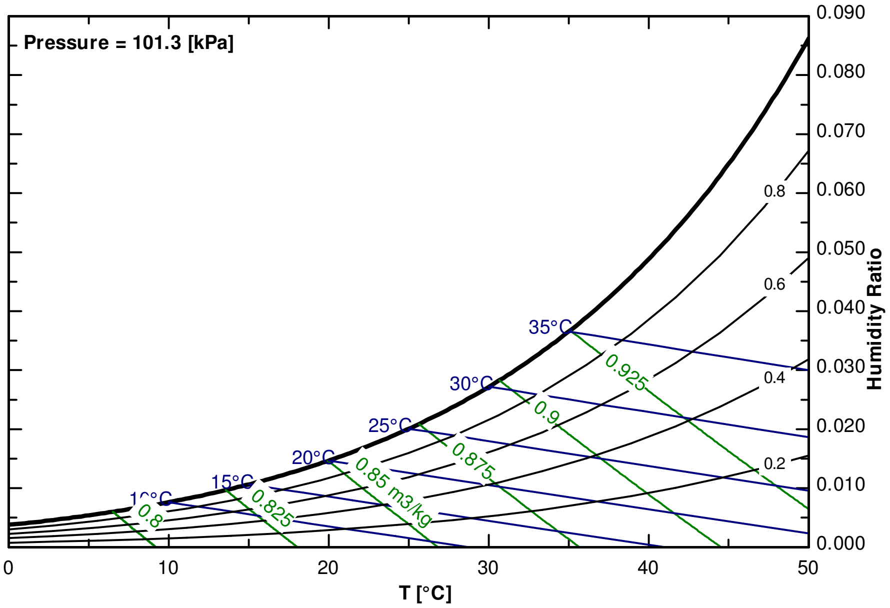


(a) Sketch the process on a psychrometric chart.

(b) Determine the minimum dry bulb temperature that could be attained in the process.

(c) If the air leaves the cooler at a dry bulb temperature of 20°C, find the relative humidity of the air.

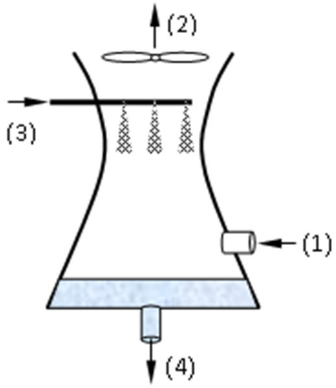
(d) If the cross sectional area of the cooler is constant, what happens to the velocity of the air as it passes through? Why? How might you calculate the new velocity?



EXAMPLE: Yes, they use these in nuclear power plants

Warm water enters a cooling tower at 45°C at a rate of 130 kg/s to be cooled to 30°C. Atmospheric air at a dry bulb temperature of 25°C and $\varphi = 50\%$ enters the tower to effect the cooling, and leaves the tower at a saturated state at 32°C. Neglecting the power input to the fan, determine

(a) the mass flow rate of dry air into the tower,
(b) the volumetric flow rate of air entering the tower (at 1), and
(c) how much water evaporates in kg/s.



Combustion

_________ + ___________________ → Products + ______________

Most commonly

C_H_ + _______ → __ ___ + ___ __ + ___

or

C_H_ + _______ → __ ___ + __ __ + ___ ___ + ___ + ___________

Complete combustion

- Only __ ___ and ____ formed.
- N_2 is _______-_________________.
- Enough ___ supplied to convert **all** __ and __ to CO_2 and H_2O.

Model for air

For _______ air (by volume)

Component	_________ fraction
O_2	
N_2	

Dalton's other model strikes again!

or

__ _______ O_2 + ___.____ _______ N_2 = ___.__ __ _______ Air

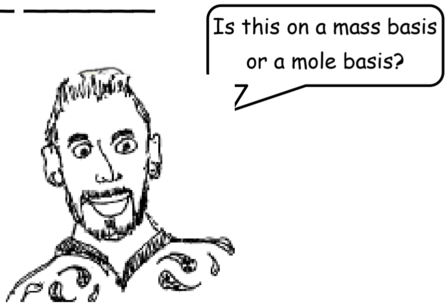
Remember M_{air} = _____._____ kg/kmol

Stoichiometric reaction

- Complete combustion. I.e., no __________ ___
- The correct amount of air needed for above is

  _______________________ or ____________ ______

- More or less air is
  - % ____________ air
  - % _____________________ air
  - % _______________________ air, etc.



Air-fuel ratio

AF = ____________ = _________

FA = ____________ = _________

Equivalence ratio

Φ = __________

Φ < __ → "Lean"

Φ > 1 → "________"

Balancing chemical reactions

It's just ________ ____ ______!

You remember how to do it from CHEM101, yes?

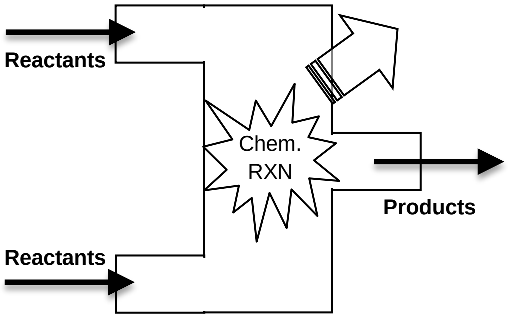
EXAMPLE: Blowing stuff up

Acetylene (C_2H_2) at a fuel flow rate of 1 kg/min is burned with dry air with an air fuel ratio of 17:1. Assuming **complete combustion** and a total pressure of 110 kPa, find

(a) the percent excess air used,
(b) the **equivalence ratio**,
(c) the percentage of CO_2 in the products by volume,
(d) the dew point temperature of the products in °C,
(e) the percentage of water vapor condensed if the products are cooled to 20°C, and
(f) the required volume flow rate of dry air if it if supplied at 22°C and 110 kPa.
(g) If the actual air supplied has a humidity ratio of 16 g H_2O per kg of dry air, find the dew point temperature of the products.

Conservation of energy and combustion

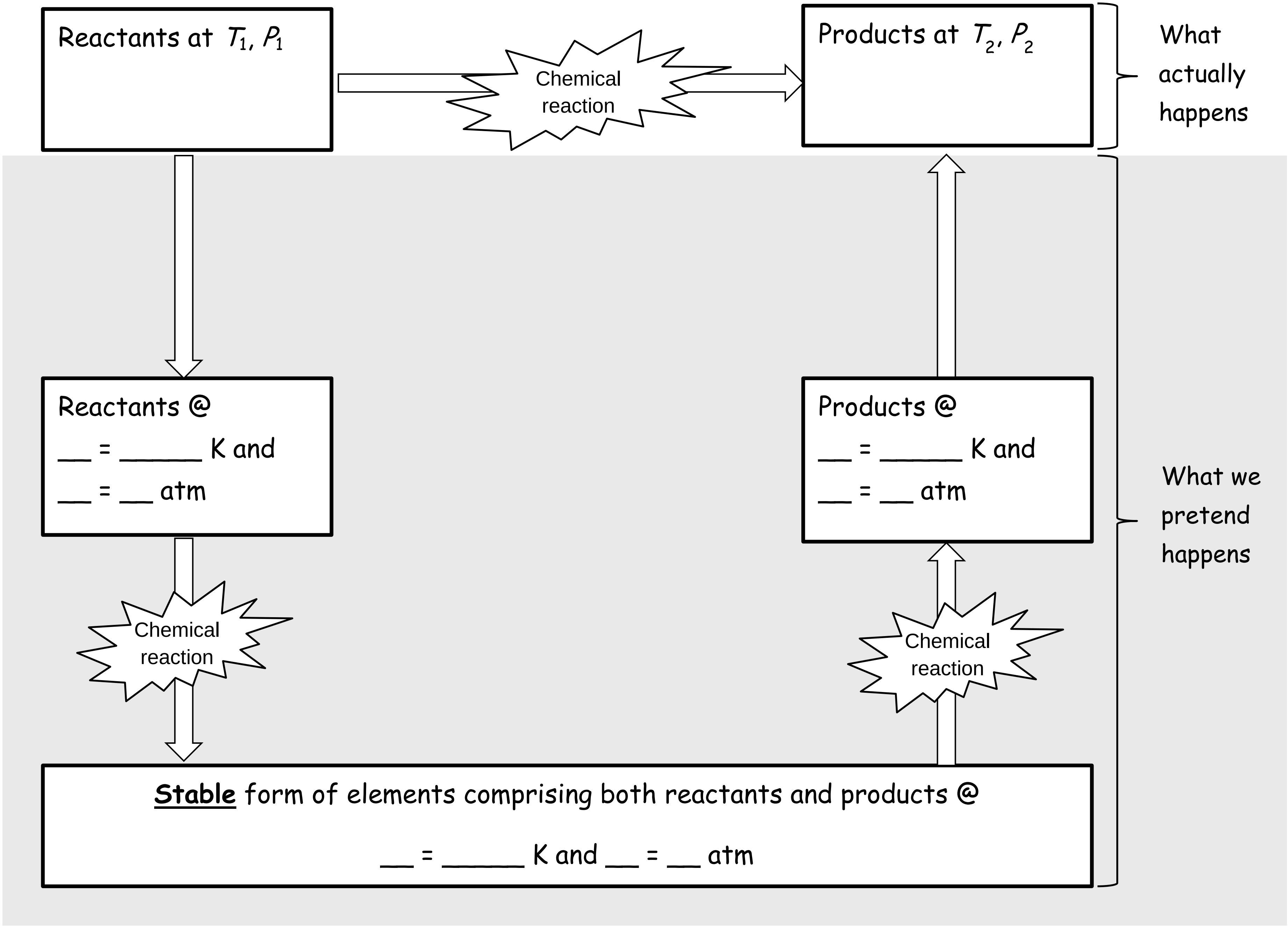
Consider a combustion reaction happening in a steady-flow reaction chamber:



Write conservation of energy for the process. Will you use a mass-based specific enthalpy or a mole-based specific enthalpy? Why?

Is $dE_{chem}/dt = 0$? If not, how could you assume steady-state?

And now the big question: How are you going to deal with the specific enthalpies given that *different stuff leaves than comes in*? Is there a specific enthalpy change associated with the chemical reaction?


Reactants at T_1, P_1
Chemical reaction
Products at T_2, P_2
What actually happens
Reactants @
__ = ______ K and
__ = __ atm
Products @
__ = ______ K and
__ = __ atm
What we pretend happens
Chemical reaction
Chemical reaction
Stable form of elements comprising both reactants and products @
__ = ______ K and __ = __ atm

(Specific) **enthalpy of formation**:

$\bar{h}_f^0 =$

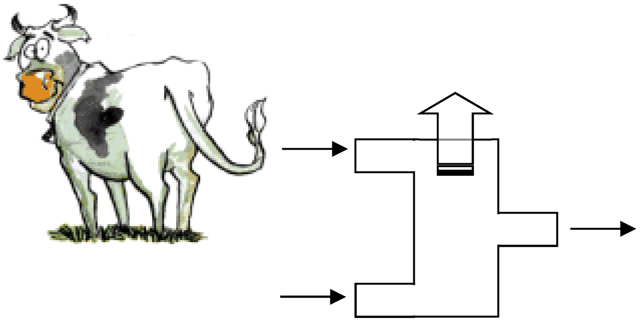
Write a sentence that defines enthalpy of formation!

And so for any one species, reactant or product

$\bar{h} =$

EXAMPLE: Really, this is a thing

In his younger days, Dr. Thom got mixed up with a get-rich-quick scheme that proposed using bovine flatulence as an energy source. The proposed process was to combust methane (CH_4) with air in a steady-state reaction chamber. The process used sufficient air to produce 90% CO_2, 10% CO and no O_2 in the products. Both the methane and the air enter at 1 bar and 25°C. The products leave the chamber at 500 K and 1 bar. Find the heat transfer rate per unit molar flow rate of fuel for the process.



i	T [K]	$\Delta\bar{h}_f^0$ [kJ/kmol]	$\bar{h}(T)$ [kJ/kmol]	$\bar{h}(298\text{K})$ [kJ/kmol]	$\bar{h}$ [kJ/kmol]
$CO_2)_2$					
$CO)_2$					
$H_2O)_2$					
$N_2)_2$					
$CH_4)_1$					
$O_2)_1$					
$N_2)_1$					

EXAMPLE: Open system mixing

Let us reconsider the dubious bovine flatulence energy source problem yet again. As before, the proposed process combusts methane (CH_4) with air in a steady-state reaction chamber and produces 90% CO_2, 10% CO and no O_2 in the products. Both the methane and the air enter at 1 bar and 25°C.

This time, however, we will *not* assume that the products leave the chamber at 500 K and 1 bar. Rather, we will assume the chamber operates *adiabatically* and at constant pressure. You are to find the exit temperature of the products. That is, you are to find the

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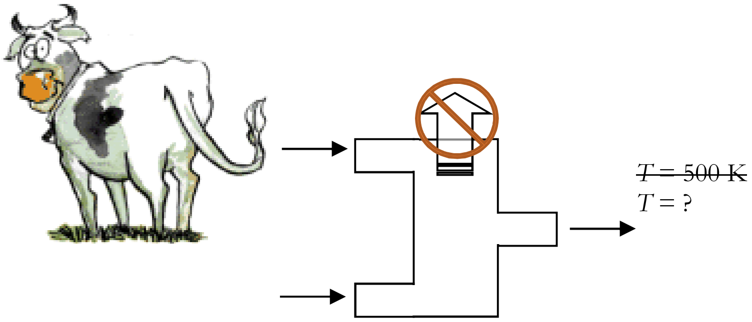
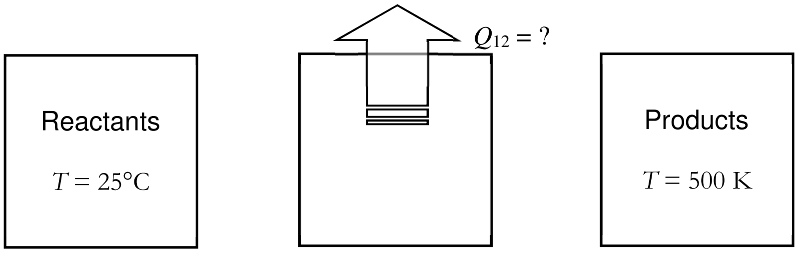


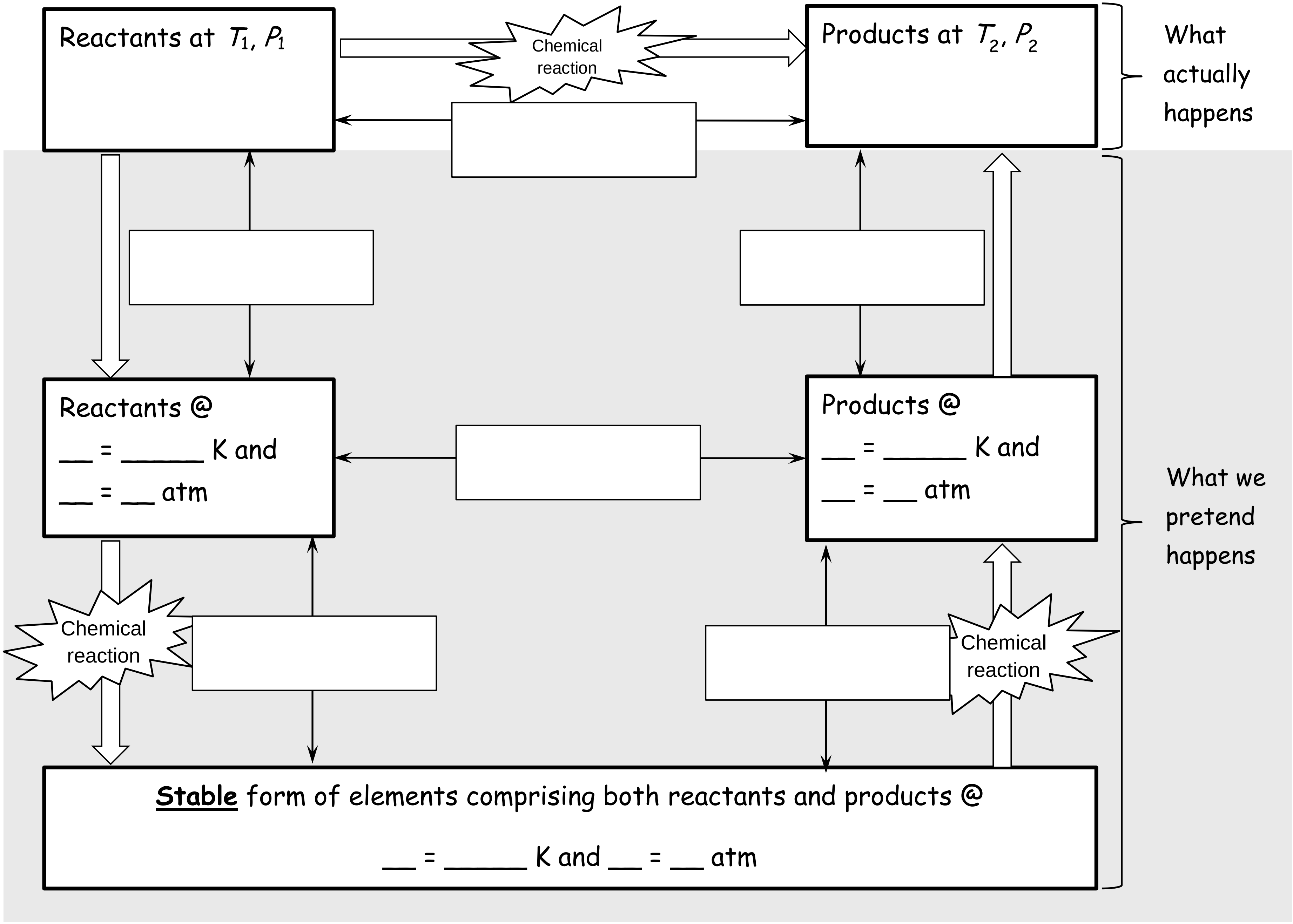
i	T [K]	$\Delta\bar{h}_f^0$ [kJ/kmol]	$\bar{h}(T)$ [kJ/kmol]	$\bar{h}(298\text{K})$ [kJ/kmol]	$\bar{h}$ [kJ/kmol]
$CO_2)_2$					
$CO)_2$					
$H_2O)_2$					
$N_2)_2$					
$CH_4)_1$					
$O_2)_1$					
$N_2)_1$					

EXAMPLE: Combustion in a closed system

Let us reconsider the dubious bovine flatulence energy source problem. As before, the proposed process combusts methane (CH_4) with air and produces 90% CO_2, 10% CO and no O_2 in the products. This time, however, the reaction occurs in a **closed system at constant volume**. The methane and the air are at 1 bar and 25°C before the combustion process, producing products at T = 500 K after the reaction. Find the amount of heat transfer out (in kJ) for the process.



i	T [K]	$\Delta\bar{h}_f^0$ [kJ/kmol]	$\bar{u}(T)$ [kJ/kmol]	$\bar{u}$(298K) [kJ/kmol]
$CO_2)_2$				
$CO)_2$				
$H_2O)_2$				
$N_2)_2$				
$CH_4)_1$				
$O_2)_1$				
$N_2)_1$				


Reactants at T_1, P_1
Chemical reaction
Products at T_2, P_2
What actually happens
Reactants @
__ = ______ K and
__ = __ atm
Products @
__ = ______ K and
__ = __ atm
What we pretend happens
Chemical reaction
Chemical reaction
Stable form of elements comprising both reactants and products @
__ = ______ K and __ = __ atm

If you do this on a **per mass basis**, you have the

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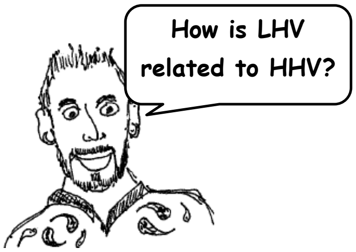
HHV =

LHV =



LHV =

EXAMPLE: Heating values

Reconsider the dubious bovine flatulence problem, but this time assume *complete combustion*. The enthalpy of reaction for methane is –802,290 kJ/kmol-CH_4 at 25°C (298 K) and 1 atm. As before, both the methane and the air enter at 1 bar and 25°C, and the products leave the chamber at 500 K and 1 atm.

(a) Find the heat transfer rate per unit molar flow rate of fuel for the process.
(b) Find the higher heating value, HHV.
(c) Find the higher heating value, LHV.