SESA2023 Propulsion

Lecture 4: Thermodynamics - fundamentals

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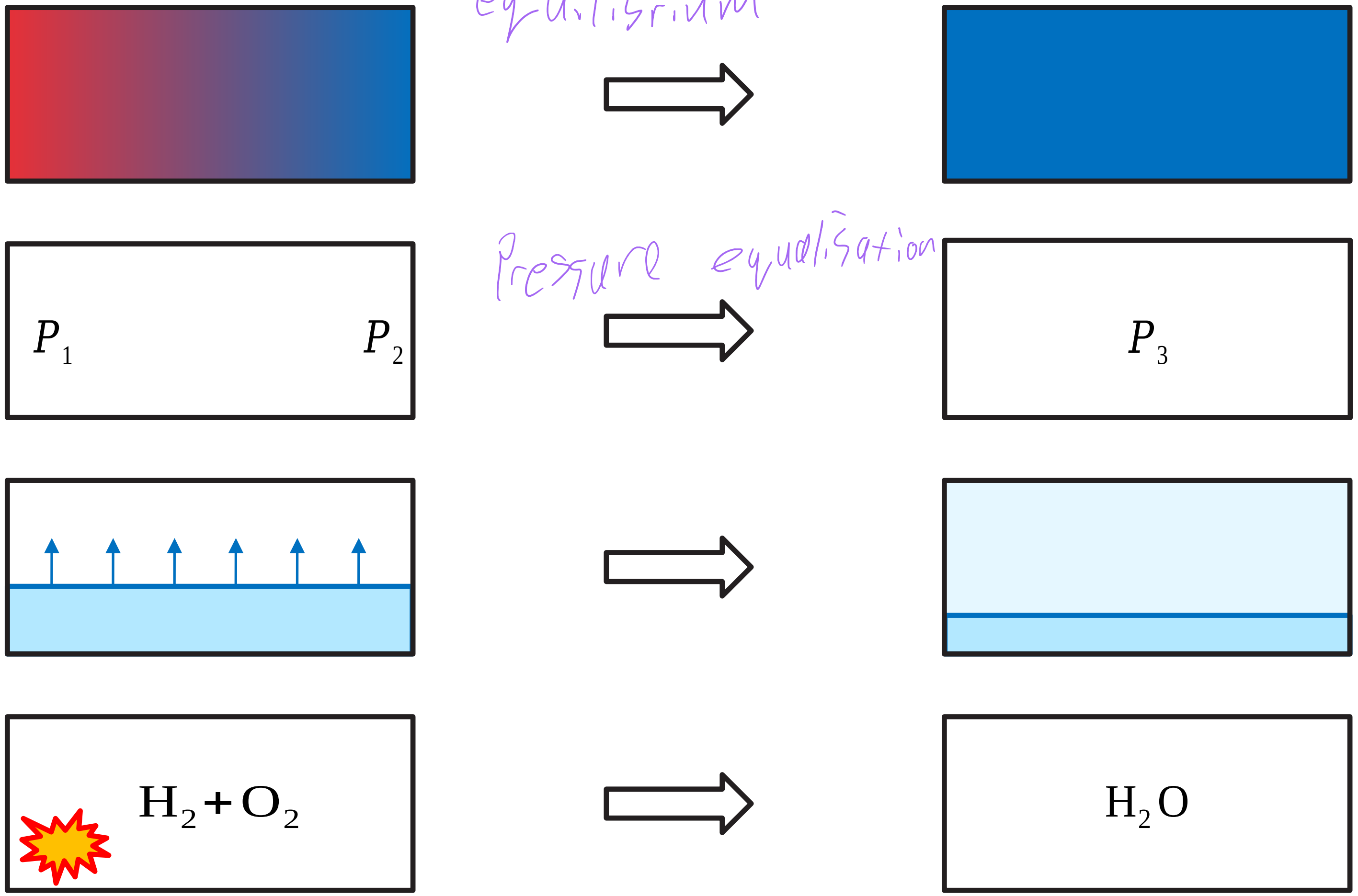
THIS LECTURE

- Equilibrium, state, properties, two-property rule
- Processes and the First Law
- Specific Heat, Ideal Gas, Perfect Gas

THERMODYNAMIC EQUILIBRIUM

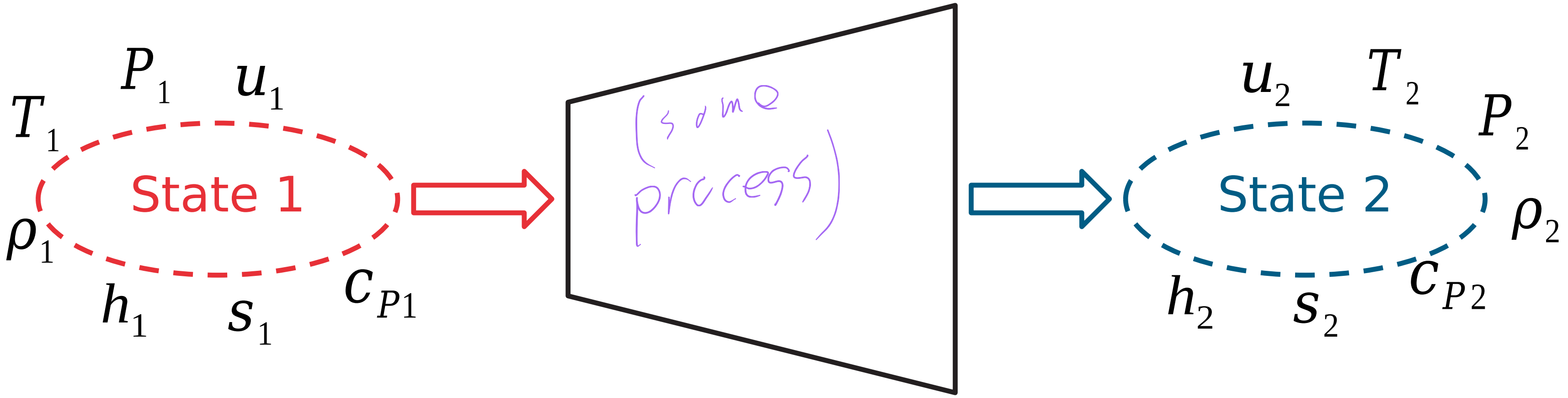
means all of these are in equilibrium

- Thermal equilibrium
- Mechanical equilibrium
- Phase equilibrium
- Chemical equilibrium



STATE AND PROPERTIES

The state of a system defines all properties of that state:

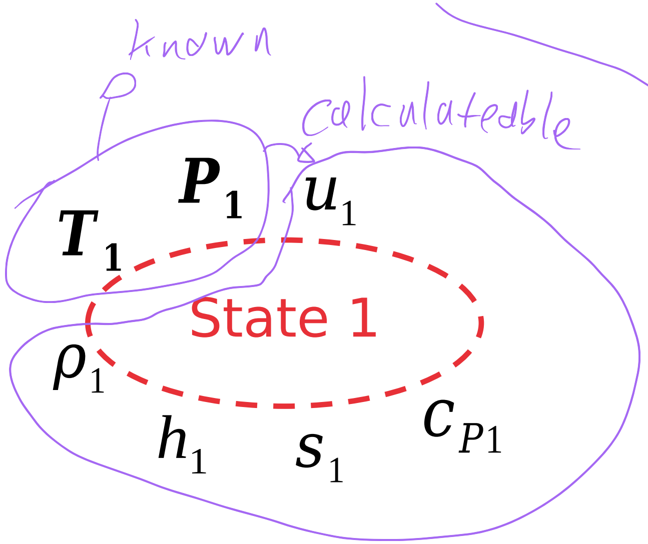


Thermodynamics is predicting/calculating these properties

Which, and how many properties do we need to define a state?

TWO-PROPERTY RULE (STATE POSTULATE)

"The state of a simple compressible system is completely specified by two ***independent*****,** ***intensive*** *properties."*



Note that for an *ideal* gas:

internal energy and temp not independent for ideal gas

$$u = u(T)$$

$$h = h(T)$$

T, *u*, and *h* are not independent!

INTENSIVE, EXTENSIVE, AND SPECIFIC PROPERTIES

are a type of intensive property

Property	Intensive	Extensive	Specific
Temperature	T (K)		
Pressure	P (Pa)		
Volume	v ($\mathrm{m^3\,kg^{-1}}$)	V ($\mathrm{m^3}$)	v ($\mathrm{m^3\,kg^{-1}}$)
Internal Energy	u ($\mathrm{J\,kg^{-1}}$)	U (J)	u ($\mathrm{J\,kg^{-1}}$)
Enthalpy	h ($\mathrm{J\,kg^{-1}}$)	H (J)	h ($\mathrm{J\,kg^{-1}}$)
Entropy	s ($\mathrm{J\,kg^{-1}\,K^{-1}}$)	S ($\mathrm{J\,K^{-1}}$)	s ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Specific heat at constant volume	c_V ($\mathrm{J\,kg^{-1}\,K^{-1}}$)	C_V ($\mathrm{J\,K^{-1}}$)	c_V ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
Specific heat at constant pressure	c_P ($\mathrm{J\,kg^{-1}\,K^{-1}}$)	C_P ($\mathrm{J\,K^{-1}}$)	c_P ($\mathrm{J\,kg^{-1}\,K^{-1}}$)

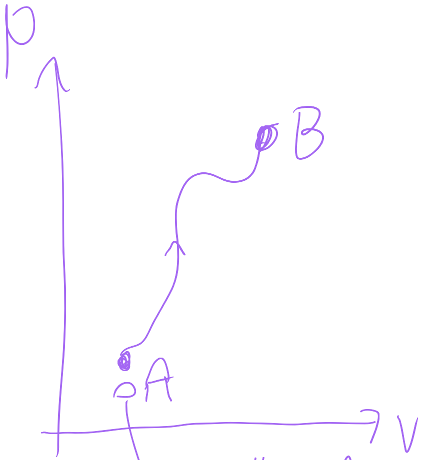
independent of quantity

dependent of quantity

converting extensive to intensive by dividing

Extensive properties depend on the amount of material, with $v = \dfrac{V}{m}, u = \dfrac{U}{m}, \ldots$

PROCESSES AND THE FIRST LAW



state fully defined because mass is constant ∴ have 2 intensive properties (volume becomes specific)

$$\underbrace{U_A - U_B}_{\text{internal energy}} = \underbrace{Q_{AB}}_{\text{heat in}} - \underbrace{W_{AB}}_{\text{work done}}$$ → applicable regardless of path for a system. (first law)

by knowing the process you get information on the path, eg:

- Isothermal ∴ $\Delta U = 0$ →

- Isobaric ∴ $P = \text{const}$ →

ect

note that isenthalpic is constant enthalpy (h)

(aka $h = \underbrace{u}_{\text{int energy — thermal energy} \approx \text{temperature}} + \underbrace{pv}_{\text{pressure energy}}$)

PROCESSES AND THE FIRST LAW: EXAMPLE

$c_v = 0.718$ kJ/kg
ideal air

- Air in state 1 has a temperature T_1 = 300 K.
- During an adiabatic process, 100 kJ/kg of work is done on the air.
- Find the temperature in state 2.

$w_{AB} = -100 \times 10^3$ J/kg

$u_A - u_B = c_v(T_2 - T_1)$

specific

$U_A - U_B = Q_{AB} - W_{AB}$

$\underbrace{u_A - u_B = q_{AB} - w_{AB}}_{\text{first law}}$

$q_{AB} - w_{AB} = c_v(T_2 - T_1)$

know $q_{AB} = 0$

$\therefore -\frac{w_{AB}}{c_v} + T_1 = T_2$

$T_2 = 439$ K

SPECIFIC HEATS, IDEAL AND PERFECT GAS

$$C_v \equiv \left.\frac{\partial u}{\partial T}\right|_{V=const}$$

$$C_p \equiv \left.\frac{\partial h}{\partial T}\right|_{p=const}$$

$$\gamma \equiv \frac{C_p}{C_v}$$

always true (no assumptions)

note that for a real gas C_v, C_p, γ are not constant and are funtions of temp and pressure!

$C_v(T, p)$

$C_p(T, p)$

note $C_v(T, v)$ also valid (2 intensive properties)

approximations to get constants

done for practical approximations

assumptions

1) Ideal gas

i.e. $[pV = RT]$

consequentially

$u = u(T)$, $h = h(T)$ functions of only temp

consequentially

$C_v = C_v(T)$

$C_p = C_p(T)$

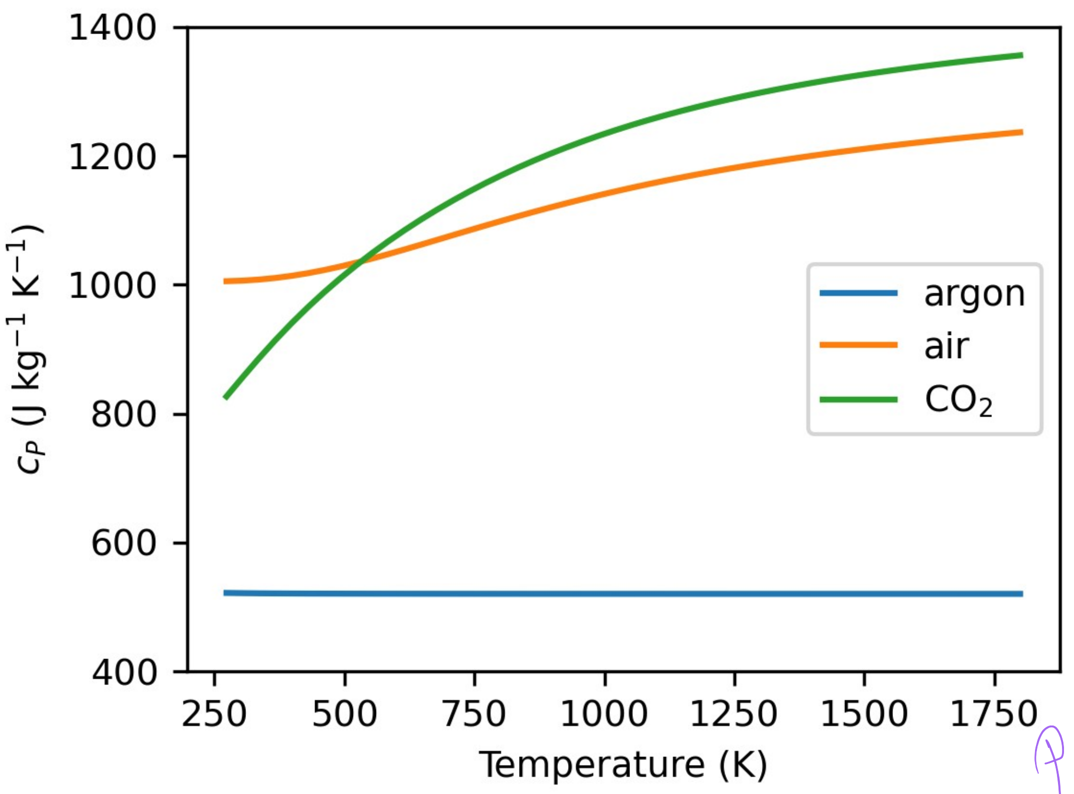
2) Perfect gas

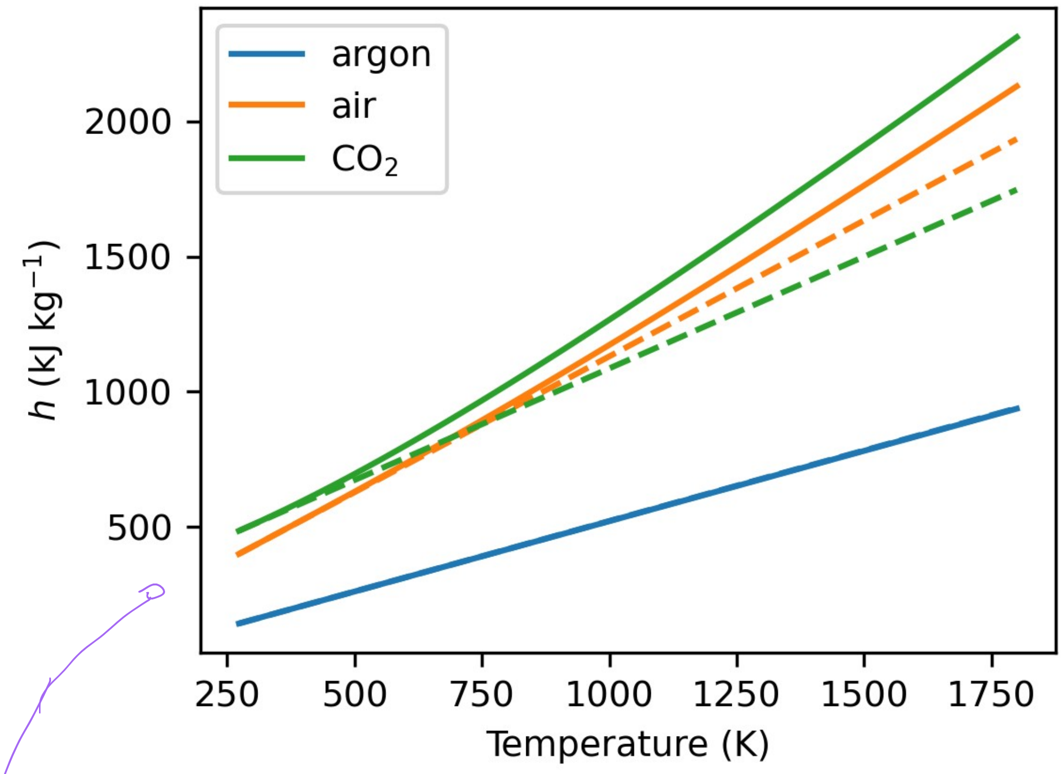
assumes C_p and C_v are constants

$\therefore \Delta u = C_v \Delta T$

$\therefore \Delta h = C_p \Delta T$

SPECIFIC HEATS, IDEAL AND PERFECT GAS





Dashed lines: perfect gas assumption

approximations are ok
for some conditions

REAL FLUID PROPERTIES

CoolProp example Jupyter notebook on Blackboard:

Example: isentropic compression of nitrogen

Below an example of compressing nitrogen isentropically from 1 bar, 300 K to 25 bar, finding the change in enthalpy.

In [10]:
```
# Inlet conditions:
p1 = 1e5
T1 = 300
s1 = props('S', 'P', p1, 'T', T1, 'nitrogen')
h1 = props('H', 'P', p1, 'T', T1, 'nitrogen')
# Outlet conditions:
p2 = 25e5
s2 = s1
h2 = props('H', 'P', p2, 'S', s2, 'nitrogen')
# Change in enthalpy
print('h2 - h1 = %0.2f kJ/kg' % ((h2-h1)/1000))
```

```
h2 - h1 = 469.46 kJ/kg
```

SUMMARY + 10 MINUTE BREAK

- Use the two-property rule to calculate the state of a fluid
- Processes and First Law of thermodynamics
  - Isothermal, isobaric, isochoric, adiabatic/isentropic, isenthalpic
- Specific heats
  - Definition, real fluid, ideal gas, perfect gas

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Lecture 5: Mixtures of gases

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THIS LECTURE

- Mass fractions and molar fractions
- Partial pressure and partial volume
- Properties of mixtures

MASS FRACTIONS AND MOLAR FRACTIONS

EXAMPLE: HYDROGEN AND OXYGEN MIXTURE

(From problem sheet 1) For complete combustion, for each kg of hydrogen, 7.94 kg of oxygen needs to be supplied…

Find the mass and molar fraction of hydrogen in the mixture

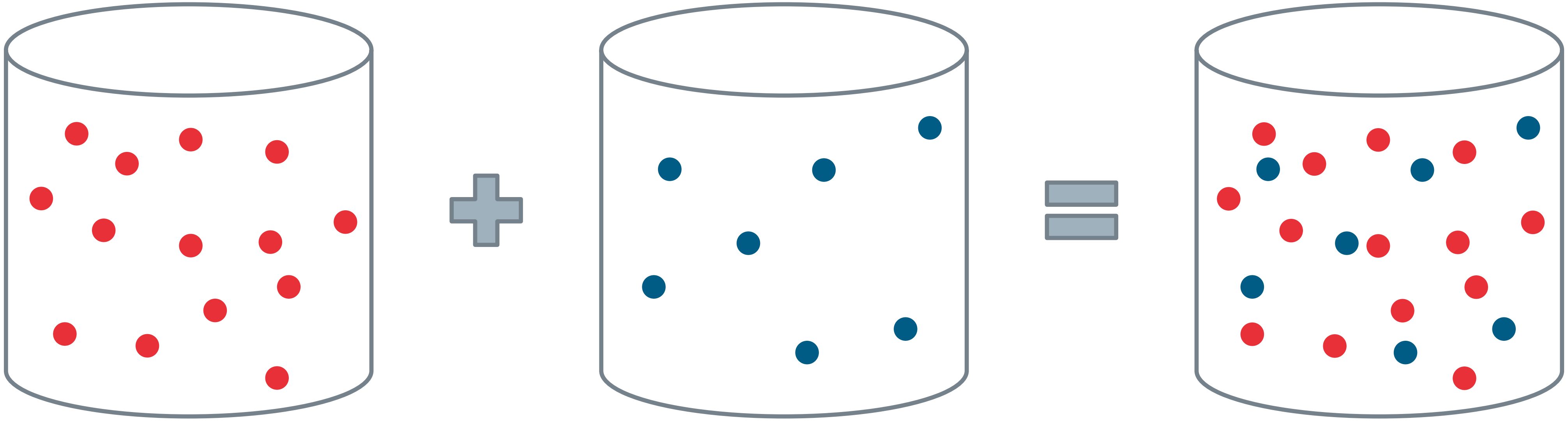
Data book on Blackboard

TABLE 2

Gas	Molar mass kg/kmol	Gas constant kJ/kg K	Specific heat capacity kJ/kg K c_p	c_v	c_p/c_v
Air	29	0.287	1.01	0.72	1.40
Atmospheric nitrogen†	28.15	0.295	1.03	0.74	1.40
N_2	28	0.297	1.04	0.74	1.40
O_2	32	0.260	0.92	0.66	1.40
A	40	0.208	0.52	0.31	1.67
H_2	2*	4.120	14.2	10.08	1.41

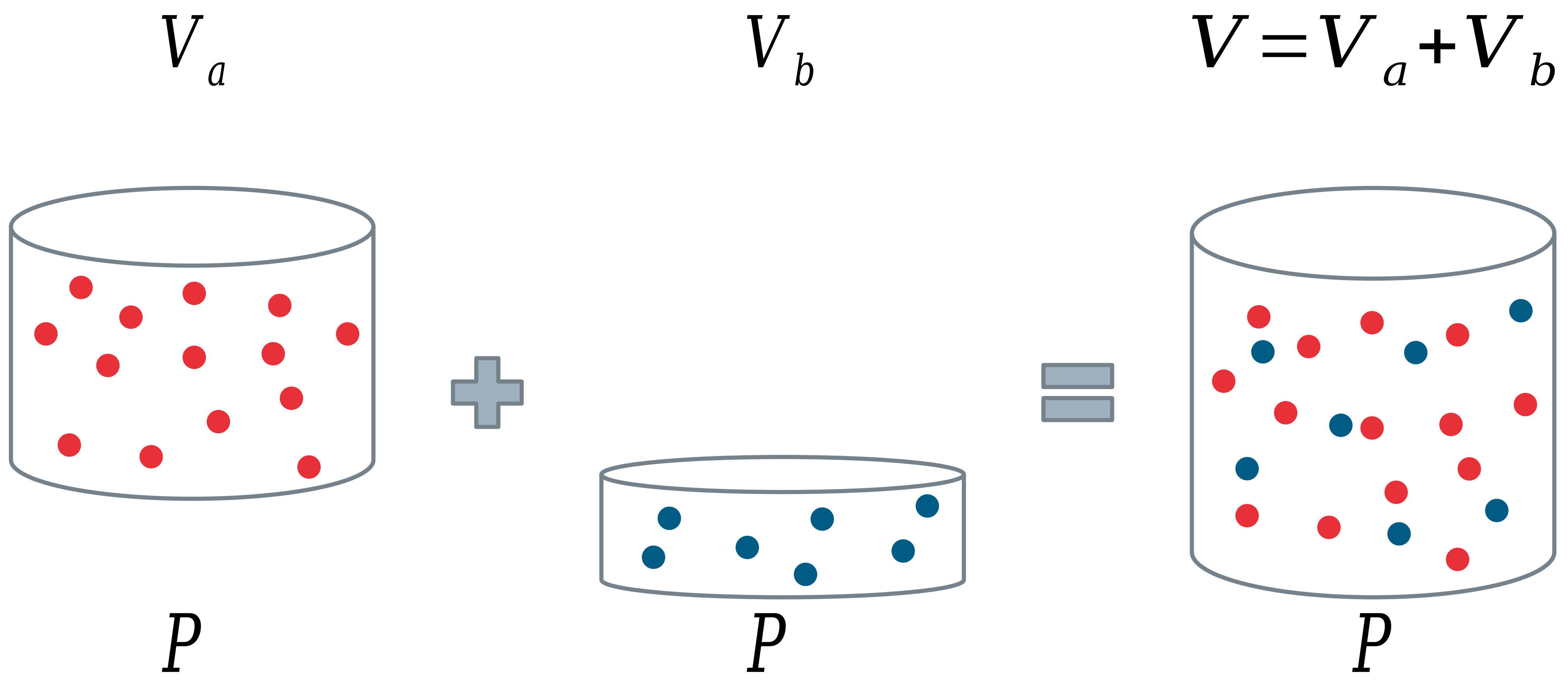
PARTIAL PRESSURE AND PARTIAL VOLUME

P_a $\qquad$ P_b $\qquad$ $P = P_a + P_b$



V $\qquad$ V $\qquad$ V

PARTIAL PRESSURE AND PARTIAL VOLUME



EXAMPLE: HYDROGEN AND OXYGEN MIXTURE PART 2

(From problem sheet 1) For complete combustion, for each kg of hydrogen, 7.94 kg of oxygen needs to be supplied…

Find the partial pressure of the hydrogen and oxygen if the gas mixture is at 20 bar.

Data book on Blackboard ⇨

TABLE 2

Gas	Molar mass	Gas constant	Specific heat capacity		c_p/c_v
	kg/kmol	kJ/kg K	kJ/kg K		
			c_p	c_v	
Air	29	0.287	1.01	0.72	1.40
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PROPERTIES OF MIXTURES

EXAMPLE: FIND THE C_P VALUE OF AIR

TABLE 2

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			c_p	c_v	
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Air composition:
Volumetric (and molar): 21.0% O_2, 79.0% atmospheric nitrogen.
Gravimetric: 23.2% O_2, 76.8% atmospheric nitrogen.

SUMMARY

- Mass and molar fractions
  - Convert between x_i and y_i using molar mass
- Partial pressure and partial volume
  - Relation to molar fraction
- Properties of mixtures
  - Add extensive properties
  - Use mass fractions for intensive properties

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Lecture 6: SFEE and Entropy

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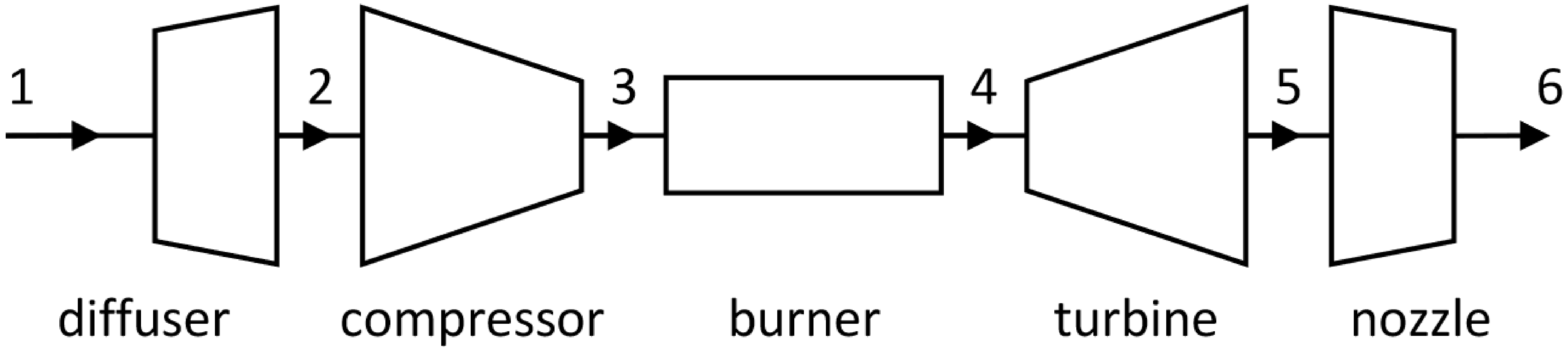
THIS LECTURE

- Steady Flow Energy Equation (SFEE) reminder, common assumptions
- SFEE for a turbojet
- Entropy definition and calculations
- Isentropic efficiency for compressor and turbine

STEADY FLOW ENERGY EQUATION

SFEE FOR A TURBOJET ENGINE



TURBOJET EXAMPLE

A turbojet engine is operating at a velocity of 200 m/s, with a local temperature of 250 K and pressure of 50 kPa.

What is the inlet temperature and pressure of the compressor?

ENTROPY

CHANGES IN ENTROPY

ISENTROPIC EFFICIENCY

TURBINE EXAMPLE

Air at p = 30 bar and T = 1500 K enters a turbine with an outlet pressure of 1 bar and an isentropic efficiency of 85%.

What is the outlet temperature and the work done by the turbine?

SUMMARY

- Steady Flow Energy Equations basics
  - Turbojet engine component analysis
- Entropy
  - Definition
  - Finite changes in entropy
- Isentropic efficiency
  - Compressor and turbine