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School of Engineering

Engineering Thermodynamics (Mechanical) 2

MECE08014

Mechanical Engineering

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15th Jan. 2025

*some course materials derived from those previously created by Dr. Brian Peterson

Outline

- Brief Intro from Yr 2 Coordinator and Cohort leads
- Course Overview
  - Lectures, tutorials, lab, exam
  - Expectations
  - Keys to success
- Brief Overview of Thermodynamics
- Lecture 1 Material: Thermodynamics – Basic Concepts

Course Layout

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Lecture Schedule & Topics

Topic 1: Basic concepts
- Lecture 1: Basic concepts
- Lecture 2: Pure substances
- Lecture 3: Pure substances

Topic 2: Energy & 1st Law
- Lecture 4: Energy via work and heat
- Lecture 5: Closed systems
- Lecture 6: Specific heats
- Lecture 7: Control volumes
- Lecture 8: Steady state flow devices

Topic 3: Entropy & 2nd Law
- Lecture 9: Heat engines
- Lecture 10: Carnot Cycle
- Lecture 12: Entropy
- Lecture 13: Entropy
- Lecture 14: Entropy

Lecture 11: Heat pump Lab lecture

Topic 4: Thermo. systems
- Lecture 15: Refrigeration cycles
- Lecture 16: Rankine cycles
- Lecture 17: Rankine cycles
- Lecture 18: Otto cycle
- Lecture 19: Diesel cycle
- Lecture 20: Brayton cycle
- Lecture 21: Brayton cycle

Lecture 22: Exam example class.

Course Layout

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Tutorial Sessions

10 Tutorial sessions (Weeks 2-11)

- Mondays 10:00 and 11:10 - Alder Lecture Theatre*
  *except weeks 3 and 7, 11:10 session will be in Yew Lecture Theatre

- **Active tutorial sessions**
- Tutors give 10-15 min lecture in the beginning of each tutorial session
- Lecture will cover topical aspects in further detail… some of these aspects will not cover in lectures
- Lecture will also help students set up the more challenging tutorial questions
- Solutions provided on Learn after tutorial sessions

Course Layout

Course Assessment

Laboratory (Weeks 6-11) – 20% coursework assessment

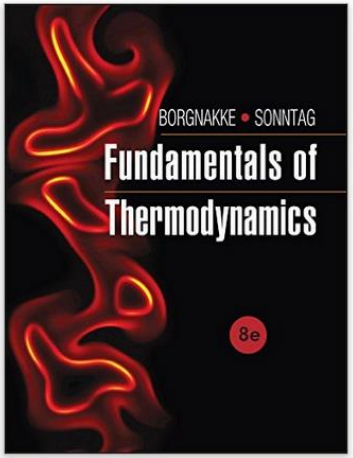
- 1 hour laboratory session per student
- Students will sign up to a single laboratory session
  - 4-6 students per lab session
  - Each student will use their own device to remotely access the system
- Laboratory will cover the heat pump / refrigeration systems

Final Exam (TBD) – 80% exam assessment

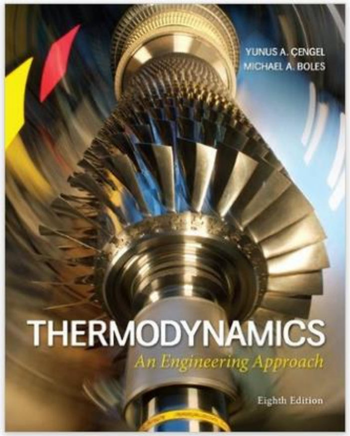
- OPEN BOOK EXAM!
  - Thermodynamic Tables will be provided for the exam.
  - Allowed: single A4 page (front & back) with handwritten notes.

Textbook

- Fundamentals of Thermodynamics ed. 8e &10e (SI units only) by Borgnakke & Sonntag
  - Available on amazon.co.uk (prices vary)
  - On-line access provided through library
  - Lectures will be based on this text



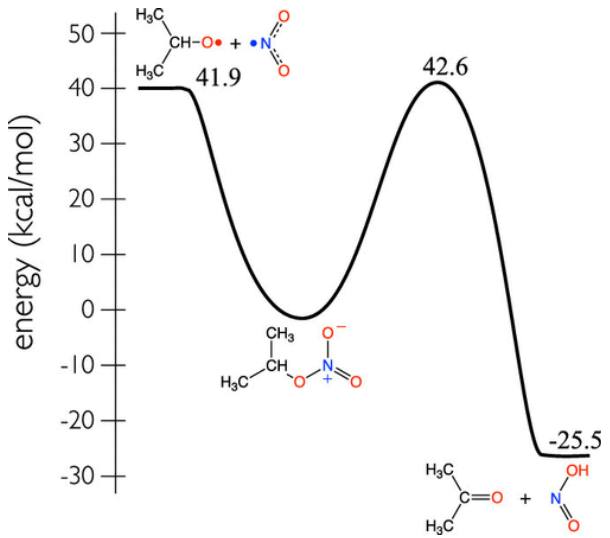
- Other Editions of Borgnakke & Sonntag can be used
- Other Thermodynamics books can be used
  - Material & Tables are the same
  - Thermodynamics: An Engineering Approach by Cengel & Boles
    - Available in Library
    - Used for Thermodynamics 4



Course Perspective

- This course is often the student's first exposure to thermodynamics
  - Can be difficult for those who do not like chemistry

- Physical chemistry
  - Principles of physics applied to chemical systems to describe energy, motion, force, amongst many other things.
  - Problems involve several variables that are dependent upon each other (e.g. temperature, pressure, volume, etc.)



Preparation for Success

How does one do well in this course?

- Attend lecture & tutorials
  - Detailed example problems worked out on board
  - Take notes!!!
  - Actively participate – answer / ask questions
- Read the textbook
- Do not study the problem, study the material so that you can solve *any* problem
  - Understand and learn how to apply first principles
  - All solutions can be solved by deriving from first principles
- Use office hours (2.2418 JCMB: Thursdays 13:00-14:00)

Brief Overview of Thermodynamics

- What is thermodynamics?
- How does it affect our daily lives?
- Why should we study thermodynamics?

What is thermodynamics?

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- Thermodynamics – branch of science concerned with heat and temperature and their relation to energy and work.

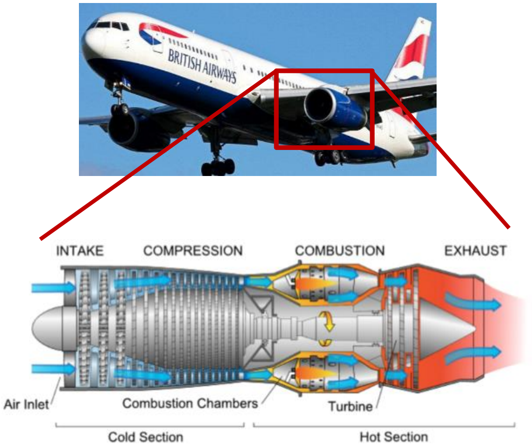
- The study of thermodynamics includes a broad range of topics related to *energy* and *energy transformations*, which involve *heat* and *work*.

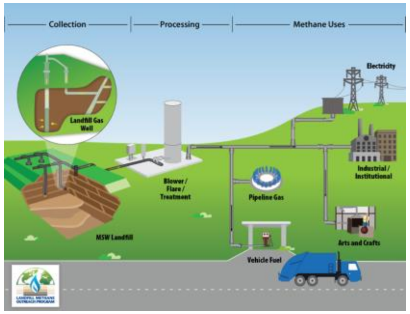
What is Thermodynamics?

A common theme within thermodynamics is energy transformation

Heat ↔ Δ Energy ↔ Work

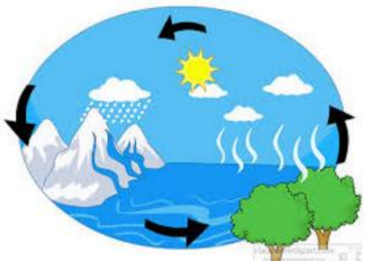
chemical energy → heat → mechanical propulsion





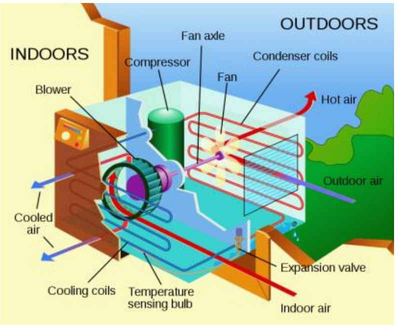
Waste carbon power generation

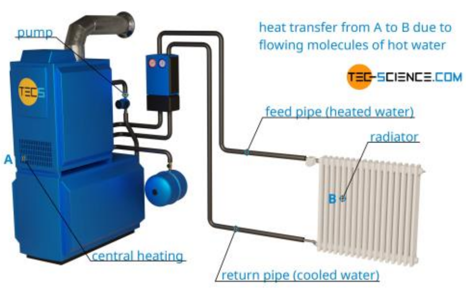
Nature



Solar, wind, tidal energy
Weather, phase change

chemical energy + mechanical work → heat





Why Study Thermodynamics?

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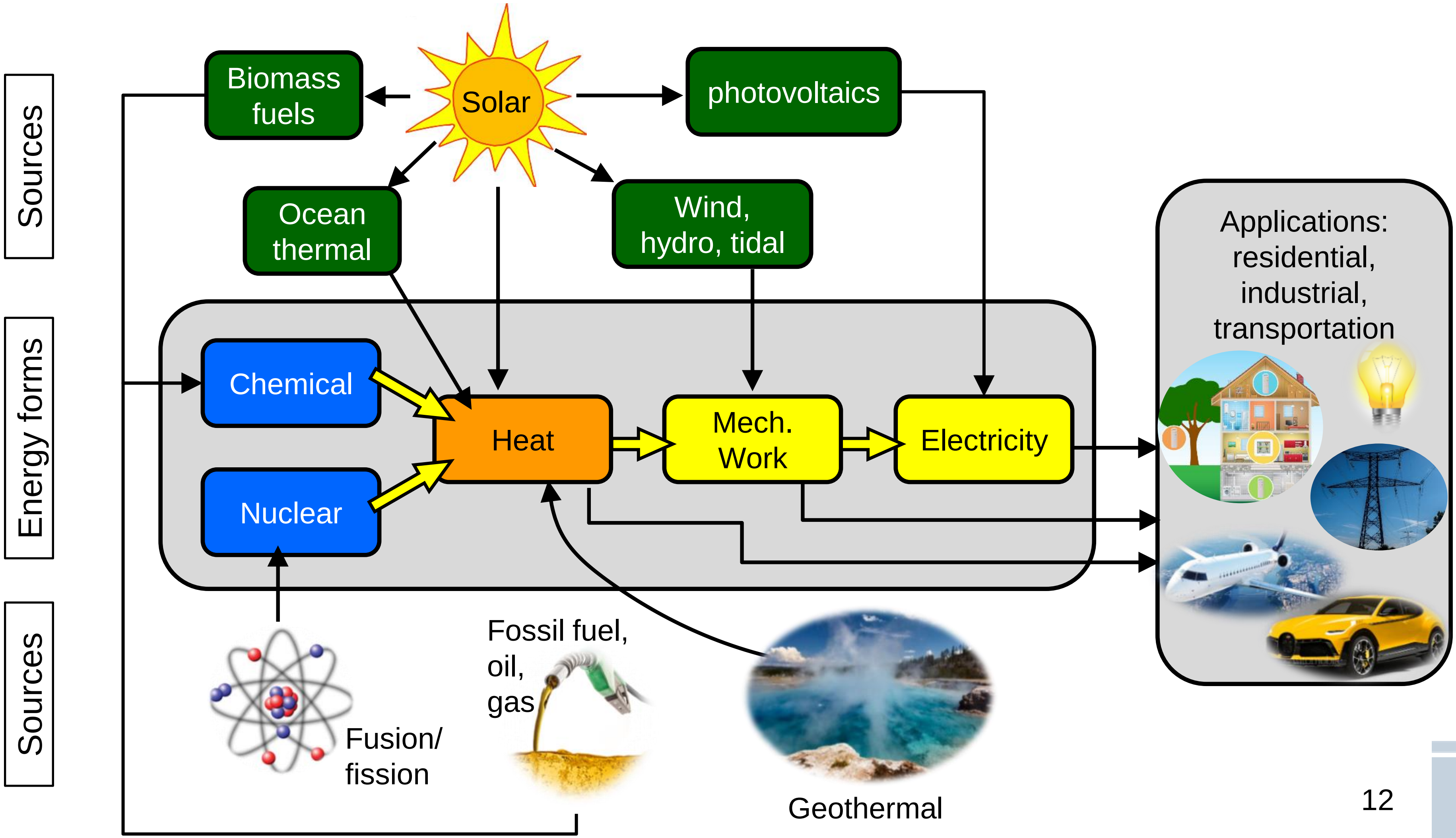
Objective: convert available energy into work in the most efficient manner, while considering cost, size, safety and environment.



Why Study Thermodynamics?

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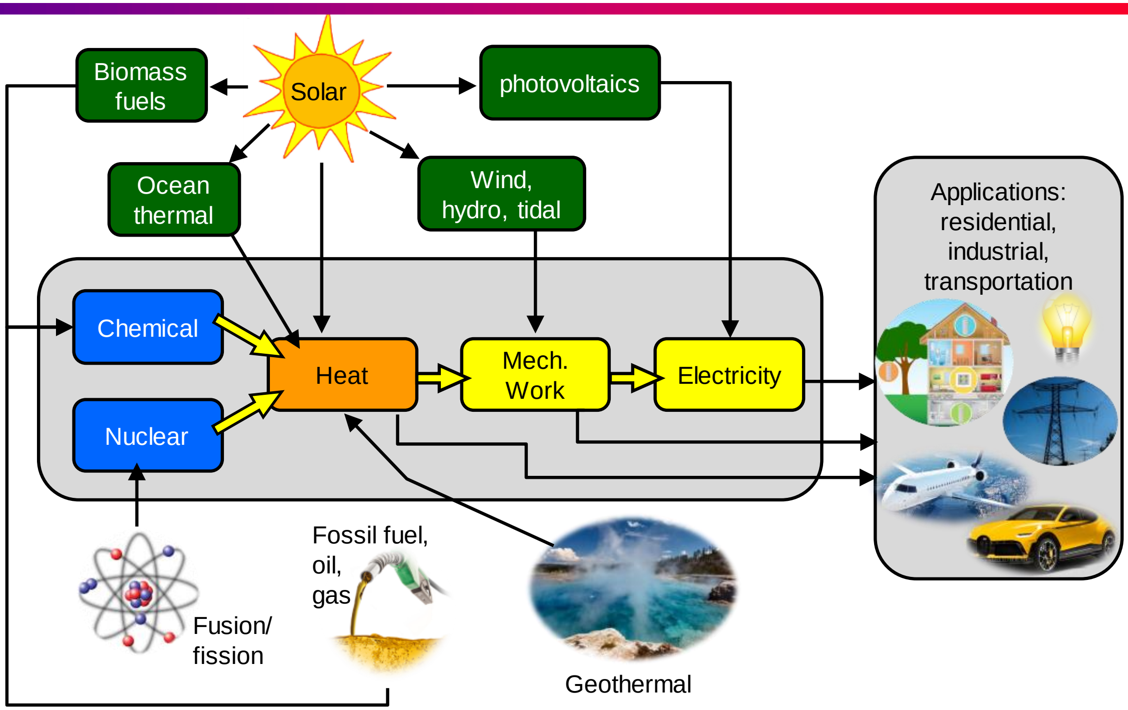


- Society depends on energy (too much!)
  - No single energy supply can accommodate the demand!
- Improve & innovate
  - Cleaner & more reliable technologies
  - Renewable & fossil fuels
- Strong understanding of thermodynamics is needed

Lecture 1

Topic 1.1:

Basic Concepts

reading material
Ch. 1 Borgnakke & Sonntag: Introduction
Ch. 1 Cengel and Boles

Underpinning concepts in thermodynamics
Relationships between pressure, volume and temperature

1.1.1 Thermodynamic Systems

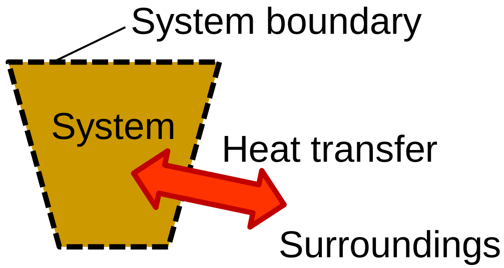
- **Thermodynamic system**: quantity of matter (e.g. fluid/solid) that is described by thermodynamic state variables (e.g. temperature, pressure, volume, internal energy, … etc.)
- **Surroundings**: physical space outside the system boundary
- **System boundary**: real or imaginary surface that separates the system from surroundings. Boundary may be fixed or moveable.

- Example:

Cup of Coffee

1.1.1 Thermodynamic Systems

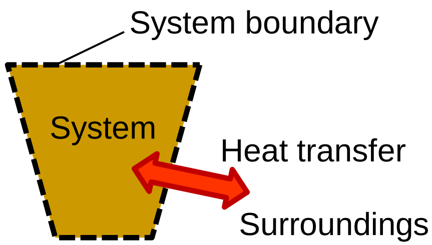
- Important to always define the thermodynamic system, boundary, and surroundings
  - Draw it out!

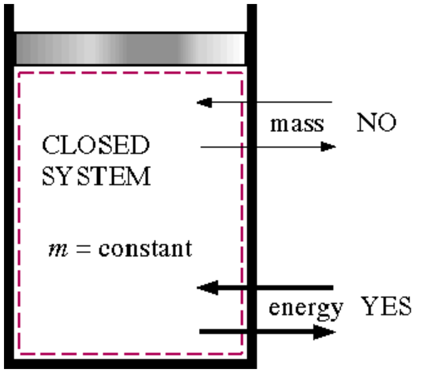


Systems may be considered to be closed or open, depending on whether a fixed mass or a fixed volume in space is chosen for study.

1.1.1.1 Closed System

- A closed system consists of a fixed amount of mass
- **NO** mass may cross the system boundary
  - Energy in the form of **heat** and **work** may cross the boundaries.

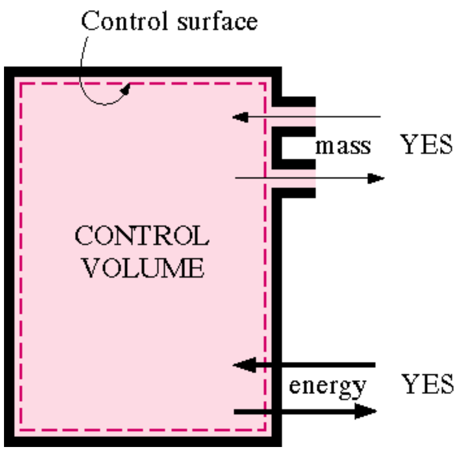




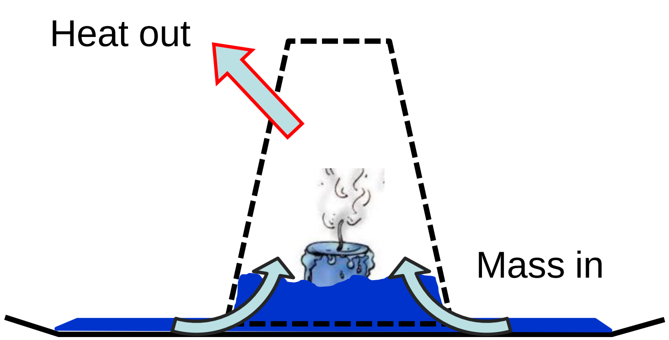
- Work usually occurs as boundaries move
  - Volume can be displaced (i.e. may not be fixed!)
  - Example: piston cylinder device

1.1.1.2 Open System

- Open system, or control volume:
  - Mass and energy can cross the boundary
  - Boundary is called a <u>control surface</u>.

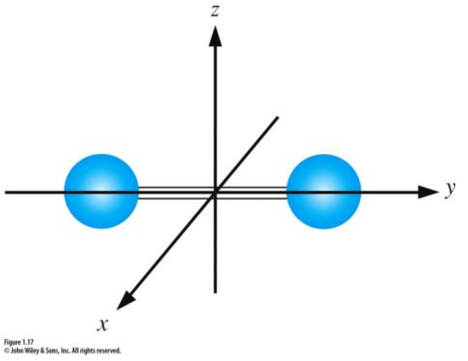


- Water/glass experiment is an example of an open system
  - Mass (water) flows into the system (glass)

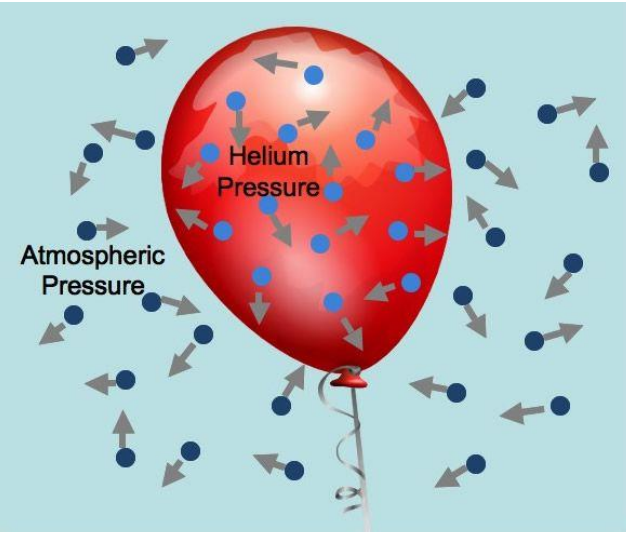


1.1.2 Classical Thermodynamics

- Microscopic (statistical) thermodynamics
  - Based on average behavior of individual particles of a system
  - Statistical considerations and probability theory used to model particle behavior



- Macroscopic (classical) thermodynamics
  - Measurable effects of entire system (avg. effect of ALL particles)
  - Overall exchange of energy, work, and heat
  - Force / pressure example: particles under pressure/vaccuum apply normal force on boundaries.



1.1.3 Properties and State of a Substance

Thermodynamic Properties

- Measurable property whose value describes a state of the thermodynamic system <u>in equilibrium</u>.
  - Pressure (P), temperature (T), volume (V), mass (m), internal energy (U), enthalpy (H), entropy (S)

- Properties of substance in a given state can only have one value (i.e. properties always have the same value for a given state)

<u>Water @ 20C, 4.246 kPa</u>
- Specific volume: 0.001004 m^3/kg
- Internal Energy (u) = 125.77 kJ/kg

<u>Steam @ 100C, 10 kPa</u>
- Specific volume: 17.2 m^3/kg
- Internal Energy (u) = 2515.5 kJ/kg

- ***<u>State postulate</u>: the state of a substance is completely specified by two independent, intensive properties***

1.1.3 Properties and State of a Substance

Thermodynamic Properties

- Extensive vs. intensive properties

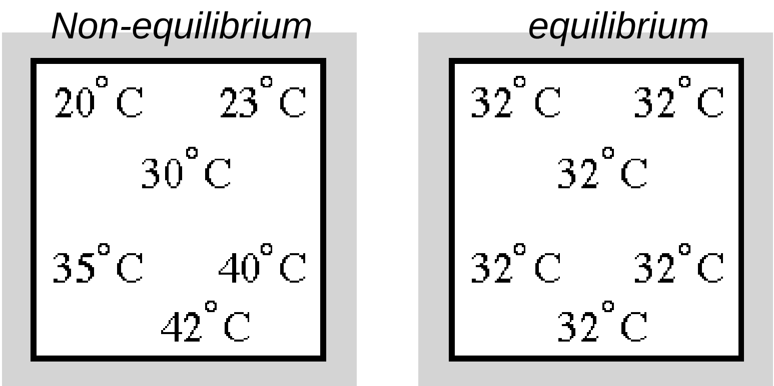
- Extensive: properties that vary directly with mass
- Intensive: properties that are independent of mass

<u>Extensive Properties</u>
a. mass
b. volume
c. total energy
d. mass dependent property

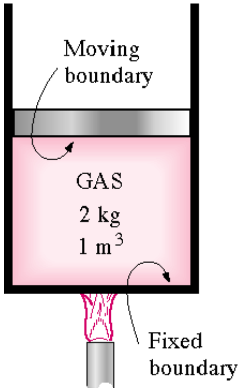
<u>Intensive Properties</u>
a. temperature
b. pressure
e. any mass independent property

1.1.4 Equilibrium

Equilibrium – system is in equilibrium if macroscopic physical properties are not changing



(*a*) Before (*b*) After



Example: heat added to gas, expanding the system. Less concerned with incremental steps between states

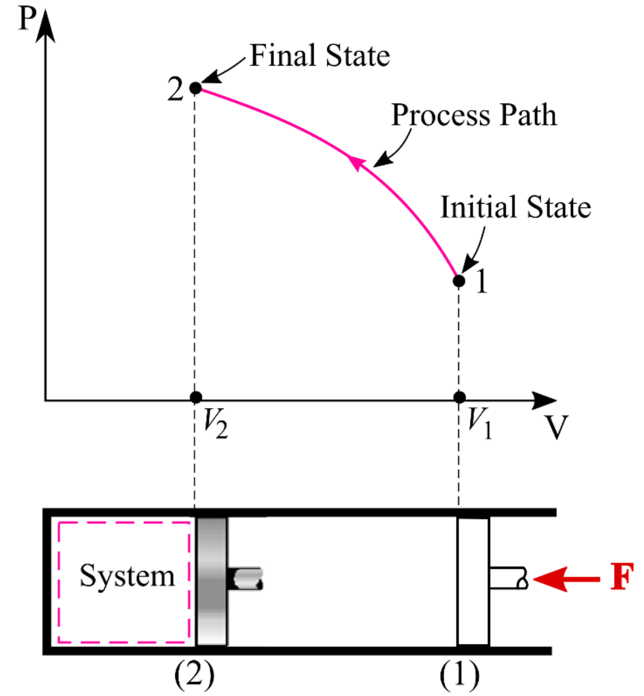
- When one or more system properties change, a change in state has occurred
- Assume <u>quasi-equilibrium</u> process – each incremental step reaches equilibrium
    - System remains in equilibrium at all times

1.1.5 Processes and cycles

- **Thermodynamic State**: condition that is fully described by system variables (i.e. physical properties: T, P, V, etc.)
- **Process** - Path of succession of states which the system passes
  - Describes how one arrives from one state to another.
  - Process path describes energy transfer between states.

- Process paths are often shown in 2D diagrams such as the *P-V* (Pressure-Volume) diagram

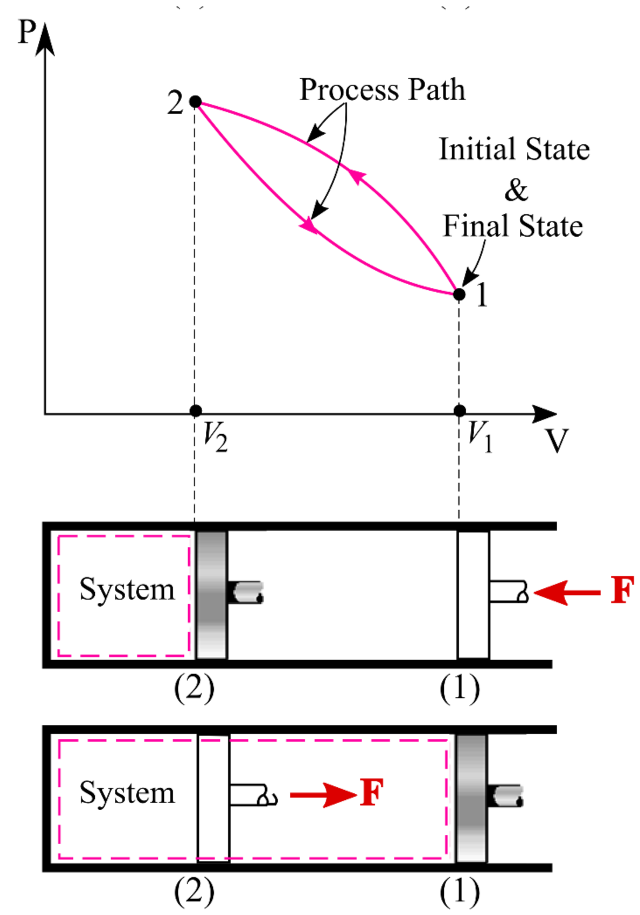
- A state is *independent* of the process path



1.1.5 Processes and cycles

- Process path often defines the energy involved in the process
  - Example: WORK is area under P-V curve

- **Cycle** – a series of connected processes with identical start & end states



Let's look back at the water/glass experiment

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Thermodynamic definitions:

System: contents inside glass

Surroundings: contents outside glass

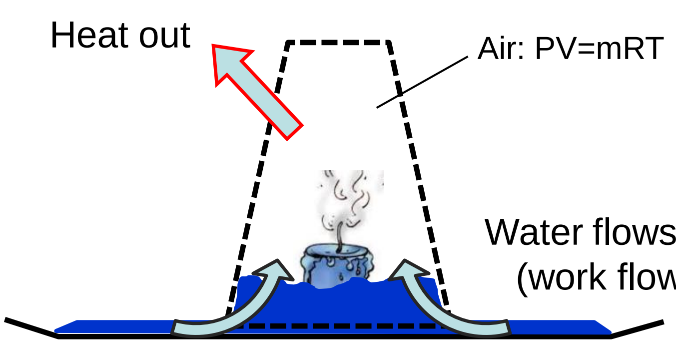
Objective:

Describe Energy Processes from state 1 → 2 → 3.

- State 1: cool air/water + candle lit
    - Process:
- State 2: higher temperature air, water
    - Process:
- State 3: cool air, vacuum
    - Process:

Heat → Δ Energy → Work

Experiment



Air behaves similar to ideal gas (PV = mRT)

$$\frac{P_2V_2}{m_2RT_2} = \frac{P_3V_3}{m_3RT_3}$$

$$P_3 \sim P_2\frac{T_3}{T_2}$$

1.1.6 Variables & Units

- Consistent use of units in calculations is essential.
- Many systems exist. We will use SI units in this course.

	SI	USCS/Imperial	Slug
Mass	**Kilogram (kg)**	Pound-mass (lbm)	Slug-mass (slug)
Time	**Second (s)**	Second (s)	Second (s)
Length	**Meter (m)**	Foot (ft)	Foot (ft)
Force	**Newton (N)**	Pound-force (lbf)	Pound-force (lbf)

- Below is a list of common units we will use for variables in this course

Variable	**Symbol**	**Unit(s)**	**Variable**	**Symbol**	**Unit(s)**	**Variable**	**Symbol**	**Unit(s)**
Pressure	P	Pa, kPa, bar	Work	W	Joules (J)	Internal energy	u	kJ/kg
Temperature	T	^{o}C, K	Heat	Q	Joules (J)	Enthalpy	h	kJ/kg
Volume	V	m^3, Liter (L)	Velocity	v	m/s	Entropy	s	kJ/kg*K
Density	ρ	kg / m^3	Mass	m	kg, g	Molecular weight	M	g/mol, kg/kmol
Specific volume	*v*	m^3/kg	Force	F	N	Energy	E	J, kJ

* Character k in front of symbol indicates kilo (10^3), M indicates Mega (10^6)

1.1.7 Pressure

Definition

- Normal force per unit area. SI unit is the pascal: N/m^2.

$$P = \lim_{\delta A \to \delta A'} \frac{\delta F}{\delta A} \qquad P = \frac{Force}{Area} = \frac{F}{A}$$

$$1\ kPa = 10^3 Pa\ or\ N/m^2$$
$$1\ MPa = 10^6 Pa = 10^3 kPa$$
$$1\ bar = 10^5 Pa = 100 kPa$$
$$1\ atm = 101.3\ kPa$$

- Example: piston/cylinder filled with gas
  - Pressure from gas acts on boundaries
  - Pressure fixed by external force
  - Increase force on piston, increases gas pressure
  - If force on piston remains constant, yet piston moves, pressure in chamber will remain constant

1.1.7 Pressure

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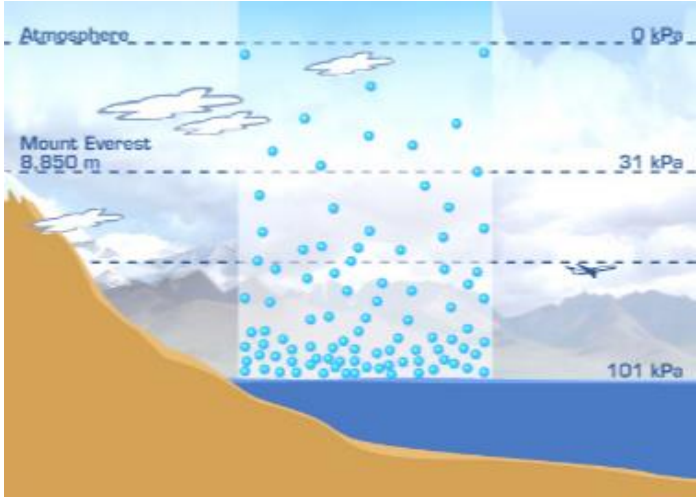
Absolute, atmospheric, gauge and vacuum

- The pressure used in calculations of state is the <u>absolute pressure</u>
  - Relative to absolute zero pressure (absolute vacuum).
- Atmospheric pressure: exerted by weight of atmosphere
  - Sea level: 1atm, 101.325 kPa, 760 mmHg, 14.696 psia



- Gauge pressure is relative to atmospheric pressure.

- Pressure Relations:

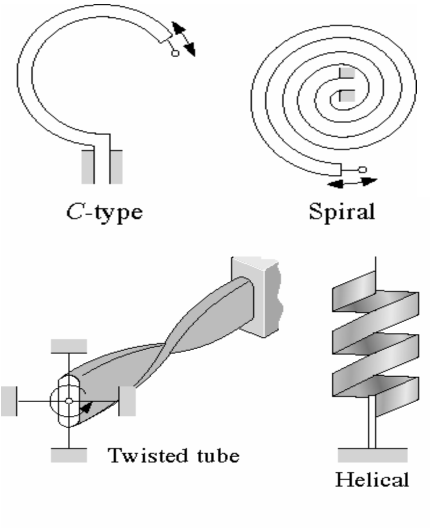
$$P_{abs} = P_{atm} \pm P_{gage} \qquad P_{gage} = P_{abs} - P_{atm} \qquad P_{vac} = P_{atm} - P_{abs}$$

Note: $+P_{gage}$ is used when $P_{abs} > P_{atm}$ and $-P_{gage}$ is used for a vacuum gauge.

1.1.7 Pressure

Measuring pressure

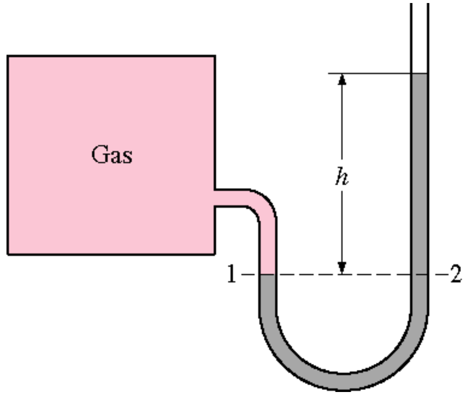
- Several devices for measuring pressure differences.
- Often electronic pressure gauges are used to measure small displacements in a gauge diaphragm.



Examples of devices are all forms of a Bourdon gauge

- Small to moderate pressure differences can be measured by a <u>manometer</u>
  - Pressure difference is determined from the manometer fluid displaced height as:

$$\Delta P = \rho g h \qquad (kPa)$$



1.1.8 Temperature

Definition

- Temperature often recognized as a measure of “hotness” or “coldness”.
- Thermodynamic property that is a measure of the energy content of a mass.
  - When heat is transferred to a system, the system's energy increases.
  - A temperature difference results in **heat transfer**. Energy flows from a hotter to a colder body.
  - Two bodies are in thermal equilibrium when they have reached the same temperature. If two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. Known as the ***zeroth law of thermodynamics***.

Temperature scales

- SI: Celcius (^oC)　　　　Imperial: Fahrenheit (^oF)

$$T^\circ F = \frac{9}{5} T^\circ C + 32$$

1.1.8 Temperature.

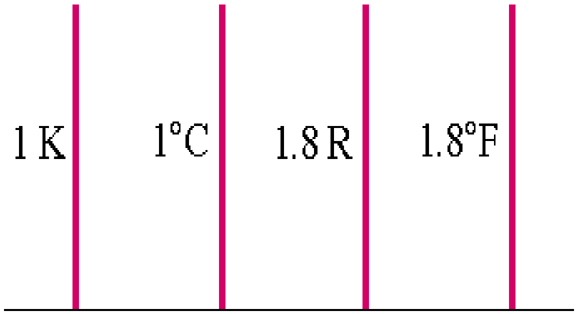
Absolute unit of temperature

- SI: Kelvin (K), Imperial: Rankine (R)

$$T\,K = T\,^\circ\mathrm{C} + 273.15 \qquad\qquad T\,R = T\,^\circ\mathrm{F} + 459.67$$

- Also, note that: $T\,R = 1.8\,T\,K$

- The magnitudes of each division of 1 K and 1°C are identical, and so are the magnitudes of each division of 1 R and 1°F. That is,



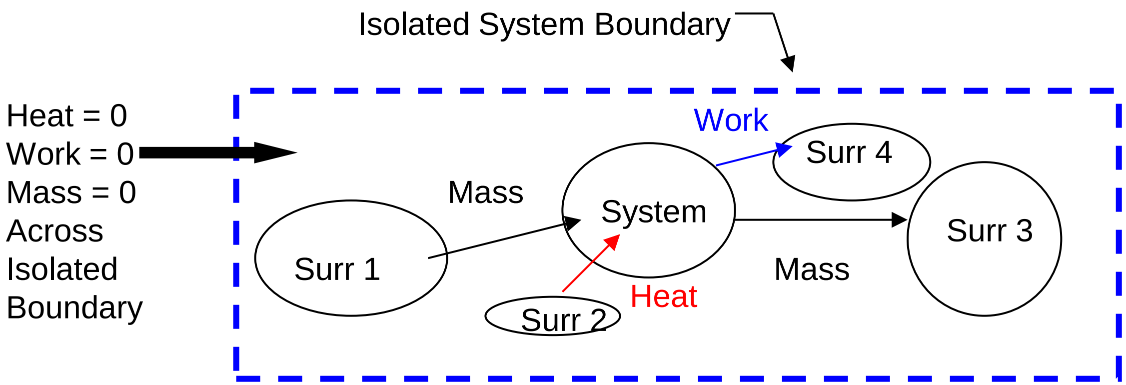
$$\Delta T\,K = (T_2\,^\circ\mathrm{C} + 273.15) - (T_1\,^\circ\mathrm{C} + 273.15)$$
$$= T_2\,^\circ\mathrm{C} - T_1\,^\circ\mathrm{C} = \Delta T\,^\circ\mathrm{C}$$
$$\Delta T\,R = \Delta T\,^\circ\mathrm{F}$$

1.1.9 Energy.

- Finite amount of mass posses energy
  - Internal energy, kinetic energy, & potential energy
  - $E = U + KE + PE$
  - In per unit mass form: $e = E/m = u + ke + pe = u + \frac{1}{2}V^2 + gz$
- KE: translational energy: $\frac{1}{2}mV^2$
- PE: energy associated with external gravitational force: mgz
- U: set of energies associated with microscopic motion of individual molecules of a substance
  - $u = u_{external\ molecule} + u_{translational} + u_{internal\ molecule}$

1.1.10 Isolated system

- System of fixed mass where no heat or work may cross the boundaries.
- Closed system with no energy crossing the boundaries
- Collection of a main system and immediate surroundings that exchange mass and energy among themselves but with no other system.

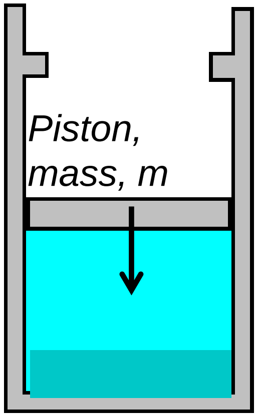


- Example: classroom and students are exchanging heat amongst themselves

1.1.11 Examples - Pressure

Example 1-1

A piston has a mass of 4 kg and cross sectional area of 0.01 m^2. If the piston is at equilibrium, and surrounding's atmosphere is P = 100 kPa, what is the absolute pressure inside the cylinder? Find absolute pressure of cylinder



Piston/cylinder

Solution:

$$F_{weight\ of\ piston} = mg = 4kg * 9.81\,m/s^2 = 39.2\text{N}$$

Pressure exerted by piston = (weight of piston / area) + atmospheric pressure

$$P_{abs\ cylinder} = 39.2N/0.01m^2 + 100{,}000\ Pa = 103{,}920\ Pa$$

$$or\ 103.92\ kPa$$

1.1.11 Examples - Pressure

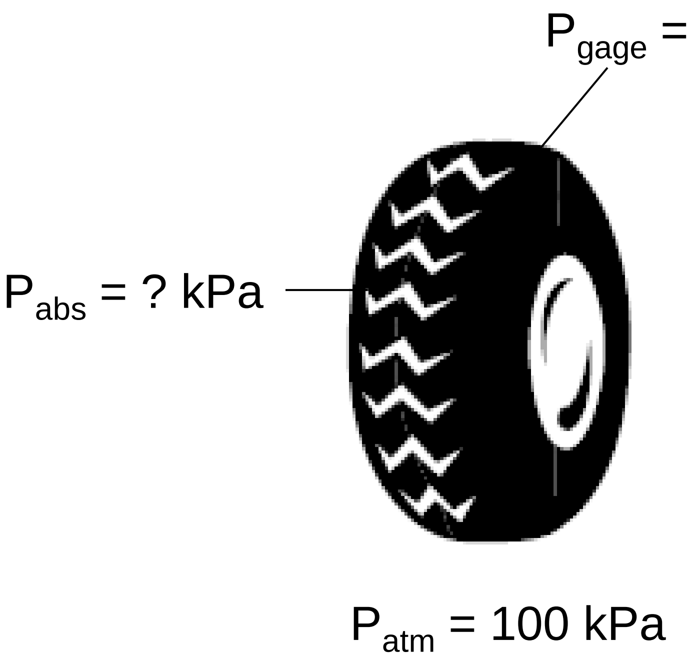
Example 1-2
A vacuum gauge connected to a vessel reads 30 kPa at a location where the atmospheric pressure is 98 kPa. What is the absolute pressure in the vessel?

Ans: 68 kPa

1.1.11 Examples - Pressure

Example 1-3

A pressure gauge connected to a valve stem of a vehicle tire reads 240 kPa at a location where the atmospheric pressure is 100 kPa. What is the absolute pressure in the tire, in kPa. What is the tire pressure in psia and the gauge pressure in psig? Note: 1 Pa = 14.5 psia.

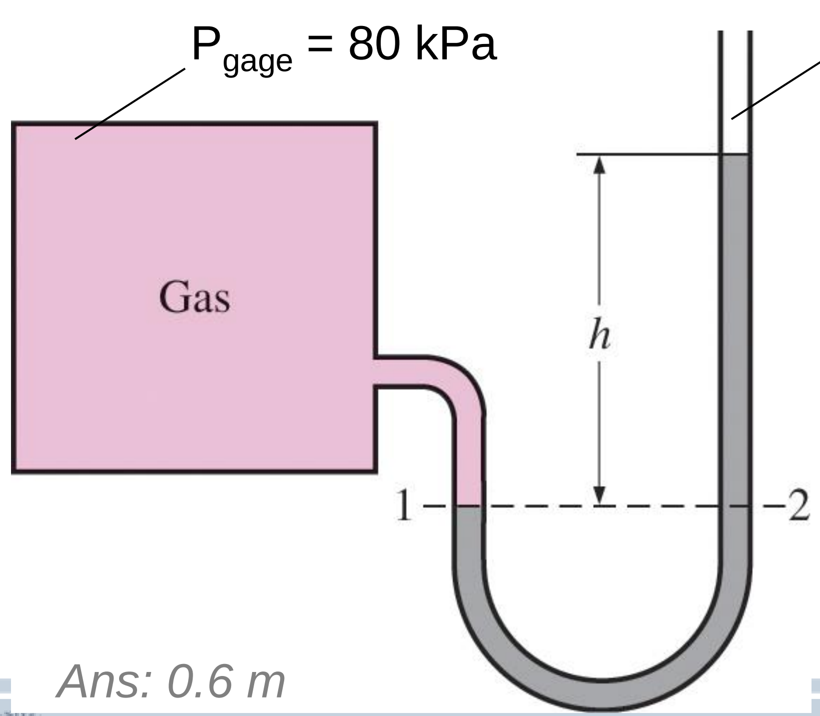


Ans: P_{abs} = 340 kPa, 49,3 psia, 34,6 psig

1.1.11 Examples - Pressure

Example 1-4

Both a gauge and a manometer measure the pressure inside a vessel. If the pressure gauge reads 80 kPa, determine the distance between the two fluid levels of the manometer if the fluid is mercury, whose density is 13,600 kg/m^3. Take *g* as standard: 9.81 m/s^2.



$$\Delta P = \rho g h \qquad (kPa)$$

Note: mmHg and mmH$_2$O sometimes used as units of measurement

Ans: 0.6 m

Nomenclature (1)

- A area (m^2)
- C_P specific heat at constant pressure (kJ/(kg·K))
- C_V specific heat at constant volume (kJ/(kg·K))
- COP coefficient of performance
- d exact differential
- E stored energy (kJ)
- e stored energy per unit mass (kJ/kg)
- F force (N)
- g acceleration of gravity (9.81 m/s^2)
- H enthalpy (H= U + PV) (kJ)
- h specific enthalpy (h= u + Pv) (kJ/kg)
- h convective heat transfer coefficient (W/(m^2·K)
- K Kelvin degrees
- k specific heat ratio, C_P/C_V
- k 10^3
- k_t thermal conductivity (W/(m-°C))
- M molecular weight or molar mass (kg/kmol)
- M 10^6
- m mass (kg)
- N moles (kmol)
- n polytropic exponent (isentropic process, ideal gas n = k)
- η isentropic efficiency for turbines, compressors, nozzles
- η_{th} thermal efficiency (net work done/heat added)
- P pressure (kPa, MPa, psia, psig)
- Pa Pascal (N/m^2)

Nomenclature (2)

- Q_{net} net heat transfer ($\sum Q_{in} - \sum Q_{out}$) (kJ)
- q_{net} Q_{net} /m, net heat transfer per unit mass (kJ/kg)
- R particular gas constant (kJ/(kg·K))
- R_u universal gas constant (= 8.314 kJ/(kmol·K))
- S entropy (kJ/K)
- s specific entropy (kJ/(kg·K))
- T temperature (°C, K,°F, R)
- U internal energy (kJ)
- u specific internal energy (kJ/(kg ·K))
- V volume (m³)
- $\dot{V}$ volume flow rate (m³/s)
- $\vec{V}$ velocity (m/s)
- v specific volume (m³/kg)
- $\bar{v}$ molar specific volume (m³/kmol)
- W_{net} net work done $[(\sum W_{out} - \sum W_{in})_{other} + W_b]$ (kJ) where W_b = for closed systems and 0 for control volumes
- w_{net} W_{net} /m, net work done per unit mass (kJ/kg)
- W_t weight (N)
- X distance (m)
- X exergy (kJ)
- x dryness fraction or quality
- Z elevation (m)
- δ inexact differential
- ε regenerator effectiveness
- ϕ relative humidity
- ρ density (kg/m³)
- ω humidity ratio

Typical subscripts, superscripts

- *A* actual
- *B* boundary
- f saturated liquid state
- g saturated vapour state
- fg saturated vapour value minus saturated liquid value
- gen generation
- *H* high temperature
- HP heat pump
- *L* low temperature
- net net heat added to system or net work done by system
- other work done by shaft and electrical means
- *P* constant pressure
- REF refrigerator
- rev reversible
- *s* isentropic or constant entropy or reversible, adiabatic
- sat saturation value
- v constant volume
- 1 initial state
- 2 finial state
- *i* inlet state
- *e* exit state
- . per unit time