# THERMODYNAMICS

## BASIC NOTIONS OF THERMODYNAMICS

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# References

- Bahman Zohuri, Patrick McDaniel (2015). Thermodynamics of Nuclear Power Plant Systems, Springer International Publishing Switzerland.

- Cengel Y., Boles M. (2008) Thermodynamics an engineering approach, 6th ed. McGraw Hill, Boston.

# Content

- Introduction
- Basic notions and definitions:
    - Definitions and characteristics of thermodynamic parameters
    - Definitions and characteristics of thermodynamic processes
    - Definitions and characteristics of thermodynamic cycles
- Laws of thermodynamics
- Conclusion

# Abbreviations

- TPP – Thermal power plant
- NPP – Nuclear power plant
- KMT – Kinetic molecular theory

***Thermodynamics*** is the study of mutual conversions of heat energy and other forms of energy and its conditions in various physical-chemical processes.

Independent sections of thermodynamics:

- **engineering thermodynamics;**
- chemical thermodynamics;
- thermodynamics of biological systems, etc.

# Particular features of engineering thermodynamics as a scientific branch

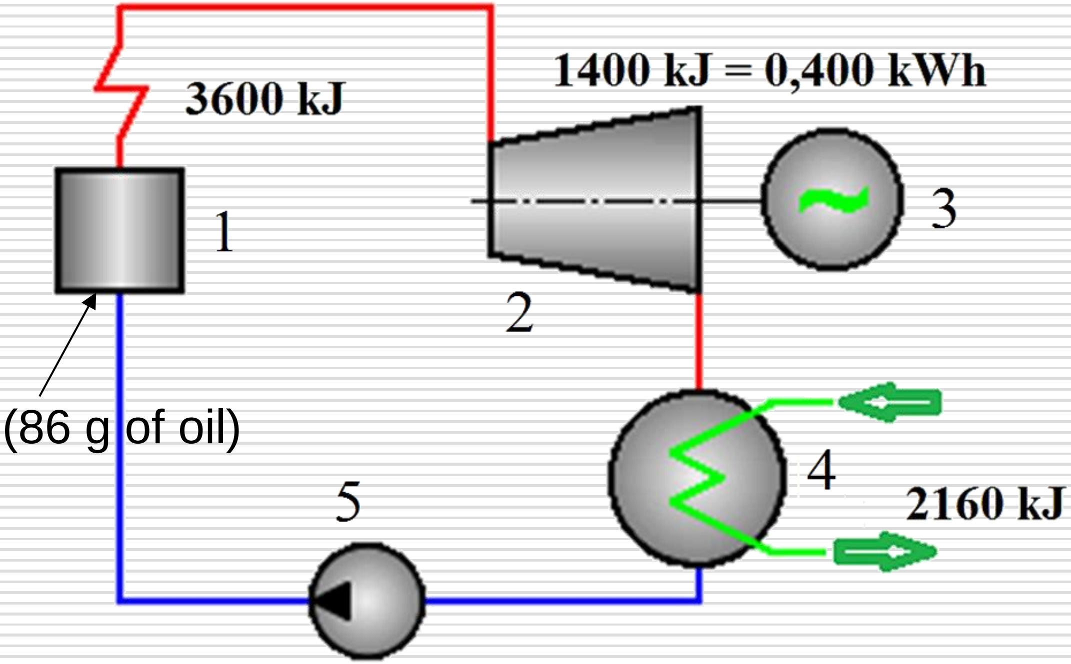
- The main goals:
  - to study regularities of mutual conversion of heat and mechanical energy;
  - to study properties of bodies engaged in these processes of conversion;
  - to examine efficient methods of energy conversion.
- Subject of study
  - Physical phenomena in macroscopic bodies and systems.

Regularities of engineering thermodynamics serve as a basis for calculation and design of thermal engines as well as thermo-technical equipment

From historical point of view, thermodynamics appeared due to the study of heat conversion into work within the steam engines.

# Subjects of engineering thermodynamics are *processes of mutual conversion of heat and work*

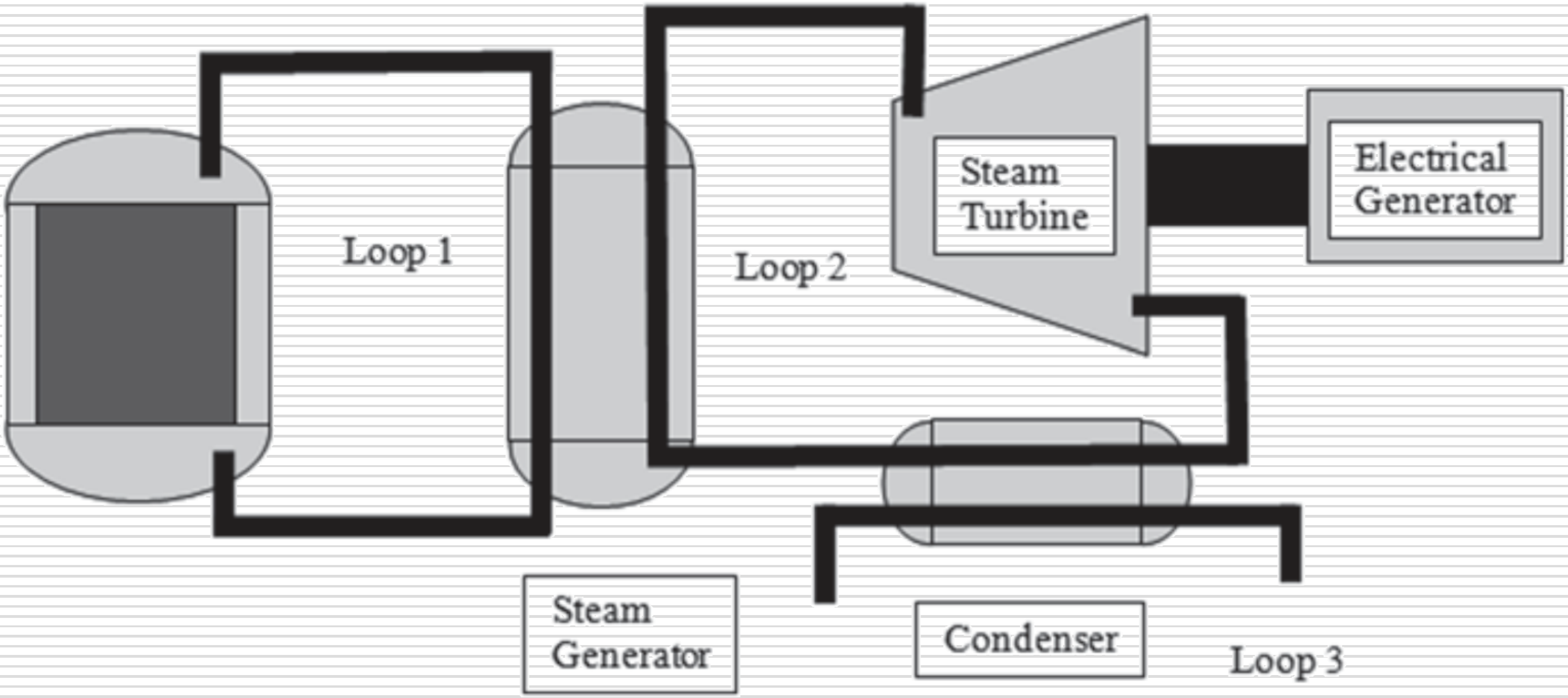
**Efficiency of steam turbine installation - 40 %**



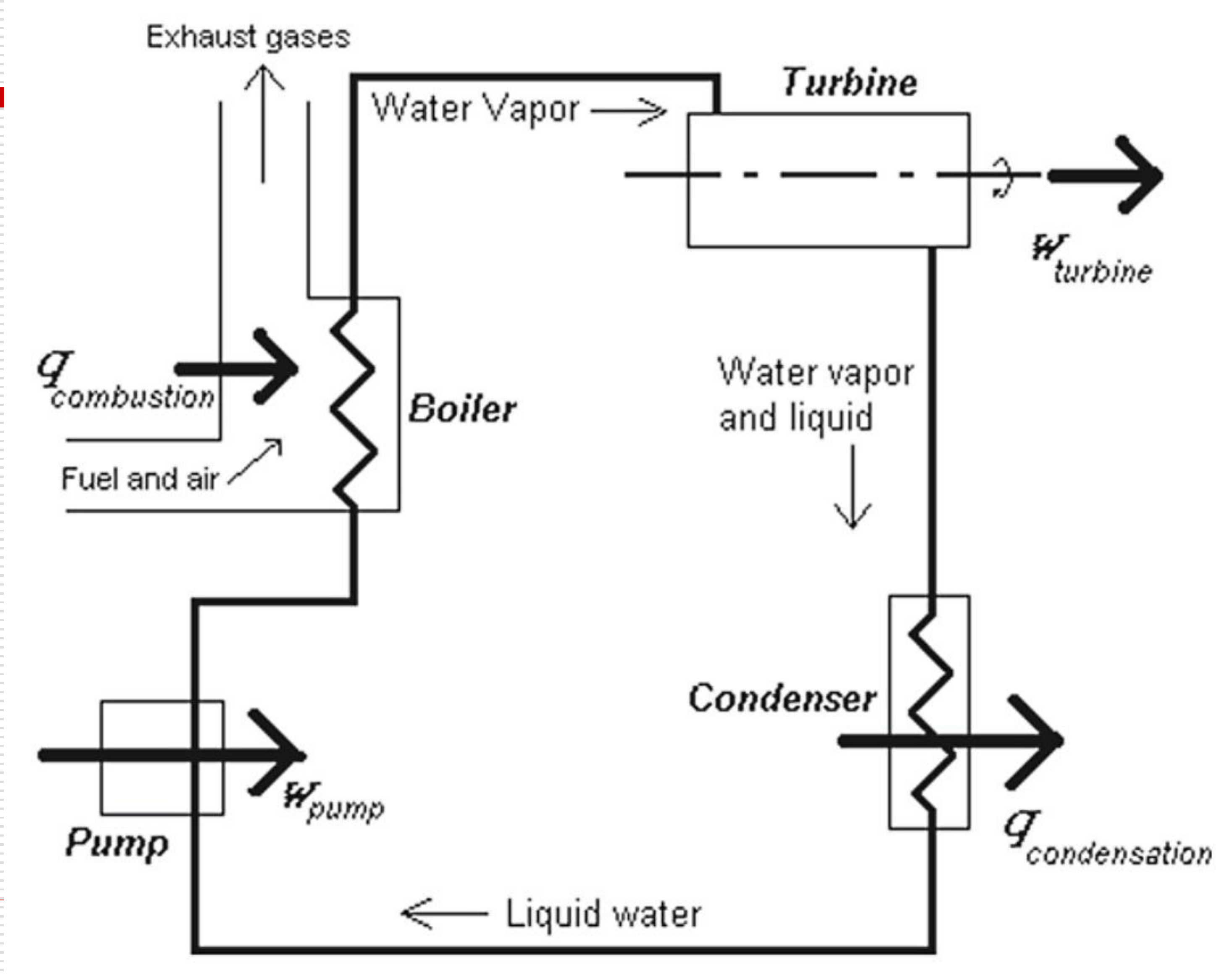
An example of a unit for converting heat into work and electrical energy (basic action principle of TPP and NPP)

**1 – boiler**
**2 – steam turbine**
**3 – electrical generator**
**4 – condenser**
**5 – feed pump**

# Example of a pressurized water nuclear reactor



# Scheme of a steam power plant



# Pressurized water reactor

- PWR converts *nuclear energy* into electrical energy by transforming nuclear energy, first, into *thermal energy*, and then thermal energy into *mechanical energy* which is finally converted into *electrical energy*.
- Thermodynamics deals with each of these conversion processes. To quantify each of these processes, we must understand and apply *the laws of thermodynamics*.

# Basic notions and definitions of engineering thermodynamics

- Thermodynamic system;
- Working medium;
- State parameters;
- Thermodynamic processes;

# Thermodynamic system

*Set of material bodies and fields mutually affecting one another and the environment, i.e., exchanging energy and substance.*

**Systems can be:**

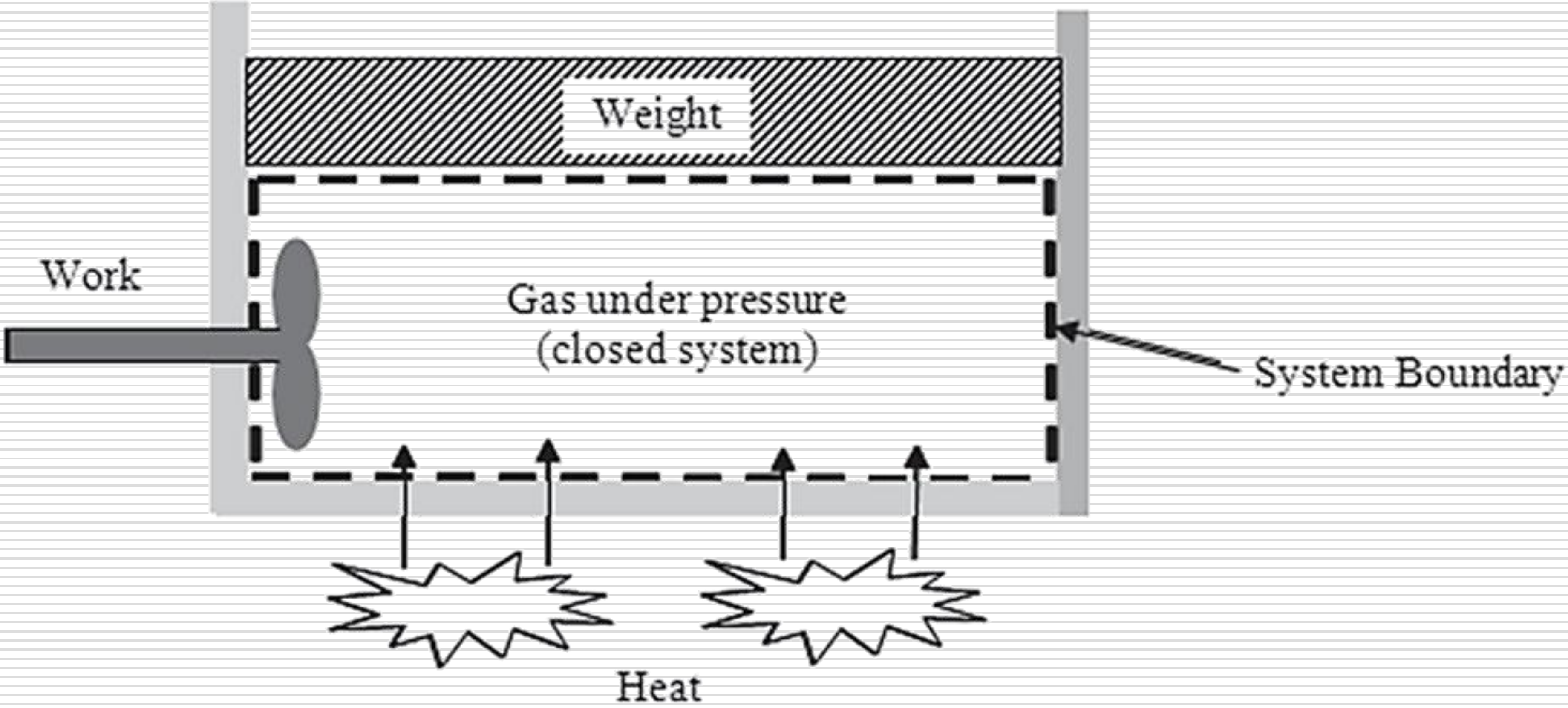
1. ***isolated***
    - ***closed*** – without substance exchange
    - ***adiabatic*** – without exchange

2. ***non-isolated***

# Isolated thermodynamic systems

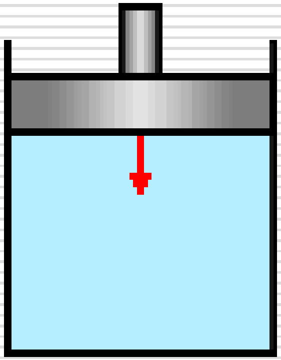
- ***Closed system*** features a fixed mass value which is limited to fixed bounds.
- ***Adiabatically isolated*** thermodynamic system doesn’t exchange heat with the environment.

# A closed system

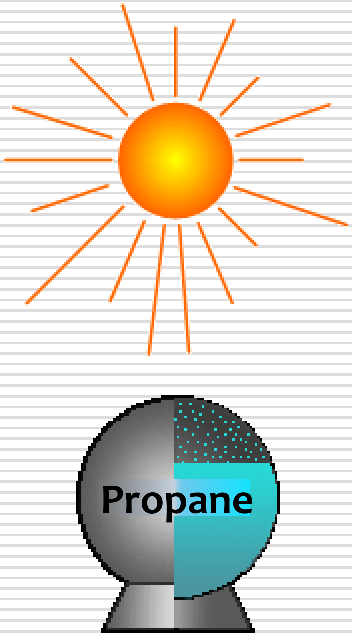


# Examples of closed systems

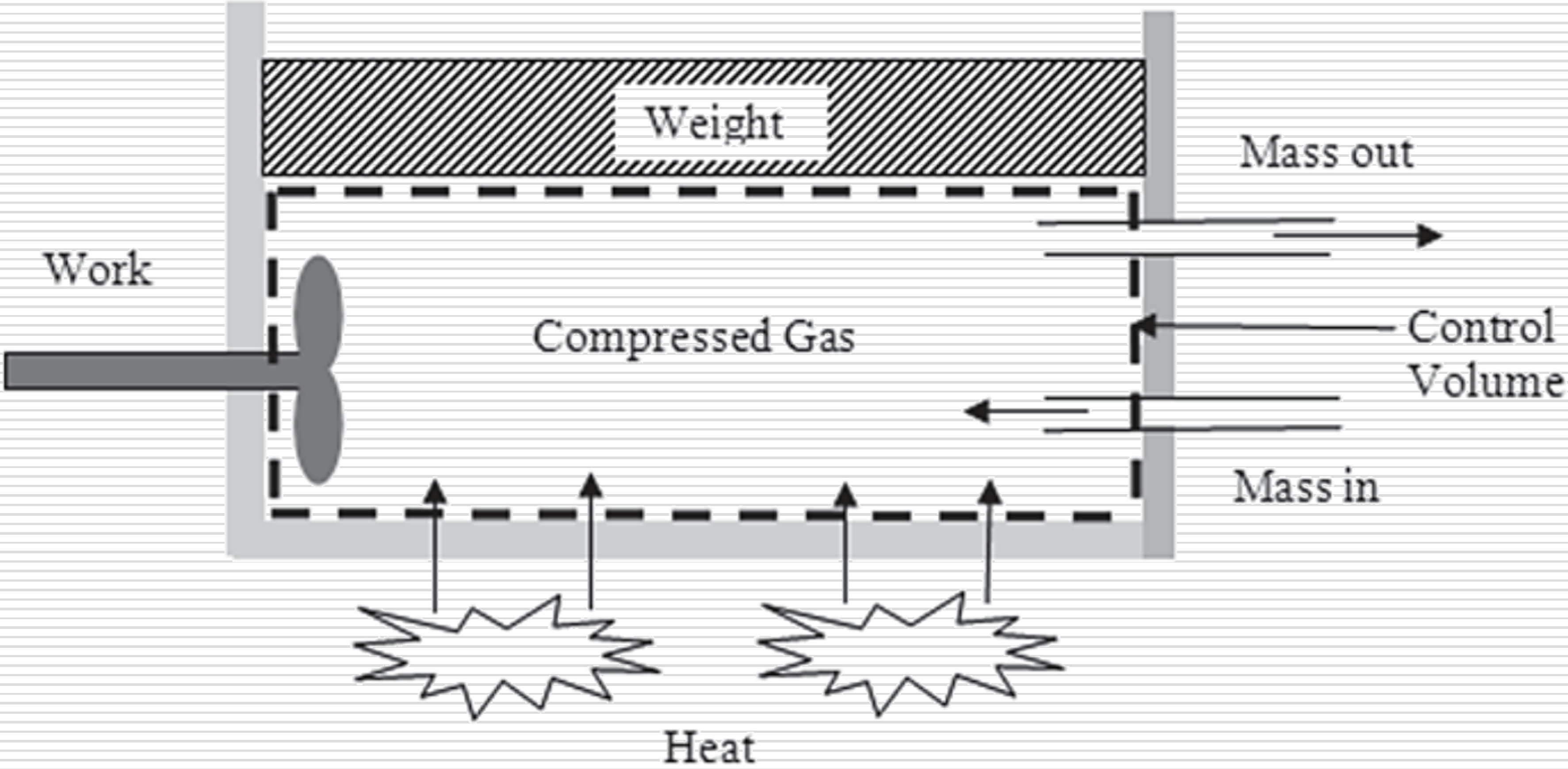
The gas is compressed under a moveable piston



The container is heated

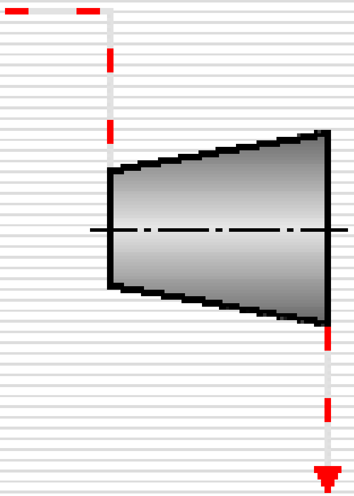


# An open system

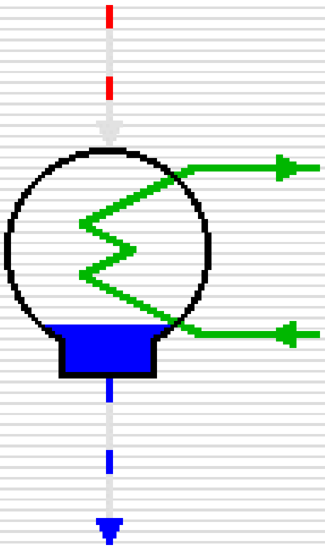


# Examples of open systems

Steam turbine



Condenser of steam turbine



# Example of an adiabatic thermodynamic system

Gas, stored in a closed cylinder **with ideal thermal insulation,** is a closed and, at the same time, adiabatic system.

# Elementary thermodynamic system is *a working medium*

Substance, characterized by the capability to considerably change its working volume in various thermodynamic processes, is called a *working medium.*

Examples:

- in *internal combustion engines* working medium is *fuel combustion product*;
- in *steam turbine installations* working medium is *water steam.*

# ***Thermal parameters of state***

Macroscopic values characterize the state of thermodynamic system.

**Thermal parameters:**

- absolute temperature *T;*
- absolute pressure *p;*
- specific volume *v* (reciprocal value is density *ρ*).

# Absolute temperature

- In KMT absolute temperature is determined by average kinetic energy of progressive motion of molecules.
- Numerical value of temperature is measured by means of thermometers. The action principle of a thermometer is based on the dependence of a substance property on temperature:
  - thermal expansion of a working medium;
  - electrical resistance;
  - electromotive force (EMF), etc.

# Temperature scales

- The scale of temperature is set for two *arbitrary constant temperature values*, e.g., the freezing point (**$t=0°C$**) and the boiling point (**$t=100°C$**) of water.
- Difference of temperature for these values, divided by a number of equal parts, is called a *degree*.
- Degrees Celsius and Kelvin are used simultaneously: $1^{o}C = 1$ К.

**<u>Examples of temperature scale</u>:**

- Celsius scale;
- Kelvin scale (**$T_{К} = t°C + 273{,}15$**);
- Fahrenheit scale (**$t°F = 32 + 1{,}8 \cdot t°C$**);
- Reaumur scale;
- Rankine scale, etc.

# Pressure

From the view of *molecular-kinetic theory,* pressure is caused by the fact that gas molecules, moving constantly and chaotically, collide with walls of a cylinder.

Pressure value equals the force value affecting a unit of surface square at a right angle to the surface.

**Pressure can be**:

- absolute pressure $p$ (thermal parameter);
- barometric (atmospheric) pressure $p_b$;
- gage pressure (above atmospheric pressure)

$$p_{over} = p - p_v$$

- underpressure (below atmospheric pressure)

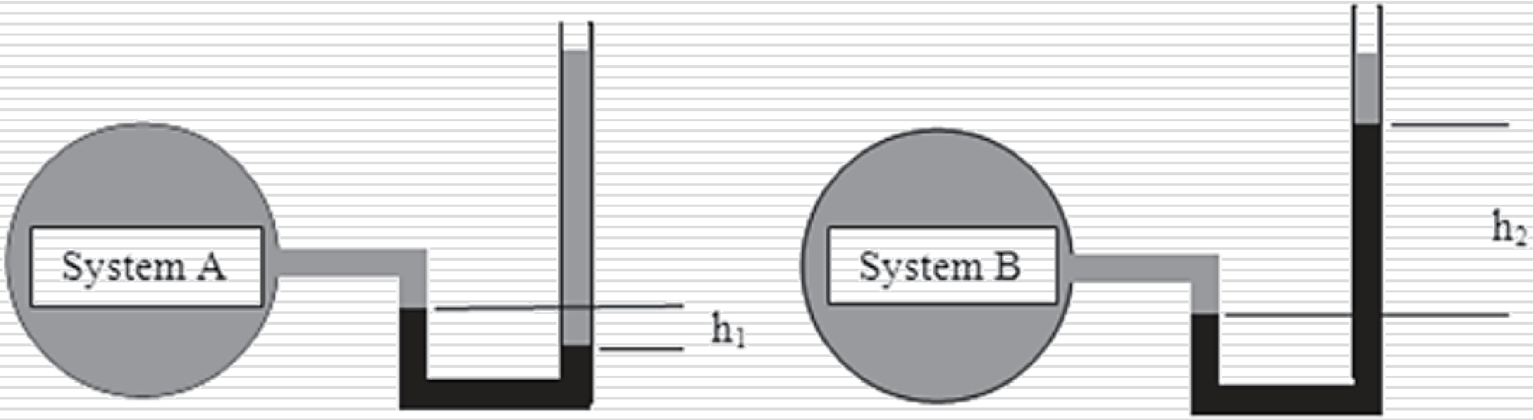
$$p_{vac} = p_b - p$$

- vacuum

$$V = p_{vac}/p_b \cdot 100\%$$

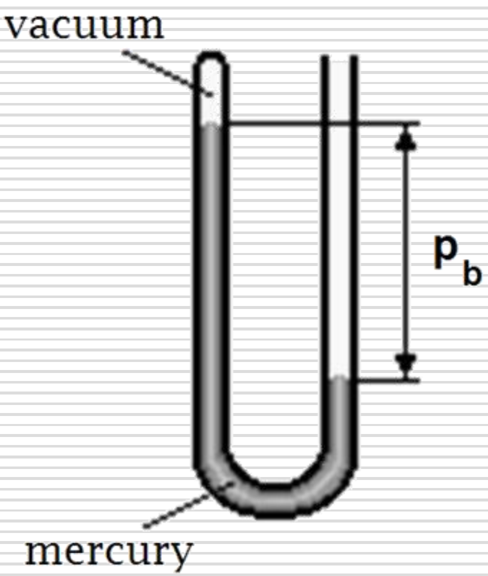
# Pressure measurement

A manometer measures the difference in height of a fluid in contact with two different pressures.



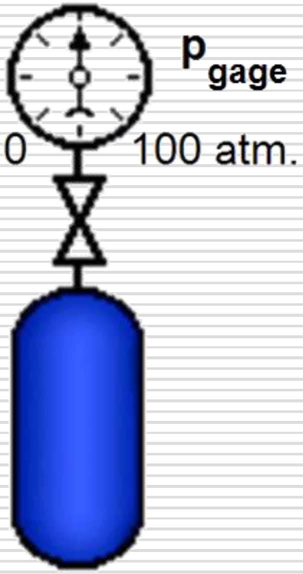
# Pressure measurement

Barometer
(atmospheric pressure)



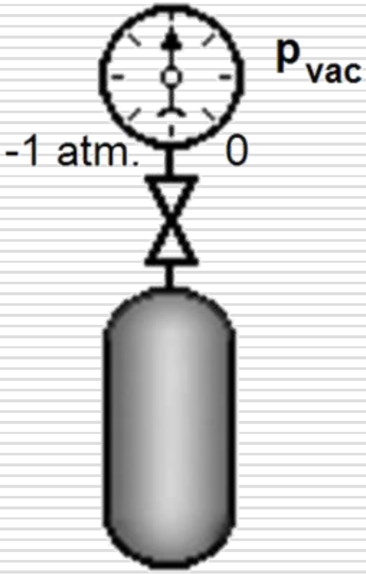
$$p_{atm} = p_b$$

Manometer
(gage pressure)



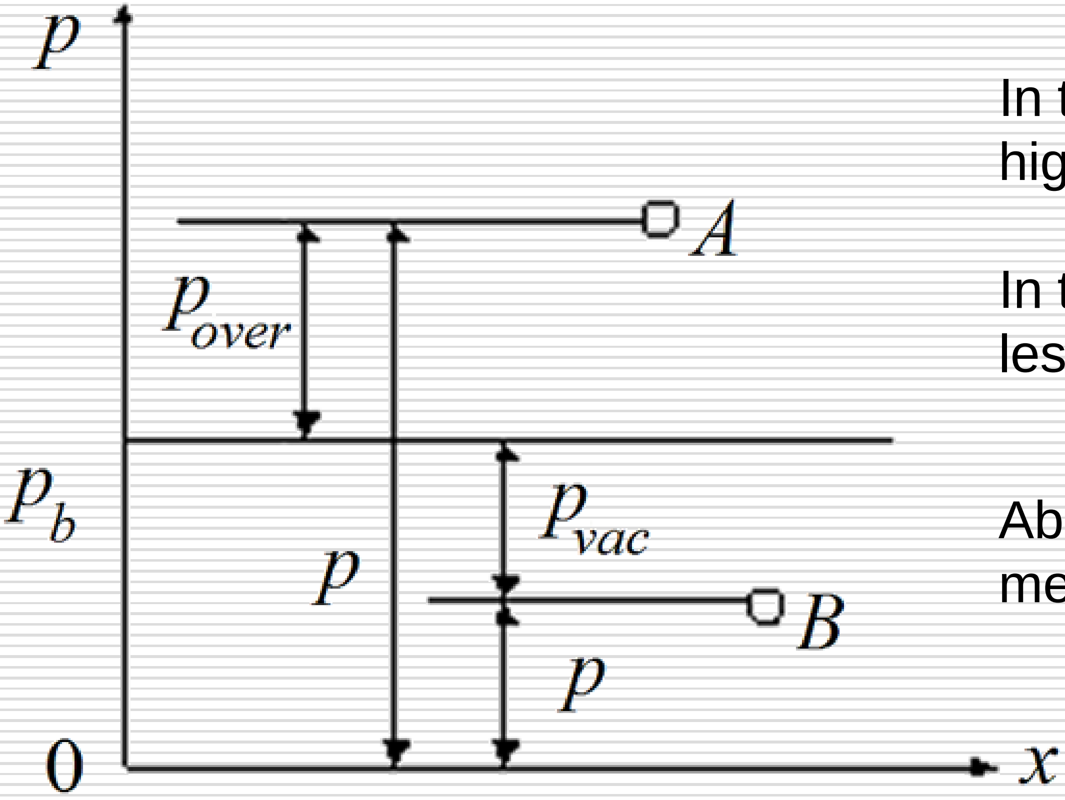
$$p = p_b + p_{over}$$

A vacuum gauge
(underpressure)



$$p = p_b - p_{vac}$$

# Relationships between the absolute pressure *p* and pressures measured by instruments



In the point *A* – pressure is higher than atmospheric one

In the point *B* – pressure is less than atmospheric one

Absolute pressure is measured from zero

# Measurement units of parameters in the SI system

- ***Pressure* p** in pascals (1 Pa = 1 N/m$^2$)
  - **1 bar** = $10^5$ Pa =100 kilopascals (kPa) (approximately equal to atmospheric pressure)
  - **1 at** = 1 kgf/cm$^2$ = 98 kPa
  - **1 atm** =101,3 kPa = 760 mmHg
  - Pressure less than atmospheric is often called ***underpressure***

$$H=B-p$$

  - **Vacuum**

$$V=H/B \cdot 100\%$$

# Ratios between pressure measurement units

$$1\ \text{Pa} = 1\ \text{N/m}^2$$

$$1\ \text{kPa} = 10^3\ \text{Pa} = 10^{-2}\ \text{bar} = 1{,}01972 \cdot 10^{-2}\ \text{kgf/cm}^2$$

$$1\ \text{bar} = 10^5\ \text{Pa} = 1{,}01972\ \text{kgf/cm}^2$$

$$1\ \text{bar} = 750{,}06\ \text{mmHg} = 10{,}1972\ \text{mH}_2\text{O}$$

$$1\ \text{kgf/cm}^2 = 9{,}80665 \cdot 10^4\ \text{Pa} = 0{,}980665\ \text{bar}$$

$$1\ \text{kgf/cm}^2 = 735{,}55\ \text{mmHg} = 10\ \text{mH}_2\text{O}$$

$$1\ \text{atm} = 760\ \text{mmHg} = 1{,}01325\ \text{bar}$$

# Specific volume

- Specific volume $v$ [m$^3$/kg] is volume of a mass unit (1 kg of substance)
- Density of a mass unit $\rho$ [kg/m$^3$] is reciprocal of specific volume ($\rho = 1/v$)

# Equilibrium state

Under constant external conditions, state parameters of thermodynamic system do not change

- in the course of time;
- by volume.

# Thermal equation of working medium state

**For equilibrium state of a system,** pressure of homogeneous medium can be represented as function of only temperature and specific volume:

$$\mathbf{f\,(p,\,v,\,T) = 0}$$

The form of the equation of state is determined only by an experiment or KMT.

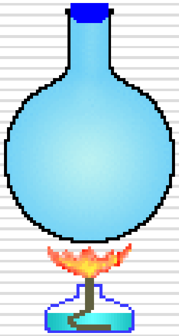
# Thermodynamic process

- If the system state changes, a process will occur. The sequence of changes of system state makes a **thermodynamic process;**
- **Equilibrium process** (quasi-steady process) is a sequence of equilibrium states.

In nature there are processes that can never be equilibrium ones. E.g., processes of mixing gases and liquids, processes of heat transfer through the finite temperature difference, etc.

- Example of non-equilibrium process:

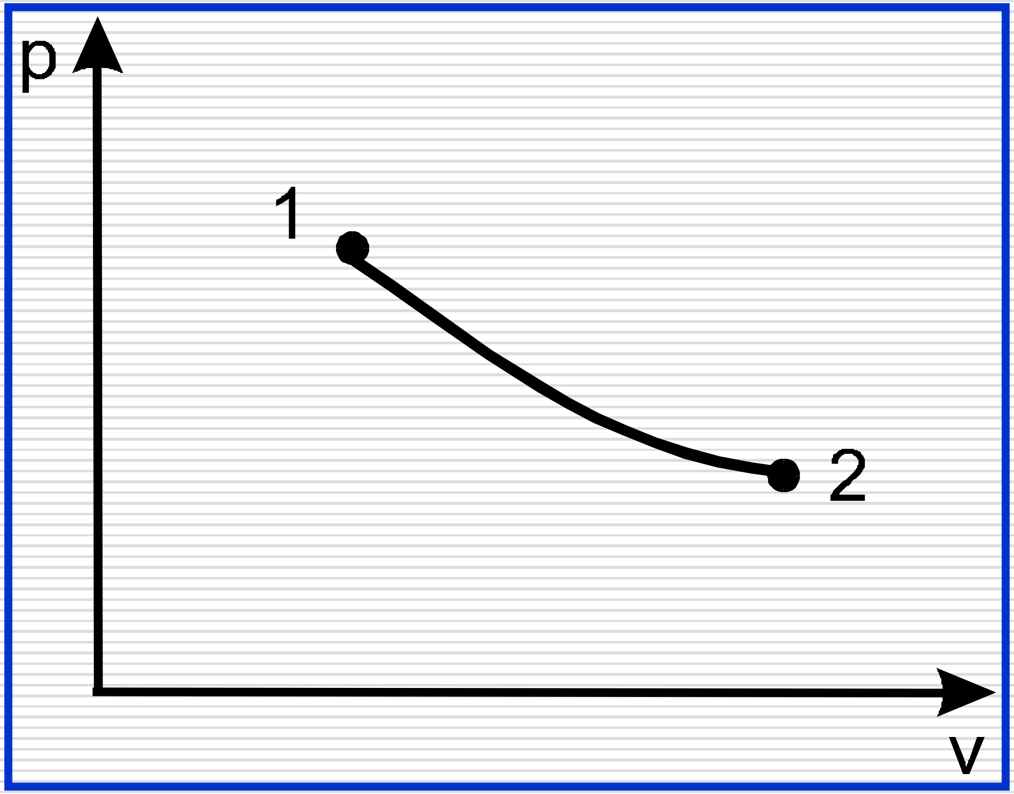
*Gas density along the height of the vessel is heterogeneous.*



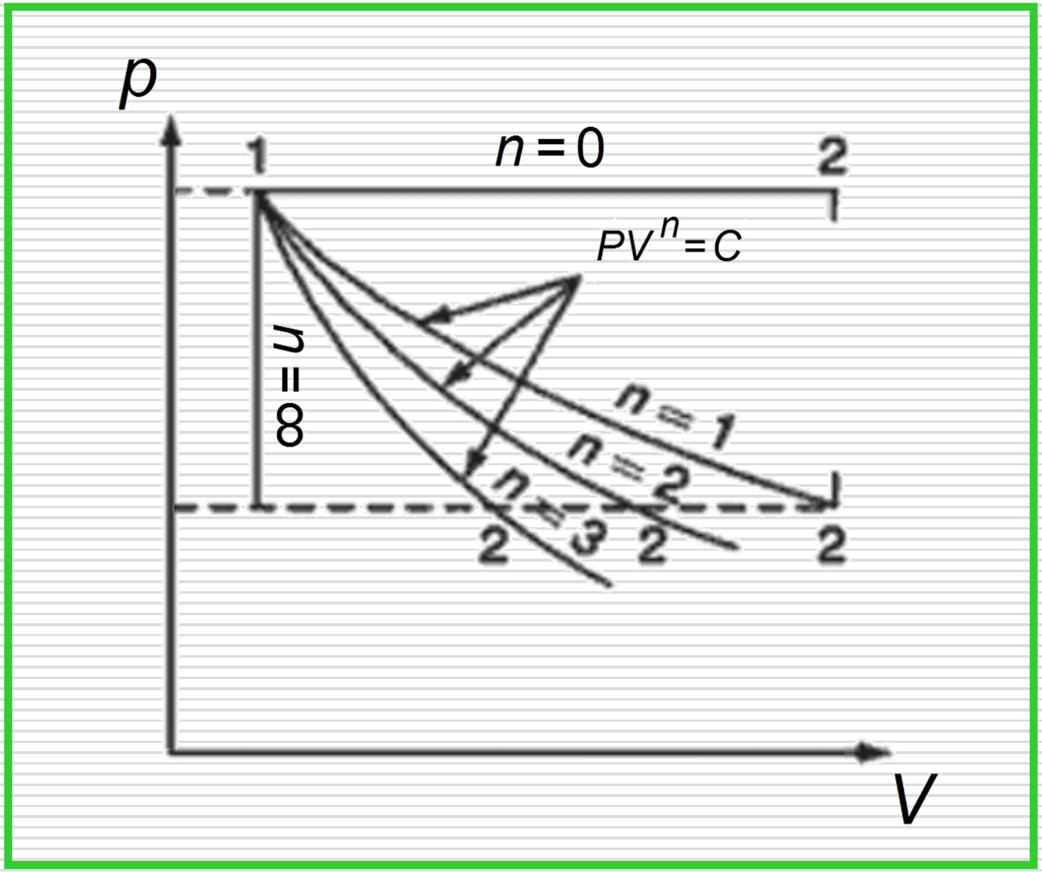
# Types of thermodynamic process

- ideal and real;
- equilibrium and non-equilibrium;
- steady, quasi-steady, dynamic;
- closed and open;
- reversible and irreversible;
- isobaric, isochoric, isothermal, adiabatic and polytropic.

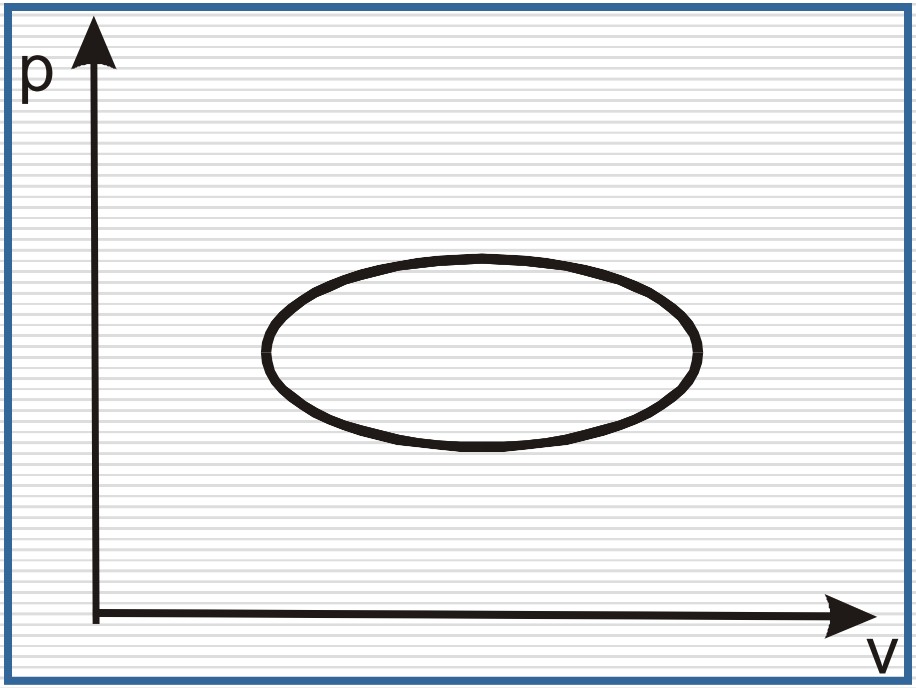
# Isothermal process in p·V-diagram (p·V is constant)



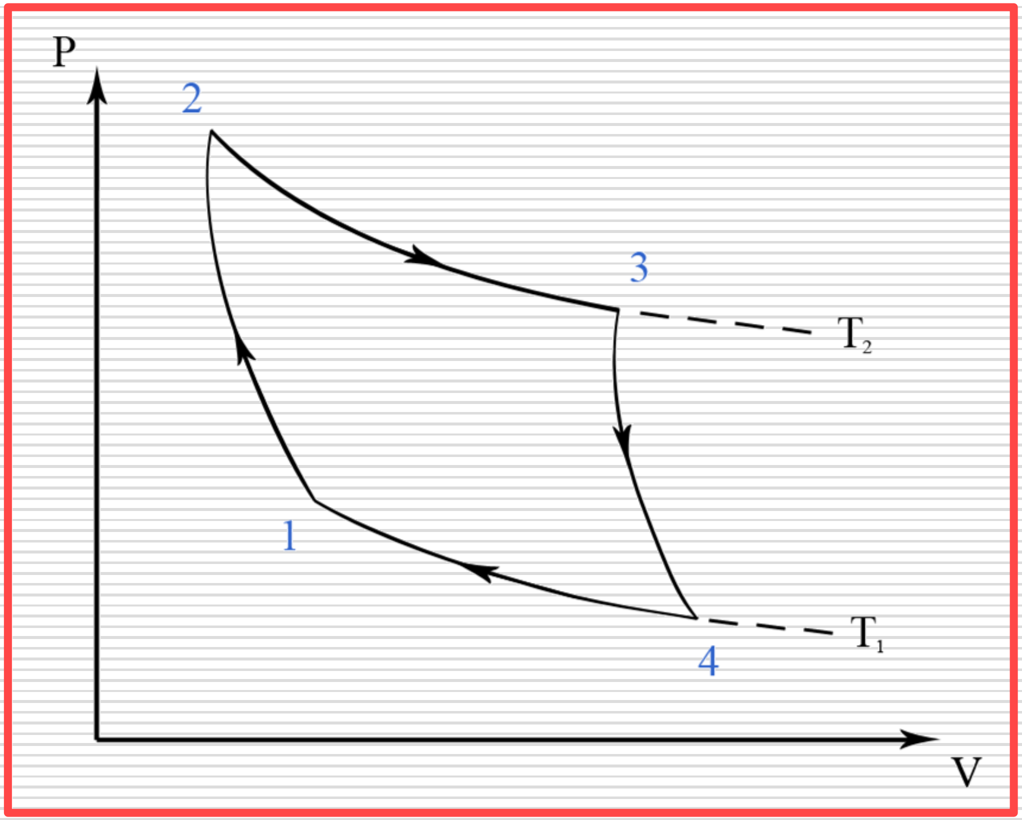
# Polytropic processes in p·V-diagram ($p \cdot V^n$ is constant)



# Circular process in p·V-diagram



# **Carnot cycle** (clockwise)



1-2: Adiabatic compression

2-3: Isothermal expansion

3-4: Adiabatic expansion

4-1: Isothermal compression

# Energy definition

- **«activity», «operation»** (from the Ancient Greek)

***Energy is defined as potential to do the work***

***(quantitative measure of different***

***forms of matter motion)***

- ***Different kinds of energy:*** mechanical, thermal, magnetic, nuclear, potential, etc.

# Energy of thermodynamic system *E*

Any thermodynamic system contains energy. The total energy of thermodynamic system:

$$\mathbf{E = E_{kin} + E_{pot} + U}$$

$E_{kin}$ – kinetic energy of the system motion;

$E_{pot}$ – potential energy of the system, determined by the relative position of thermodynamic system and its parts in the external force field (e.g., gravity field);

U – total internal energy, determined by the speed of molecule motion and the relative position of molecules.

A special case: $E_{kin} = E_{pot} = 0$

$$\mathbf{E = U}$$

# Internal energy of the system ***U***

- For the first time it was identified in Joule's experiments to establish the mechanical equivalent of heat;
- ***U*** has two components: **kinetic** energy of particles and **potential** energy;
- ***U*** depends only on state of the system:

  *U* (v, T) or *U* (*p*, T) or *U* (*p*, v)
- internal energy is a total differential:

$$dU = \left(\frac{\partial U}{\partial T}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_T dV$$

- internal energy may change from an initial value $U_1$ to a final value $U_2$:

$$\int dU = U_2 - U_1 = \Delta U$$

# A thermodynamic system is characterized by:

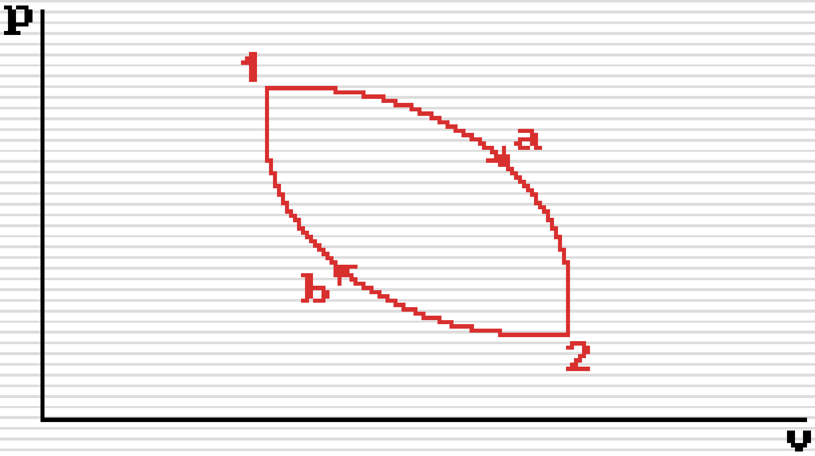
- total internal energy ***U***, J (or in kilojoules);
- specific internal energy ***u***, J/kg (or in kilojoules per kilogram)

$$u = \frac{U}{m},$$

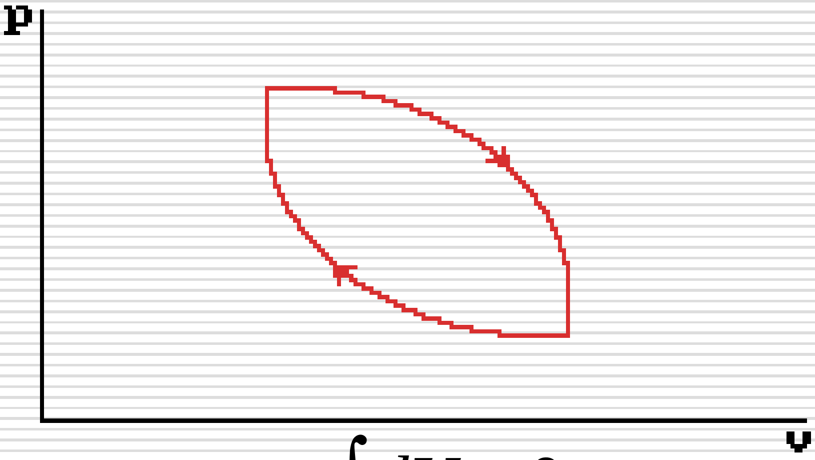
where ***m*** is mass of substance (in kilograms).

# Change of internal energy in processes

- change of internal energy doesn’t depend on the process type: $(U_2 - U_1)_{1a2} = (U_2 - U_1)_{1b2}$
- change of internal energy in circular process equals zero.



$$\Delta U_{1a2} = \Delta U_{1b2}$$



$$\oint dU = 0$$

# Internal energy of an ideal gas

- For an ideal gas, the internal energy depends only on temperature, not on pressure or volume:

$$U = U(\mathrm{T})$$

# Internal energy of a real gas

$$dU = \left(\frac{\partial U}{\partial T}\right)_V dT + \left(\frac{\partial U}{\partial V}\right)_T dV$$

# Caloric equation of the system state

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

The type of the dependence $u = f(v, T)$ is determined on the basis of an experiment or KMT.

# Heat and work as methods of energy transfer

- ***Work*** of m kg of gas (in ***kJ***):

$$L = m \cdot l \,,$$

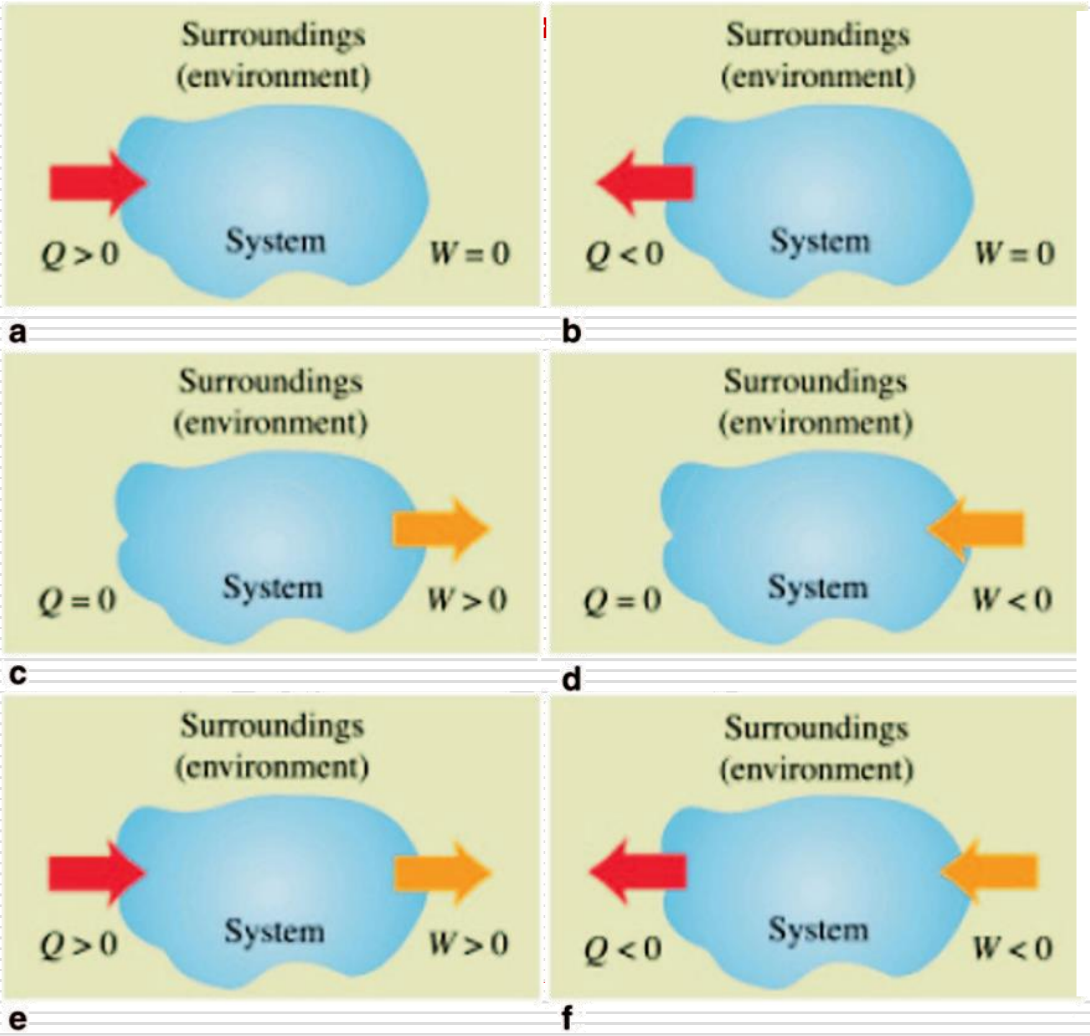
where $l$ is specific work

- ***Heat*** of process for $m$ kg of gas (in ***kJ***):

$$Q = m \cdot q \,,$$

where $q$ is specific heat of the process

# Thermodynamic system can exchange energy with its surroundings (environment) by means of heat and work



- **a.** When heat is added to the system, $Q$ is positive;
- **b.** When heat is transferred out of the system, $Q$ is negative;
- **c.** When work is done by the system, $W$ is positive;
- **d.** When work is done on the system, $W$ is negative. Energy transfer by both heat and work can occur simultaneously;
- **e.** When heat is added to the system and work is done by the system;
- **f.** When heat is transferred out of the system and work is done on the system.

# Work of process

- **The formal definition of work is “a force acting through a distance”.**

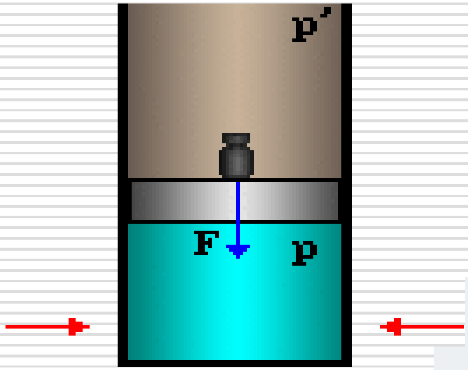
- It is the value of energy directed motion which changes, i.e., there is a displacement of the body as a single whole;
- E.g., when gas in a cylinder expands, its internal energy is converted into mechanical energy of the piston motion.

# Work of process

- Usually thermodynamics reports the mechanical work done by gas or water steam, and represents either change of the body volume (closed thermodynamic systems) or its displacement (open thermodynamic systems).

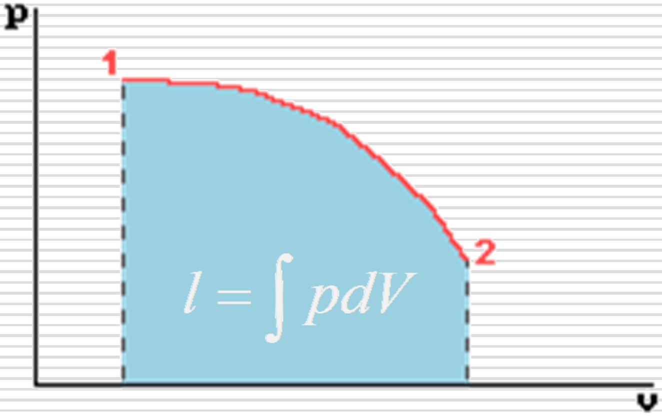
- There are three values for the description of thermodynamic process:
  1. total work *L*, kJ
  2. specific work $\ell = L/m$, kJ/kg
  3. mass of “working medium” *m*, kg

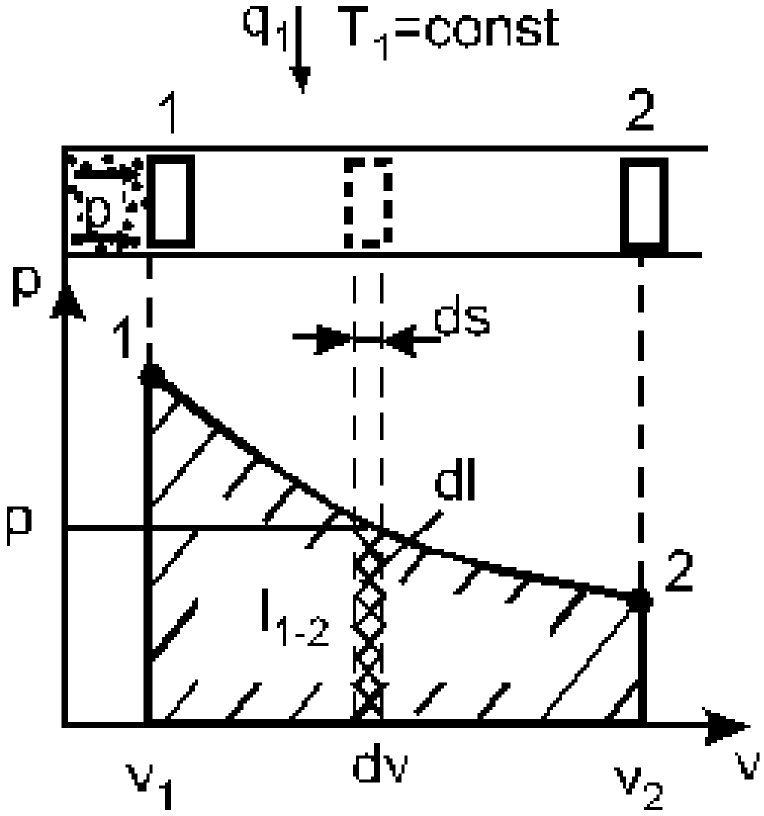
# Work to change the volume in a closed thermodynamic system



Heat delivery, dQ

$F = pS$



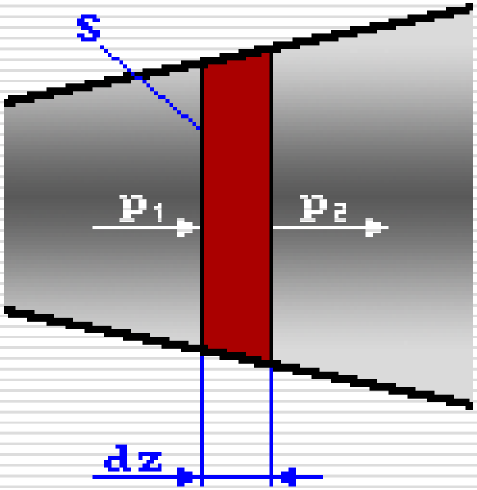


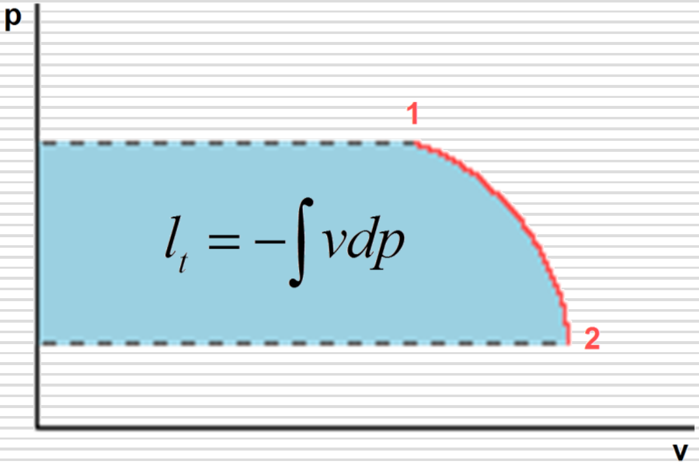
$$dl = p\cdot F\cdot ds = p\cdot d\mathrm{v} \qquad l_{1-2} = \int_{V_1}^{V_2} p\cdot d\mathrm{v}$$

# Technical work in an open thermodynamic system

In heat engines all the processes of work usually occur in a continuous solid flow.

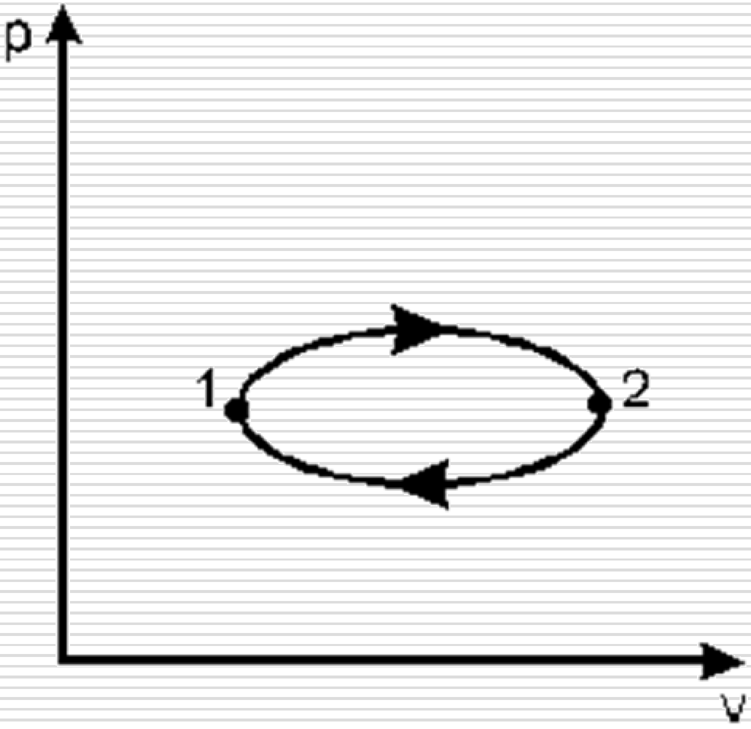
Technical work is shown in the pV-diagram by the square enclosed by the curve of the process and the axis of pressure.



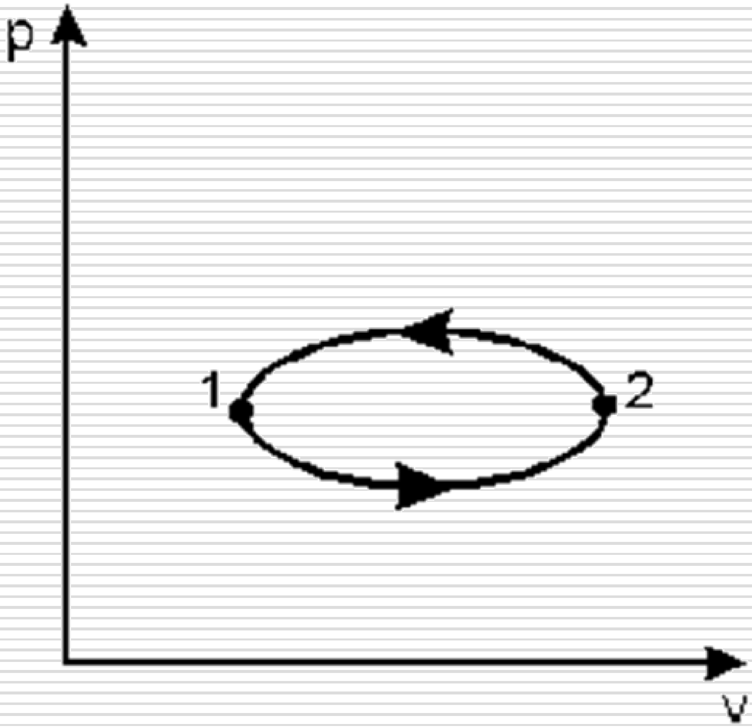


$$l_t = -\int v\,dp$$

# Work of cycle



**A cycle acting as a heat engine**
(clockwise)



**A refrigeration cycle**
(anticlockwise)

# Heat and heat capacity of process

- **Heat is a form of energy;**
- ***Heat*** of process for $m$ kg of gas is equal to

$$Q = m \cdot q \quad \text{(in kilojoules),}$$

where $q$ is specific heat of this process (kJ/kg).

# Average heat capacity in the temperature range from $T_1$ to $T_2$ $(T_2 > T_1)$

- The **heat capacity** is the ratio of heat added to an object to the resulting temperature change from $T_1$ to $T_2$:

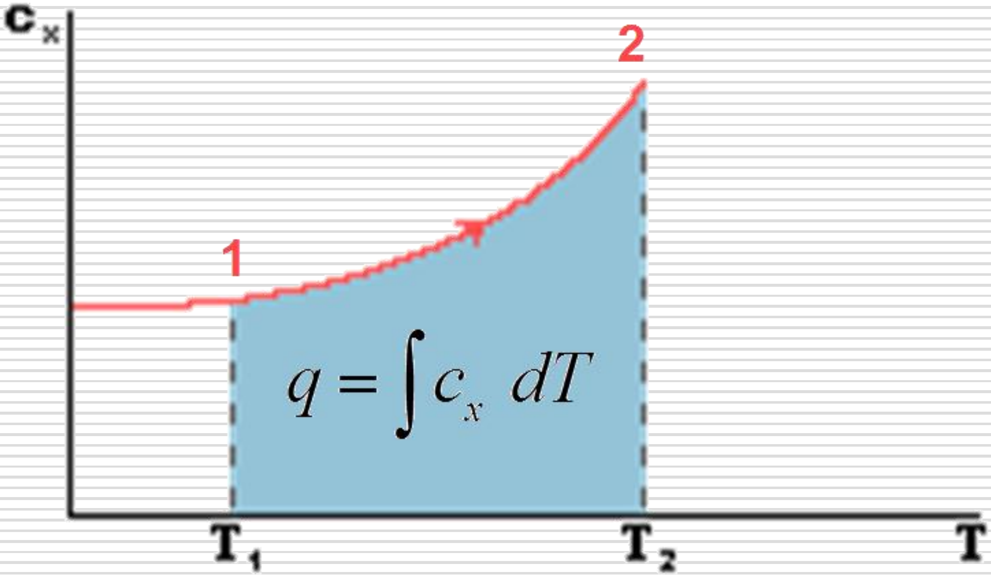
$$C_x^m = \frac{Q}{T_2 - T_1}.$$

- The **specific heat capacity** of a substance is the amount of heat needed to raise the temperature of 1 kg of mass by 1 K:

$$c_x^m = \frac{C_x^m}{m} = \frac{Q}{m \cdot \left(T_2 - T_1\right)},$$

where ***Q*** – amount of heat (Joule), ***m*** – mass of substance (kilogram)

# Average heat capacity in the temperature range from $T_1$ to $T_2$



$$c_m^x = \frac{q}{T_2 - T_1} = \frac{\int c_x \, dT}{T_2 - T_1}$$

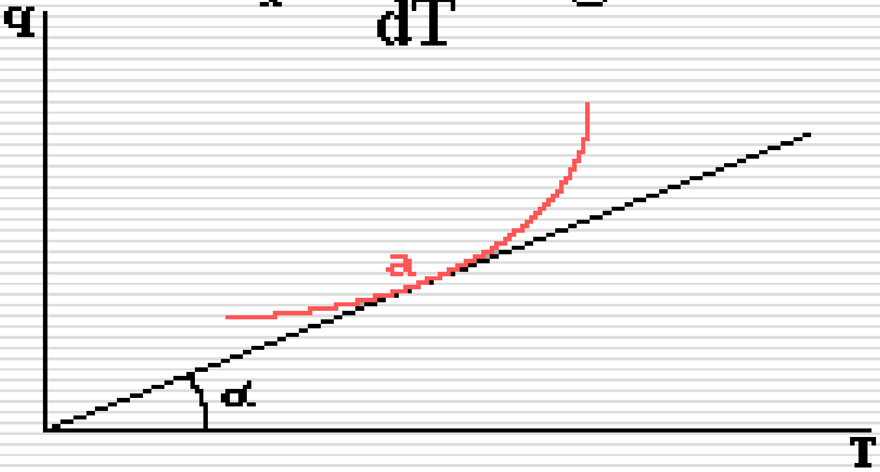
# True heat capacity $C_x$

- **True heat capacity** is defined as the derivative of the quantity of heat added to the body with respect to the temperature of this body

$$C_x = \frac{\delta Q}{dT}.$$

- **Specific true heat capacity**

$$c_x = \frac{\delta q}{dT} = \operatorname{tg} \alpha$$



# Heat capacity is the function of process

- Heat capacity depends not only on thermodynamic parameters of working medium state but also on the process.

**It can be**:

- **constant-pressure (isobaric)** heat capacity $c_p$
- **constant-volume (isochoric)** heat capacity $c_v$

# The laws of thermodynamics

- **The first law of thermodynamics**

*Energy is always conserved when it is converted from one form to another.*

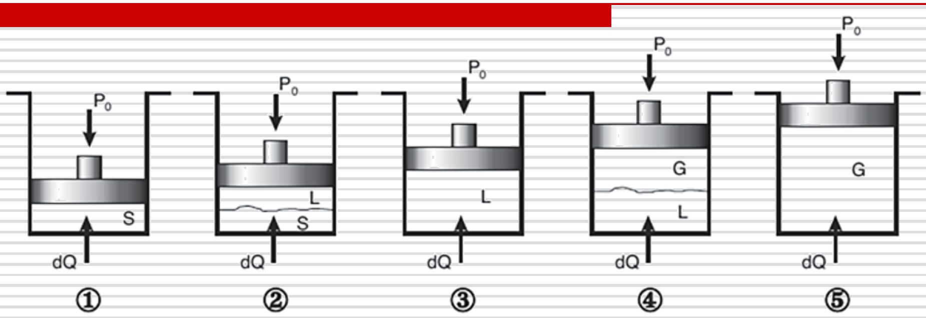
- **The second law of thermodynamics**

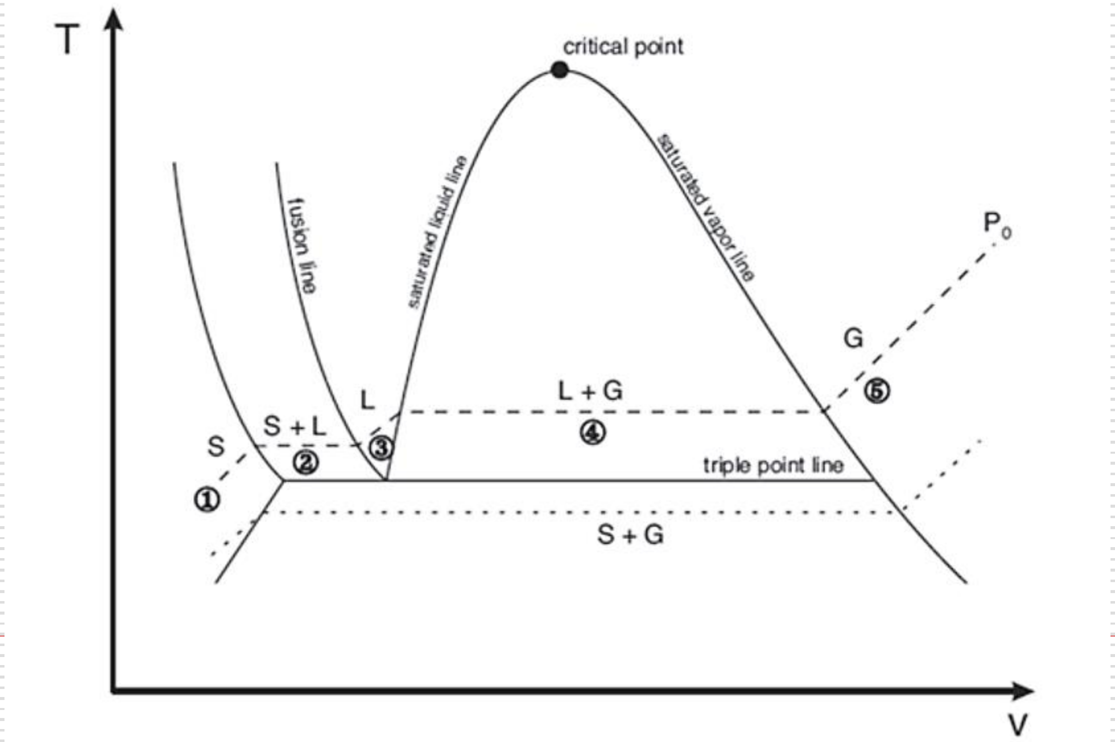
*It is impossible to construct a device that operates on a cycle and whose sole effect is the transfer of heat from a cooler body to a hotter body.*

- **The third law of thermodynamics**

*It is impossible by means of any process, no matter how idealized, to reduce the temperature of a system to absolute zero in a finite number of steps.*

# Illustration of T-v process steps and its diagram





# Enthalpy

- **Enthalpy** is a measure of the total energy of system. It includes the internal energy **(U)**, which is the energy required to create a system, and the amount of energy required to make room for it by displacing its environment and establishing its volume and pressure **(p·V)**.

$$\mathbf{H = U + p \cdot V} \text{ – enthalpy}$$

$$\mathbf{h = u + p \cdot v} \text{ – specific enthalpy}$$

# Enthalpy

- Work of filling the volume:

$$\mathbf{p \cdot V = p \cdot z \cdot S}$$

$$\mathbf{F = p \cdot S}$$

- For the reason that the values composing the enthalpy expression are total differentials, enthalpy is characterized by the following:

○ enthalpy is a function of state H = f (p, T);

○ enthalpy is a total differential;

○ enthalpy change doesn't depend on process:

$$(H_2 – H_1)_{1a2} = (H_2 – H_1)_{1b2}$$

$$\mathbf{\Delta} H_{1a2} = \mathbf{\Delta} H_{1b2}$$

# Enthalpy

- In a circular process, change of enthalpy is equal to zero, i.e., enthalpy is an additive function. Its value doesn’t depend on mass of a body (properties of extensive variables) $H = m \cdot h$, $h = H/m$.
- A thermodynamic system is characterized by:

  enthalpy ***H***, kJ (kilojoules);

  specific enthalpy ***h***, kJ/kg (kilojoules per kilogram).
- The caloric equation of the system state, which is in thermodynamic equilibrium is as follows:

  $$h = f(p, T)$$

  where ***h*** is specific enthalpy.
- The type of functional dependence $h = f(p, T)$ is determined on the basis of either an experiment or KMT.

# Conclusion

This are basic terms of thermodynamics. All further material would be given based on this basic terms and laws.