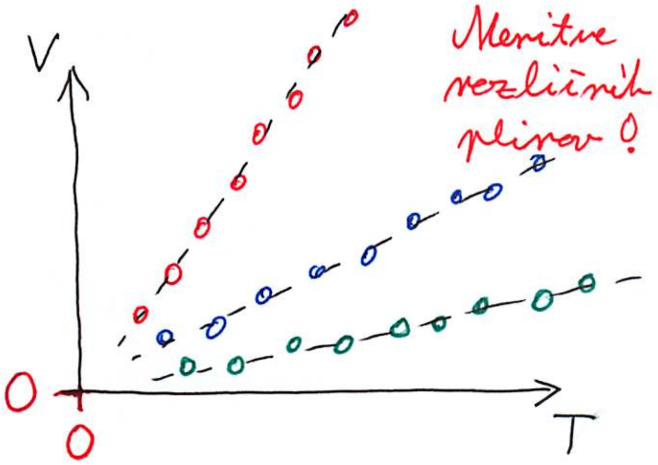
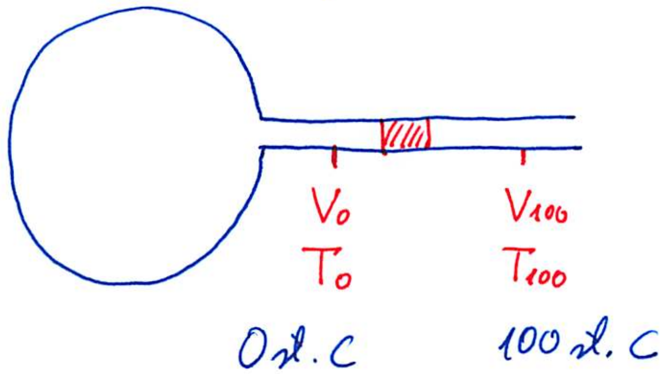
Toplota

- Makroskopski opis ~ $N_A \sim 10^{23}$ delcev
- Opis ravnovesnih stanj, faznih prehodov
- Termodinamske spremenljivke: p, V, T
- Definicija temperature:

Meritev spremembe volumna v odvisnosti od T pri konstantnem p!





Opazimo, da se vse premice sekajo v isti točki, ki ima Volumen (V) $V=0$! Ta točka ima $T=0$ v Kelvinih

$$V = k \cdot T \, !$$ velja le v Kelvinovi skali

Izmerimo: $\frac{V_{100}}{V_0} = 1,3661 = \frac{T_{100}}{T_0}$

Zahtevamo še $T_{100} - T_0 = 100$

$\rightarrow T_{100} = 1,3661\, T_0$

$$1,3661 \cdot T_0 - T_0 = 100$$

$$T_0 = \frac{100}{0,3661} = 273,15\ \mathrm{K} \, !$$

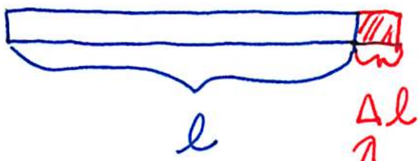
$T_0 = 273{,}15\ K = 0\ st.\ C$!

$T_K = T_C + 273{,}15\ K$ Pretvornik med Kelvinova in Celzijevo skalo

$T_F = \frac{9}{5} T_C + 32$ Fahrenheit-ova skala : T_F

Temperaturno raztezanje snovi:

Trdnine:



raztezek po segretju za ΔT

$$\Delta l = \alpha\, l\, \Delta T$$

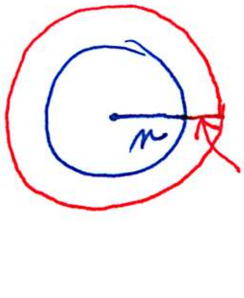
α: temperaturni koeficient dolžinskega raztezka

	Al	medenina	jeklo	
α	2,4	2	1,2	$10^{-5}\ K^{-1}$

Tekočine: $\Delta V = \beta\, V\, \Delta T$

β: temperaturni koeficient volumskega raztezka $\boxed{\beta = 3\alpha}$

ZAKAJ ?



Δr

$$V + \Delta V = \frac{4\pi}{3}\underbrace{(r+\Delta r)^3}_{r^3 + 3r^2\Delta r + \dots} = \frac{4\pi}{3} r^3 + \Delta V$$

$$\Delta V = 4\pi r^2 \Delta r \qquad \Delta r = \alpha\, r\, \Delta T$$

$$\frac{\Delta V}{V} = \frac{4\pi r^2 \Delta r\, 3}{4\pi r^3} = 3\,\frac{\Delta r}{r} = 3\alpha\, \Delta T$$

Plini, idealni plini

Idealne pline opisuje plinska enačba:

$$p\,V = n\,RT = \frac{m}{M}RT\,; \qquad R = 8{,}31\,\frac{J}{\text{mol K}}$$

tlak $\nearrow p$, volumen $\uparrow V$

$n = \frac{m}{M}$: število molov

M: molska masa

Izpeljava: kinetična teorija plinov

Velja tudi:
$$p = \frac{m}{V}\frac{RT}{M} = \rho\,\frac{RT}{M}$$

Plinska enačba predstavlja ploskev stanj v (p,V,T) 3 dim. prostoru

Primer: določi β idealnega plina: $\Delta V = \beta\,V\,\Delta T$

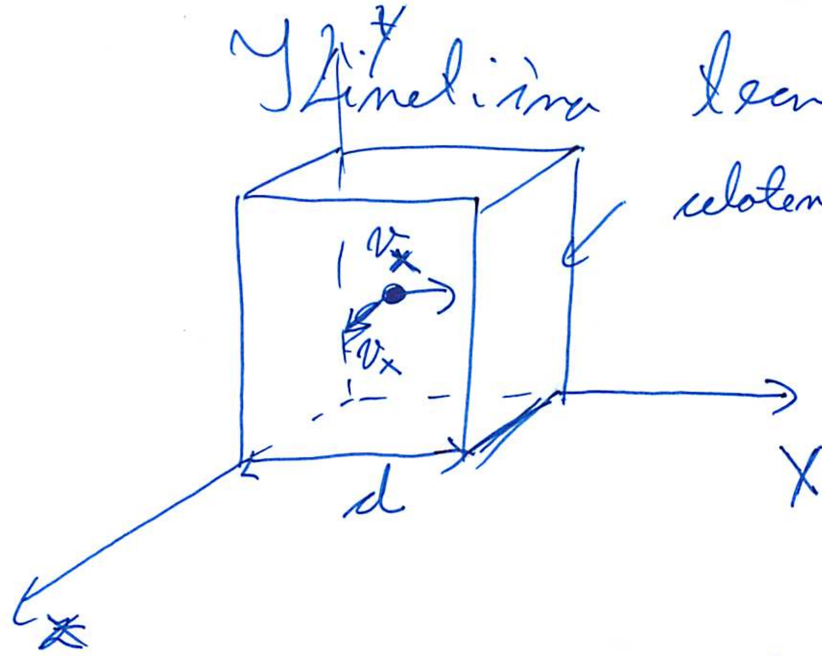
$$\Rightarrow \beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_p$$

$\left(\frac{\partial V}{\partial T}\right)_p$ je "parcialni" odvod pri konstantnem p od $V(p,T)$

$$V = \frac{nR}{p}T\,; \quad \left(\frac{\partial V}{\partial T}\right)_p = \frac{nR}{p}$$

$$\beta = \frac{1}{V}\,\frac{nR}{p} = \frac{p}{nRT}\,\frac{nR}{p} = \frac{1}{T}\,; \quad \boxed{\beta = \frac{1}{T}}$$ idealni plin!

Kinetična teorija plinov



celoten volumen!

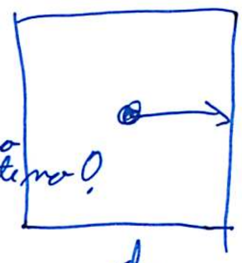
$$V = d^3$$

$$F_{st} \cdot \Delta t = -m v_x - m v_x = -2 m v_x$$

$$F_{st} = -\frac{2 m v_x}{\Delta t} = -\frac{m v_x^2}{d}$$

prepotuje razdaljo 2d predno ponovno trči ob isto steno!

$$2d = v_x \cdot \Delta t$$



$$F_{en} = \frac{m v_x^2}{\cancel{2}d}$$

$$F_{več} = \frac{m}{d}\left(v_{x_1}^2 + v_{x_2}^2 + \dots v_{x_N}^2\right) = \frac{Nm}{d}\overline{v_x^2}$$

$$\overline{v_x^2} = \overline{v_y^2} = \overline{v_z^2} = \frac{1}{3}\overline{v^2}$$

$$F = \frac{Nm}{d}\frac{\overline{v^2}}{3} \qquad p = \frac{F}{d^2}$$

$k_B = 1{,}38 \cdot 10^{-23}\ J/K$

$N_a = 6{,}02 \cdot 10^{23}\ mol^{-1}$

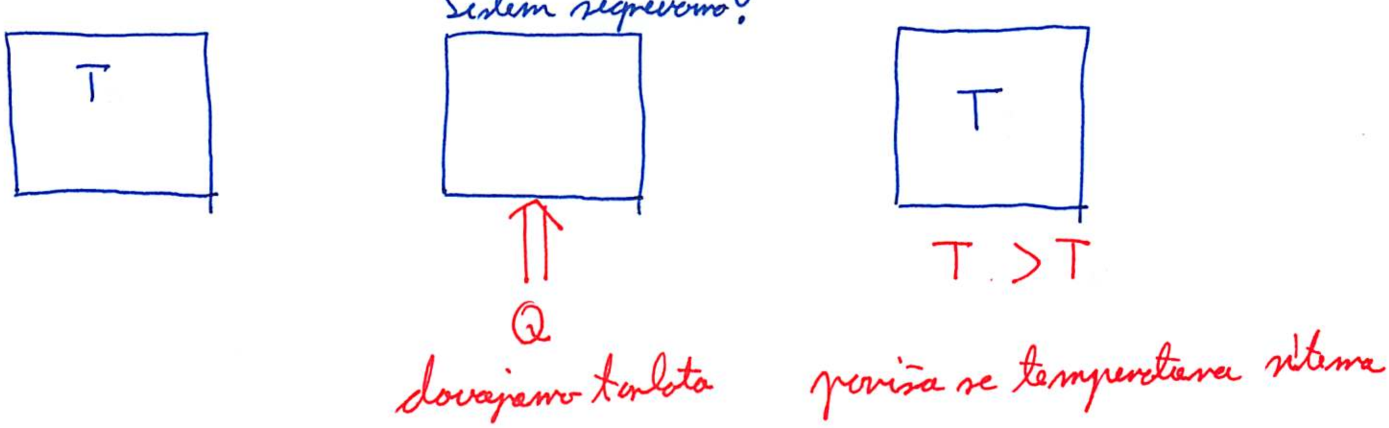
$$p = \frac{Nm}{d^3}\frac{\overline{v^2}}{3} \qquad pV = nRT =$$

$$pV = N\frac{2}{3}\left(\frac{m\overline{v^2}}{2}\right) = \qquad \frac{1}{2}m\overline{v^2} = \frac{3}{2}k_B \cdot T$$

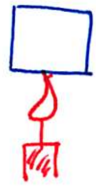
$$= N k_B T = n \cdot \underbrace{N_a k_B}_{R} T = nRT$$

$$\frac{1}{2}m\overline{v_x^2} = \frac{1}{2}k_B T = \frac{1}{2}m\overline{v_y^2} = \frac{1}{2}m\overline{v_z^2}$$ Ekviparticijski izrek!

Definicija toplote; specifična toplota



Sistem segrejemo tako, da ga postavimo v stik s toplejšim sistemom.



$$Q = m\,c\,(T_k - T_z) =$$

$$Q = m\,c\,\Delta T$$

Enote: Q [J] toploto merimo v Joulih;

c: Specifična toplota [J/kg K]

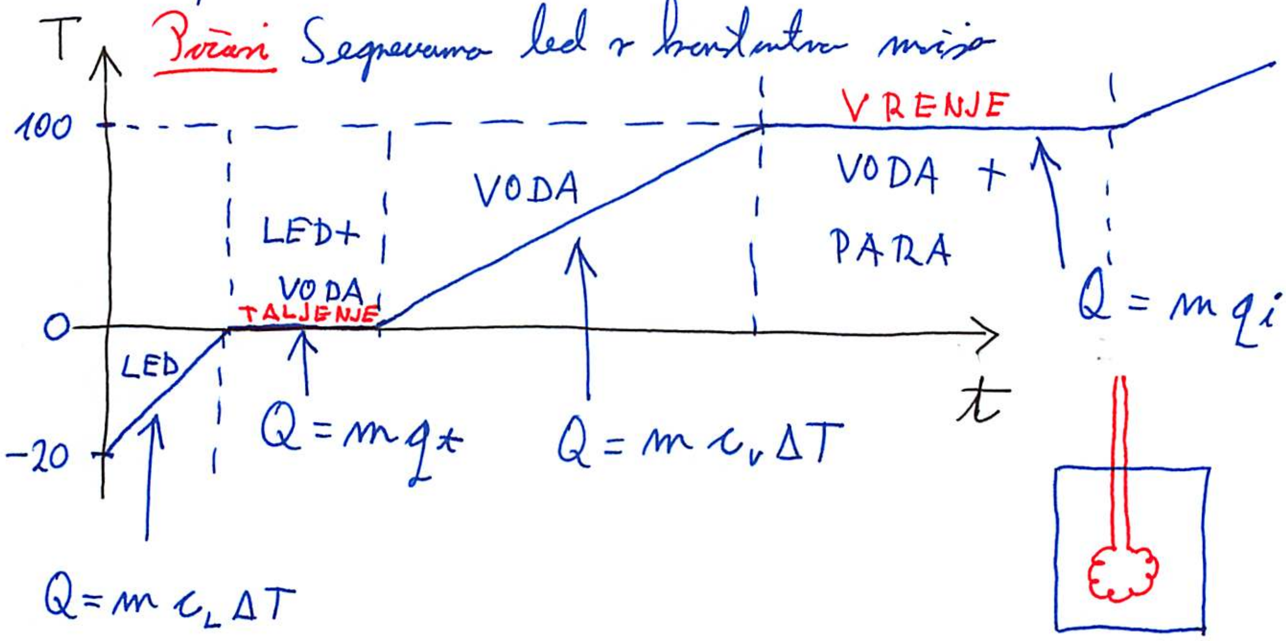
	c $\left[\frac{J}{kg\,K}\right]$
Pb	128
Ag	236
Al	900
Granit	790
Steklo	840
Led	2100
Voda	4200

Fazne spremembe

T5

Led - voda ; voda - para

Primer: Segrevamo led z konstantno močjo



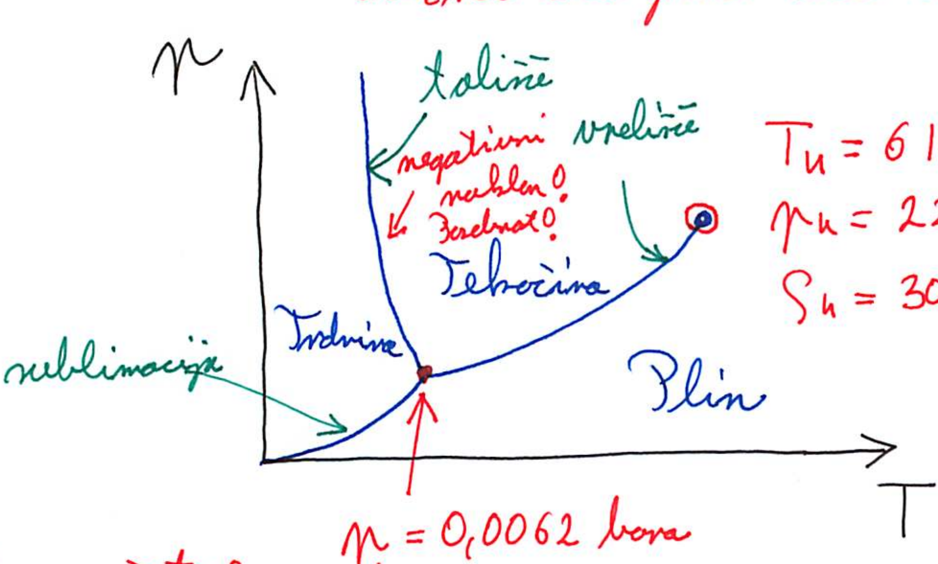
$c_L = 2\,100\ \frac{J}{kg\,K}$; $c_V = 4\,200\ J/kgK$

$q_t = 0{,}336\ \frac{MJ}{kg}$; $q_i = 2{,}26\ \frac{MJ}{kg}$

specifična talilna toplota

specifična izparilna toplota

Fazni diagram vode:

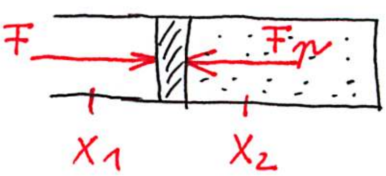


$T_k = 617\ K$
$p_k = 220\ bar$
$\rho_k = 307\ kg/m^3$
} Kritična točka

Trojna točka: $p_t = 0{,}0062\ bara$
$T_t = 273{,}16\ K$

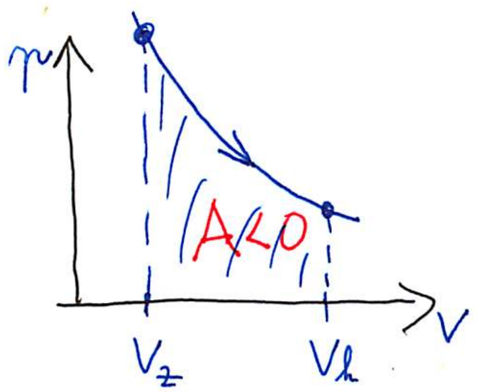
Delo plina

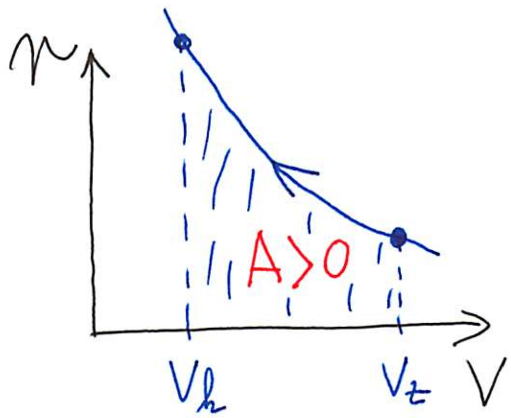
Delo sile: $A = \int_{x_1}^{x_2} F \, dx$



Izrazimo s p: $F = p \cdot S$: $A = \int_{x_1}^{x_2} p \underbrace{S \, dx}_{dV} = \int_{V_1}^{V_2} p \, dV$

Delo plina = − Delo sile $\Rightarrow$ $A = -\int_{V_1 = V_z}^{V_2 = V_k} p \, dV$





- če se plin širi (razpenja), je delo negativno oziroma plin delo <u>opravlja</u>!
- če se plin krči (stiska), je delo pozitivno oziroma plin delo <u>prejema</u>!

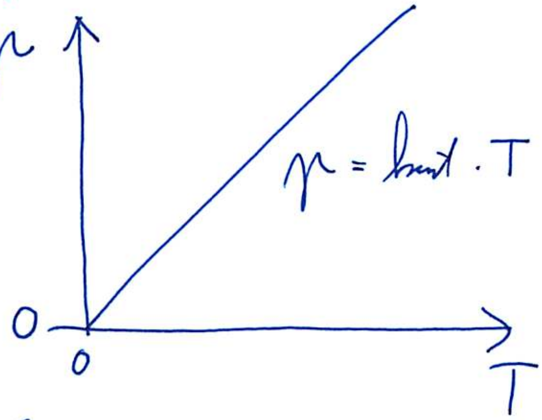
Spremembe na idealnem

(T7)

Spremembe pri konstantnem V plinu:

a.) Izohorna sprememba
($V = konst.$)

$$p = \underbrace{\frac{m}{V}R}_{konst.} T$$

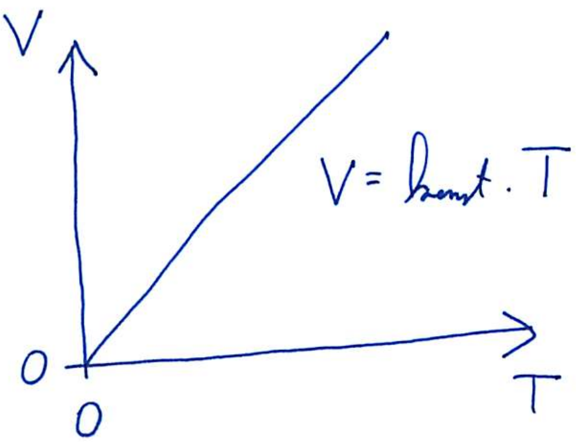


$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

$$A = -\int_{V_1}^{V_2} p\,dV = 0 \quad \text{ker} \quad V_1 = V_2 \text{!}$$

$$A + Q = \Delta W_n \Rightarrow \quad Q = \Delta W_n = m\,c_v\,\Delta T$$

b.) Sprememba pri konstantnem pritisku ($p = konst.$)
ali Izobarna sprememba!



$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \;; \quad V = \left(\frac{mR}{p}\right) \cdot T$$

$$A = -\int_{V_1}^{V_2} p\,dV = -p \int_{V_1}^{V_2} dV \Rightarrow$$

$$A = -p\,(V_2 - V_1) \qquad \text{Definiramo: } Q = m\,c_p\,\Delta T = m\,c_p (T_2 - T_1)$$

$$A + Q = \Delta W_n$$

$$-p\,(V_2 - V_1) + m\,c_p\,(T_2 - T_1) = m\,c_v\,(T_2 - T_1) \;\Big|\, : m \cdot (T_2 - T_1)$$

$$c_p = c_v + \frac{p\,(V_2 - V_1)}{m\,(T_2 - T_1)} = c_v + \frac{p\,\Delta V}{m\,\Delta T} = c_v + \frac{R}{M}$$

$$\Downarrow$$

$$p\,\Delta V = \frac{m}{M} R\,\Delta T$$

$$\boxed{c_p = c_v + \frac{R}{M}}$$

Velja torej: $A = -p\,(T_2 - T_1)$

$$Q = m\,c_p\,(T_2 - T_1)$$

$$\Delta W_n = m\,c_v\,(T_2 - T_1)$$

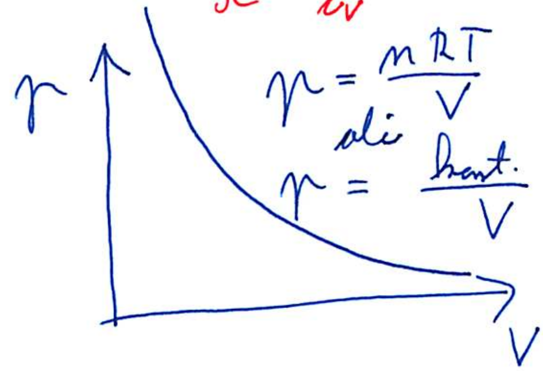
$c_p = c_v + \frac{R}{M}$

Definiramo:

$\chi = \frac{c_p}{c_v}$

$\kappa = \frac{c_p}{c_v}$

c. Sprememba pri konstantni T ali Izoterma sprememba



$$p_1 V_1 = p_2 V_2 \quad ; \quad p = \frac{nRT}{V}$$

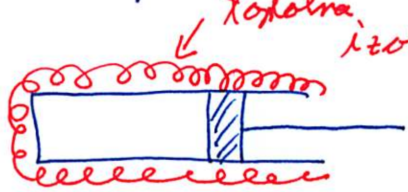
$$\Delta W_n = m\,c_v\,\Delta T = 0\ !$$

$$A + Q = 0 \Rightarrow \boxed{Q = -A}$$

$$A = -\int_{V_1}^{V_2} p\,dV = -nRT \int_{V_1}^{V_2} \frac{dV}{V} = -\underbrace{nRT}_{p_1V_1 = p_2V_2} \ln \frac{V_2}{V_1}$$

$$A = -p_1 V_1 \ln \frac{V_2}{V_1} \quad ; \quad Q = +p_1 V_1 \ln \frac{V_2}{V_1}$$

d.) Sprememba na toplotno izoliranem sistemu $Q = \text{konstantna}$



$$A + Q = \Delta W_n \quad ; \quad dQ = 0$$

Velja tudi plinska enačba:

$$pV = nRT$$

$$p = \frac{nRT}{V} = \frac{mRT}{MV}$$

$$dA = d(\Delta W_n)$$

$$-p\,dV = m\,c_v\,dT$$

$$-\frac{dV}{V} = \frac{m c_v}{nR}\frac{dT}{T} = \frac{M c_v}{R}\frac{dT}{T}$$

$$-\int_{V_1}^{V_2} \frac{dV}{V} = \frac{M c_v}{R} \int_{T_1}^{T_2} \frac{dT}{T} \Rightarrow \ln \frac{V_1}{V_2} = \frac{M c_v}{R} \ln \frac{T_2}{T_1}$$

T9

$$\left(\frac{V_1}{V_2}\right)^{\frac{R}{Mc_v}} = \frac{T_2}{T_1}$$

$$c_p = c_v + \frac{R}{M} \quad |:c_v$$

$$\kappa = 1 + \frac{R}{Mc_v}$$

$$\left(\frac{V_1}{V_2}\right)^{\kappa-1} = \frac{T_2}{T_1} = \frac{V_2 p_2}{V_1 p_1}$$

$$V_1 p_1 = mRT_1$$

$$V_2 p_2 = mRT_2$$

$$\Downarrow$$

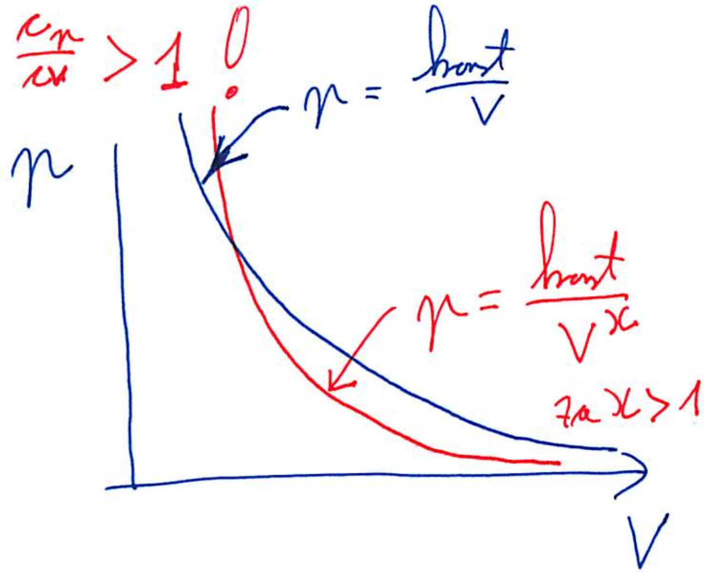
$$\left(\frac{V_1}{V_2}\right)^{\kappa} = \frac{p_2}{p_1}$$

$$\frac{T_1}{T_2} = \frac{V_1 p_1}{V_2 p_2}$$

$$\boxed{V_1^{\kappa} p_1 = V_2^{\kappa} p_2}$$

$\kappa = \frac{c_p}{c_v} > 1$!

Enačba adiabate !



$$A = \Delta W_n = m c_v (T_2 - T_1) \; !$$

Entropija

Reverzibilni

Vzmet

Prožni odboj žogice

Adiabatno stiskanje in raztezanje plina

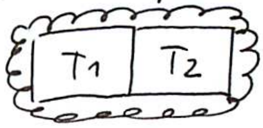
Nereverzibilni procesi

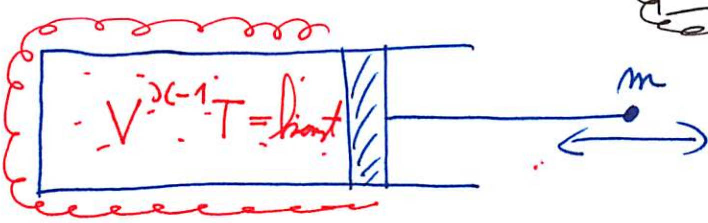
obrat časa ni mogoč

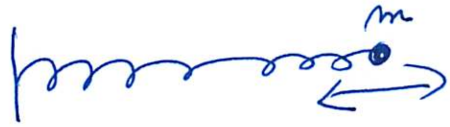
Difuzija tinte v vodi

Razbitje jajca

Joulov poizkus







Adiabatni proces: $V^{\kappa-1}\cdot T = \text{konst}$ | diferencial:

$$V^{\kappa-1}\cdot T: \quad (\kappa-1)\,V^{\kappa-2}\,T\,dV + V^{\kappa-1}\,dT = 0$$

$$(\kappa-1)\frac{dV}{V} + \frac{dT}{T} = 0$$

Za večje spremembe velja:

$$(\kappa-1)\ln\frac{V_k}{V_z} + \ln\frac{T_k}{T_z} = 0$$

Se ohranja $\Leftarrow$ proces je adiabaten $\Rightarrow$ reverzibilen!

Splošni proces

Idealni plin: $dW_n = dQ + d$

$$m\,c_v\,dT = dQ - p\,dV$$

$$\frac{dQ}{T} = m c_v \frac{dT}{T} + \frac{p\,dV}{T} \quad ; \quad \frac{p}{T} = \frac{m}{M} R \frac{1}{V}$$

$$\frac{dQ}{T} = m c_v \frac{dT}{T} + m\frac{R}{M}\frac{dV}{V}$$

$$\frac{dQ}{T} = m c_v\left(\frac{dT}{T} + \underbrace{\frac{R}{M c_v}}_{(\kappa-1)}\frac{dV}{V}\right) = m c_v\left(\frac{dT}{T} + (\kappa-1)\frac{dV}{V}\right)$$

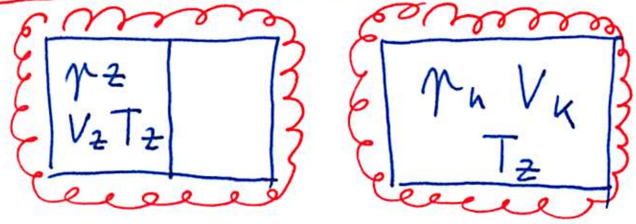
$$\Delta S \geq \int \frac{dQ}{T} = m c_v\left(\ln\frac{T_k}{T_z} + (\kappa-1)\ln\frac{V_k}{V_z}\right)$$

velja neenakost!

za idealni plin!

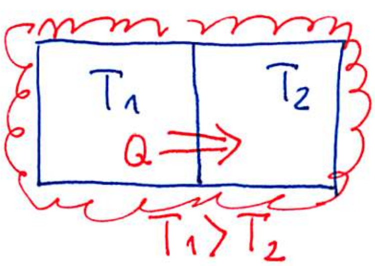
$$\Delta S = m c_v\left(\ln\frac{T_k}{T_z} + (\kappa-1)\ln\frac{V_k}{V_z}\right)$$

Primer: Hirnov poizkus



$$\Delta S > 0 \; !$$

Toplotno prevajanje



$$\boxed{\Delta S = -\frac{\Delta Q}{T_1} + \frac{\Delta Q}{T_2}} > 0 \, !$$