Thermodynamik Formelsammlung

Jonas Walkling

January 17, 2020

Contents

$$\frac{d}{dt}\left\{U+m\left(\frac{c^2}{2}+gz\right)\right\}=\sum_j\left[\dot{m}_j\left(h+\frac{c^2}{2}+gz\right)_j\right]+\sum_l\left(\dot{Q}_t\right)_l+\sum_i\left(\dot{W}_t\right)_i-p\frac{dV}{dt}$$

1 Nomenklatur

$\mathbf{An}$ = Anergie[J]

$\mathbf{c_s}$ = Schallgeschwindigkeit[m/s]

$\mathbf{c_p}$ = Spezifische Wärmekapazität dp = 0 [J/kg*K]

$\mathbf{c_v}$ = Spezifische Wärmekapazität dv = 0 [J/kg*K]

$\mathbf{E}$ = Energie[J]

$\mathbf{Ex} = -\mathbf{W_{ex}}$ = Exergie[J]

$\mathbf{F}$ = Kraft[N]

$\mathbf{F} = \mathbf{U} - \mathbf{TS}$ = Freie Energie[J]

$\mathbf{f} = \mathbf{u} - \mathbf{Ts}$ = Spezifische freie Energie[J/kg]

$\mathbf{f}$ = Fugazität[Pa]

$\mathbf{G} = \mathbf{H} - \mathbf{TS}$ = Freie Enthalpie[J]

$\mathbf{g} = \mathbf{h} - \mathbf{Ts}$ = Spezifische freie Enthalpie[J/kg]

$\mathbf{g}$ = Erdbeschleunigung[m/s²]

$\mathbf{H} = \mathbf{U} + \mathbf{pV}$ = Enthalpie[J]

$\mathbf{h} = \mathbf{u} + \mathbf{pv}$ = Spezifische Enthalpie[J/kg]

■$\mathbf{Hg}$ = Molare Reaktionsenthalpie

$\mathbf{K}$ = Konstante des Massenwirkungsgesetztes[-]

$\mathbf{M}$ = Molmasse[kg/mol]

$\dot{\mathbf{m}}$ = Massestrom[kg/s]

$\mathbf{m}'$ = Masse in der flüssigen Phase[kg]

$\mathbf{m}''$ = Masse in der gasförmigen Phase[kg]

$\mathbf{Ma} = \mathbf{c}/\mathbf{c_s}$ = Machzahl[-]

$\mathbf{n} = \mathbf{m}/\mathbf{M}$ = Molzahl[mol]

$\mathbf{n}$ = Polytropenexponent[-]

$\mathbf{P_t}$ = technische Leistung[W]

$\mathbf{Q}$ = Wärme[J]

$\dot{\mathbf{Q}}$ = Wärmestrom[W]

$\mathbf{q}$ = Spezifische Wärme[J/kg]

$\mathbf{r}$ = Spezifische Verdampfungsenthalpie[J/kg]

$\mathbf{R}$ = Gaskonstante[J/(kg K)]

$\mathbf{R_m}$ = Universelle Gaskonstante[J/(mol K)]

$\mathbf{S}$ = Entropie[J/K]

$\mathbf{s}$ = Spezifische Entropie[J/(kg K)]

$\mathbf{T}$ = Temperatur[K]

$\mathbf{t}$ = Zeit[s]

$\mathbf{t}$ = Temperatur[°C]

$\mathbf{T}$ = Sättigungstemperatur[K]

$\mathbf{U}$ = Innere Energie[J]

$\mathbf{u}$ = Spezifische innere Energie [J/kg]

$\mathbf{V}$ = Volumen[m³]

$\mathbf{v}$ = Spezifisches Volumen[m³/kg]

$\mathbf{V_m}$ = Molares Volumen[m³/mol]

$\mathbf{W}$ = Arbeit[J]

$\mathbf{w}$ = Spezifische Arbeit[J/kg]

$\mathbf{W_V}$ = Volumenänderungsarbeit[J]

$\mathbf{W_{el}}$ = Elektrische Arbeit[J]

$\mathbf{W_w}$ = Wellenarbeit[J]

$\mathbf{W_{diss}}$ = Dissipationsarbeit[J]

$\mathbf{W_t}$ = Technische Arbeit[J]

$\mathbf{W_{Virrev}}$ = Arbeitsverlust durch Irreversibilität[J]

$\mathbf{x} = \frac{m''}{m'+m''}$ = Dampfanteil[-]

$\mathbf{x} = \frac{m_{H_2O}}{m_L}$ = Wassergehalt

$\mathbf{Z}$ = Allgemeine extensive Zustandsgrößen[Z]

$\mathbf{z}$ = Allgemeine

β = Isobarer Ausdehnungskoeffizient[1/K]

γ = Isochorer Spannungskoeffizeint[1/K]

$\delta_\mathbf{T}$ = Isothermer Drosselkoeffizient[m³/kg]

$\delta_\mathbf{h}$ = Isenthalper Drosselkoeffizient[Ks²m/kg]

ε = Leistungsziffer[-]

ε = Verdichtungsverhältnis[-]

$\eta_\mathbf{th}$ = Thermischer Wirkungsgrad[-]

$\eta_\mathbf{mech}$ = Mechanischer Wirkungsgrad[-]

κ = Adiabaten- oder Isentropenexponent[-]

λ = Reaktionslaufzahl[-]

$\mu_\mathbf{i}$ = Chemisches Potential[J/mol]

$\nu_\mathbf{i}$ = Stöchiometrische Koeffizienten[-]

$\xi_\mathbf{i}$ = Masseanteil[-]

π = Druckverhältnis[-]

ρ = Dichte[kg/m³]

τ = Temperaturverhältnis[-]

ϕ = Relative Feuchte[-]

ϕ = Einspritzverhältnis[-]

ξ = Isothermer Kompressibilitätskoeffizient[m²/N]

■ = Dissipationsenergie[J]

ψ = Spezifische Dissipationsenergie[J]

ψ = Drucksteigerungsverhältnis[-]

$\psi_\mathbf{i}$ = Molanteil[-]

2 Grundbegriffe

Systeme

- Abgeschlossenes System - kein Stoff oder Energietransport
- Geschlossenes System - kein Stofftransport
- Adiabates System - kein Δq , aber Masse und Arbeit.
- Offenes System - Stoff und Energietransport
- Stationäres System $\rightarrow \Delta U = 0$

Messgrößen

- Prozessgrößen sind Wegabhängig (eg. Arbeit, Wärme)
- Zustandsgrößen sind Wegunabhängig (eg. Volumen, Druck)
- Extensive Zustandsgrößen sind abhängig von der Masse des Systems (V, m, H, S, F, G, E)
- Intensive Zustandsgrößen sind unabhängig von der Masse des Systems (T, p)

Zustandsgleichungen

- Thermisch $\rightarrow f(p,V,T) = 0$
- Kalorisch $\rightarrow f(U,V,T) = 0, \quad U = U(V,T), \quad u = u(v,T)$

Hauptsätze

0: Temperatur existiert, ihre gleichheit ist notwendige Vorraussetzung für das thermische Gleichgewicht.

1: Energie existiert, sie ist für abgeschlossene Systeme konstant.

2: Entropie existiert, sie wird bei allen irreversiblen Prozessen erzeugt. $dS = \frac{\delta Q_{rev}}{T}$

3: $0K$ exisitert, bei dieser Temperatur ist die Entropie $= 0$

3 Basisformeln

$$H = U + pV$$
$$dS = \frac{\delta Q_{rev}}{T}$$
$$F = U - TS$$
$$G = H - ST$$
$$W = -\int p\, dV$$

$$dS = \frac{Q_{rev}}{T} + S_{prod}$$
$$\Psi = \int_1^2 T\, dS_{prod}$$
$$W_{ir} = \frac{T_u}{T}\Psi$$
$$p_1 = p_a + \frac{\varphi_1 - \varphi_a}{\varphi_b - \varphi_a}(p_b - p_a)$$

4 Gibbs

$$dU = Tds - pdV + \sum_{k=1}^{K} \mu_k dn_k$$
$$dG = -SdT + Vdp + \sum_{k=1}^{K} \mu_k dn_k$$
$$dH = TdS + Vdp + \sum_{k=1}^{K} \mu_k dn_k$$
$$dF = -SdT - pdV + \sum_{k=1}^{K} \mu_k dn_k$$
$$dU = \left(\frac{\partial U}{\partial S}\right)_V dS + \left(\frac{\partial U}{\partial V}\right)_S dV + \sum_{k=1}^{K} \left(\frac{\partial U}{\partial n_k}\right)_S dn_k$$

5 Thermodynamische Beziehungen

$$T = \left(\frac{\partial U}{\partial S}\right)_V = T(S,V) \qquad -S = \left(\frac{\partial F}{\partial T}\right)_V = S(T,V)$$
$$T = \left(\frac{\partial H}{\partial S}\right)_p = T(S,p) \qquad -S = \left(\frac{\partial G}{\partial T}\right)_p = S(T,p)$$
$$p = -\left(\frac{\partial U}{\partial V}\right)_S = p(V,S) \qquad V = \left(\frac{\partial G}{\partial p}\right)_T = V(p,T)$$
$$-p = \left(\frac{\partial F}{\partial V}\right)_T = p(T,V) \qquad \mu = \left(\frac{\partial U}{\partial n}\right)_{S,V} = \mu(S,V,n)$$

6 Guggenheim

-S	U	V	U	= U(S,V)
H		F	H	= H(S,p)
-p	G	T	F	= F(T,V)
			G	= G(T,p)

$$\overbrace{\frac{d}{dt}\left\{U + m\left(\frac{c^2}{2} + gz\right)\right\}}^{\text{Stationäres System -> 0}} = \overbrace{\sum_j \left[\dot{m}_j\left(h + \frac{c^2}{2} + gz\right)\right]_j}^{\text{Geschlossenes System -> 0}} + \overbrace{\sum_l \left(\dot{Q}_t\right)_l}^{\text{Kein Wärmestrom -> 0}} + \overbrace{\sum_i \left(\dot{W}_t\right)_i}^{\text{Keine Leistung -> 0}} - \overbrace{p\frac{dV}{dt}}^{\text{Keine Volumenänderung -> 0}}$$

7 Maxwell

$$\left(\frac{\partial T}{\partial p}\right)_{S,n_j} = \left(\frac{\partial V}{\partial S}\right)_{p,n_j}$$

$$\left(\frac{\partial S}{\partial V}\right)_{T,n_j} = \left(\frac{\partial p}{\partial T}\right)_{V,n_j}$$

$$\left(\frac{\partial S}{\partial p}\right)_{T,n_j} = -\left(\frac{\partial V}{\partial T}\right)_{p,n_j}$$

$$\left(\frac{\partial \mu_i}{\partial T}\right)_{p,n_j} = -\left(\frac{\partial S}{\partial n_i}\right)_{T,p,n_j \neq n_i}$$

$$\left(\frac{\partial \mu_i}{\partial p}\right)_{T,n_j} = \left(\frac{\partial V}{\partial n_i}\right)_{T,p,n_j \neq n_i}$$

8 Ideales Gas

$$pV = mRT$$
$$pv = RT$$
$$pV = nR_mT$$
$$\beta = \frac{1}{T}$$
$$\gamma = \frac{1}{T}$$
$$\chi = \frac{1}{p}$$
$$\beta = p\gamma\chi$$
$$R_m = 8,3143\left[\frac{kJ}{kmolK}\right]$$
$$R = c_p - c_v$$
$$R = \frac{R_m}{M}$$
$$U - U_0 = mc_v(T - T_0)$$

$H - H_0 = mc_p(T - T_0)$ $\leftarrow$ Für c_p und c_v const.

$$\begin{aligned} s - s_0 &= R\ln\left(\frac{v}{v_0}\right) + c_v\ln\left(\frac{T}{T_0}\right) \\ &= c_v\ln\left(\frac{p}{p_0}\right) + c_p\ln\left(\frac{v}{v_0}\right) \\ &= c_p\ln\left(\frac{T}{T_0}\right) - R\ln\left(\frac{p}{p_0}\right) \end{aligned}$$

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

$$\gamma = \frac{1}{T} = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_V$$

$$\chi = \frac{1}{p} = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T$$

$$u_2 - u_1 = \int_{T_1}^{T_2} c_v(T)\,dT$$

9 Van-der-Waals

$$\left(p + \frac{a}{v^2}\right)(v - b) = RT$$
$$\left(\overline{p} + \frac{3}{\overline{v}^2}\right)(3\overline{v} - 1) = 8\overline{T}$$
$$\overline{p} = \frac{p}{p_K}, \quad \overline{v} = \frac{v}{v_K}, \quad \overline{T} = \frac{T}{T_K}$$
$$p_K = \frac{a}{27b^2}, \quad T_K = \frac{8}{27}\frac{a}{b}\frac{1}{R},$$
$$a = 3p_Kv_K^2, \quad b = \frac{v_K}{3}, \quad \frac{p_Kv_K}{RT_K} = \frac{3}{8}$$
$$\beta = \frac{(v-b)Rv^2}{RTv^3 - 2a(v-b)^2}$$
$$\gamma = \frac{Rv^2}{RTv^2 - a(v-b)}$$
$$\chi = \frac{(v-b)^2v^2}{RTv^3 - 2a(v-b)^2}$$
$$du = \frac{a}{v^2}dv + c_v(T)dT$$
$$u - u_0 = \left(\frac{a}{v_0} - \frac{a}{v}\right) + \int_{T_0}^{T} c_v(\tilde{T})\,d\tilde{T}$$

$u - u_0 = \left(\frac{a}{v_0} - \frac{a}{v}\right) + c_v(T - T_0) \leftarrow$ für c_v = const.

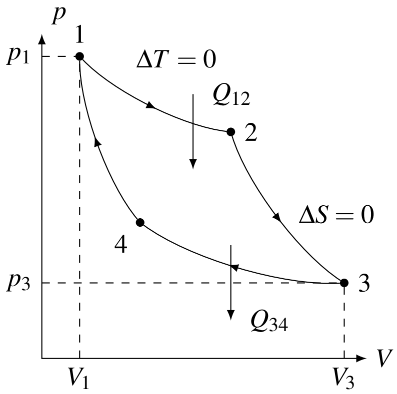
$$c_p - c_v = \frac{Tv\beta^2}{\chi}$$
$$s - s_0 = c_v\ln\left(\frac{T}{T_0}\right) + R\ln\left(\frac{v-b}{v_0-b}\right)$$

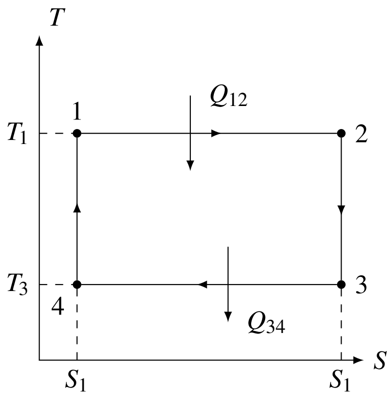
10 Carnot

$$\eta_{th} = 1 - \frac{-Q_{34}}{Q_{12}} = 1 - \frac{T_3(S_3 - S_4)}{T_1(S_2 - S_1)} = 1 - \frac{T_3}{T_1}$$

$$\frac{Q_{12}}{T_1} + \frac{Q_{34}}{T_3} = 0$$

$$\Delta S_{ges} = -Q_{34}\left(\frac{1}{T_{KK}} - \frac{T_1}{T_3}\frac{1}{T_{HK}}\right)$$





11 Gemische Idealer Gase

$$\xi_i = \frac{m_i}{m}, \quad \psi_i = \frac{n_i}{n}, \quad p_i = \psi_i p$$

$$\xi_i = \frac{M_i n_i}{\sum_{k=1}^{K} M_k n_k} = \frac{M_i}{M_G}\psi$$

$$p_i V = m_i R_i T, \quad p_i V = n_i R_m T, \quad pV = m R_G T$$

$$\sum_{k=1}^{K} p_k = p$$

$$R_G = \frac{1}{m}\sum_{k=1}^{K} m_k R_k = \sum_{k=1}^{K} \xi_k R_k$$

$$U_G = \sum_{k=1}^{K} U_k = \sum_{k=1}^{K} m_k u_k = \sum_{k=1}^{K} c_{vk} m_k T \leftarrow c_v = \text{const}$$

$$H_G = \sum_{k=1}^{K} H_k = \sum_{k=1}^{K} m_k h_k = \sum_{k=1}^{K} c_{pk} m_k T \leftarrow c_p = \text{const.}$$

$$c_{vG} = \sum_{k=1}^{K} c_{vk}\xi_k, \quad c_{pG} = \sum_{k=1}^{K} c_{pk}\xi_k$$

$$S_2 - S_1 = R_m\left(n \ln n - \sum_{k=1}^{K} n_k \ln n_k\right)$$

Adiabate Drosselung (ideal):

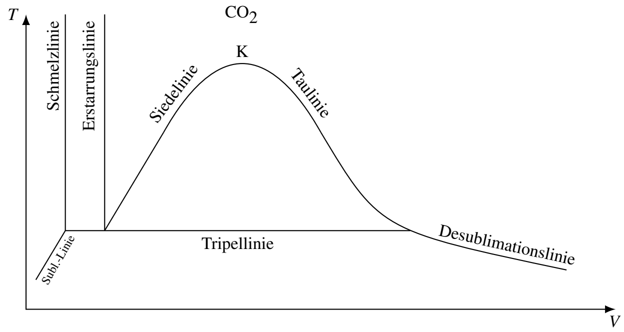
$$h + \frac{c^2}{2} + gz = \text{const.}$$

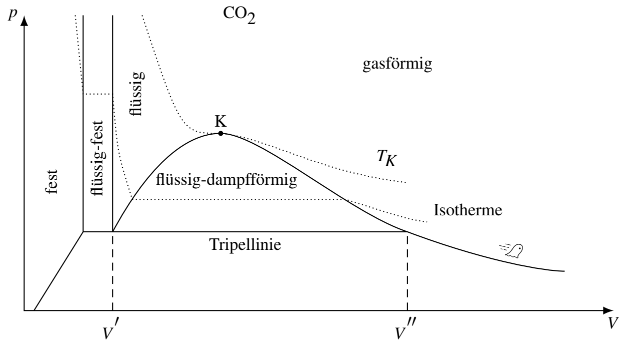
$$dh = 0$$

Adiabet Drosselung (real):

$$\delta_h = \left(\frac{\partial T}{\partial p}\right)_h = -\frac{v}{c_p}(1 - \beta T)$$

12 Nassdampf





$$v = (1-x)v' + xv''$$

$$v = v' + (v'' - v')x$$

$$u = (1-x)u' + xu''$$

$$u = u' + (u'' - u')x$$

$$h = (1-x)h' + xh''$$

$$h = h' + (h'' - h')x$$

$$s = (1-x)s' + xs''$$

$$s = s' + (s'' - s')x$$

$$r = h'' - h' = T(s'' - s')$$

$$T' = T''$$

$$p' = p''$$

$$g' = g''$$

$$dg' = v'dp' - s'dT'$$

$$dg'' = v''dp'' - s''dT''$$

$$dg' = dg''$$

$$\frac{dp}{dT} = \frac{s'' - s'}{v'' - v'}$$

$$\frac{dp}{dT} = \frac{1}{T}\frac{h'' - h'}{v'' - v'}$$

$$\frac{dp}{dT} = \frac{1}{T}\frac{r}{v'' - v'}$$

13 Realer Stoff im Nassdampfgebiet

Isobare Zustandsänderung

$$q_{12} = T(s_2 - s_1) = T\left(s'' - s'\right)(x_2 - x_1)$$

$$w_{V,12} = -\int_1^2 p\,dv = -p(v_2 - v_1) = -p\left(v'' - v'\right)(x_2 - x_1)$$

Isochore Zustandsänderung

$$q_{12} = u_2 - u_1 = u_2' + x_2\left(u_2'' - u_2'\right) - u_1' - x_1\left(u_1'' - u_1'\right)$$

Adiabate Zustandsänderung

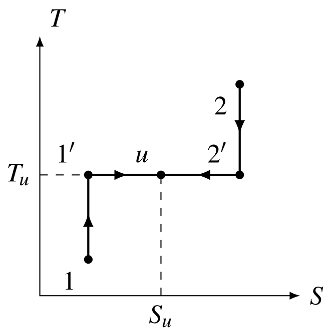
$$w_{V,12} = u_2 - u_1 = u_2' + x_2\left(u_2'' - u_2'\right) - u_1' - x_1\left(u_1'' - u_1'\right)$$

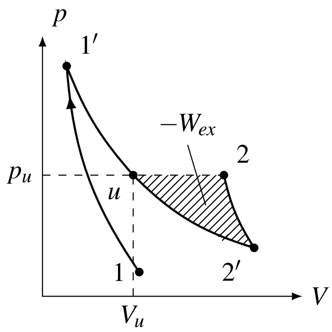
Entropieänderung wärend des Mischvorgangs

$$S_2 - S_2 = R_m\left(n\ln n - \sum_i n_i \ln n_i\right)$$

14 Maximale Arbeit und Exergie

Maxiaml nutzbare Arbeit $\rightarrow$ isentrop, reibungsfrei
$1 \rightarrow 1'$: isentrop auf T_u
$1' \rightarrow u$: isotherm auf u





$$-\dot{W}_{ex} = -(\dot{W}_t)_{rev} = -\frac{d}{dt}\left(U + m\left(\frac{c^2}{2} + gz\right) + p_u V - T_u S\right) + \sum_{j=1}^{K}\left(\dot{m}_j\left(h + \frac{c^2}{2} + gz - T_s\right)\right) + \sum_{l=1}^{K}\left(1 - \frac{T_u}{T}\right)\dot{Q}_l$$

Die Exergie der Enthalpie (offens, stationäres System)

$$-\dot{W}_{ex,1u} = \dot{m}(h_1 - h_u - T_u(s_1 - s_u))$$

Die Exergie der inneren Energie (geschlossenes, instationäres System)

$$-\dot{W}_{ex} = -\frac{d}{dt}(U + p_u V - T_u S)$$

$$-\dot{W}_{ex,1u} = U_1 - U_u - p_u(V_1 - V_u) - T_u(S_1 - S_u)$$

$$-\dot{W}_{ex,1u} = H_1 - (p_1 - p_u)V_1 - H_u - T_u(S_1 - S_u)$$

Für Ideales Gas

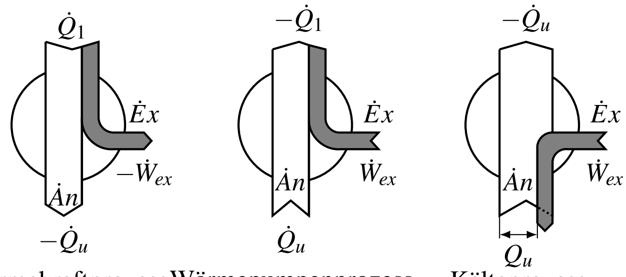
$$-W_{ex} = mc_v(T_1 - T_u) + p_u(V_1 - V_u) - T_u m\left(c_p \ln\left(\frac{T_1}{T_u}\right) - R_i \ln\left(\frac{p_1}{p_u}\right)\right)$$

Dampf/Luftdruckkammer

$$-W_{ex,1u} = m_1[u_1 - u_u + p_u(v_1 - v_u) - T_u(s_1 - s_u)]$$

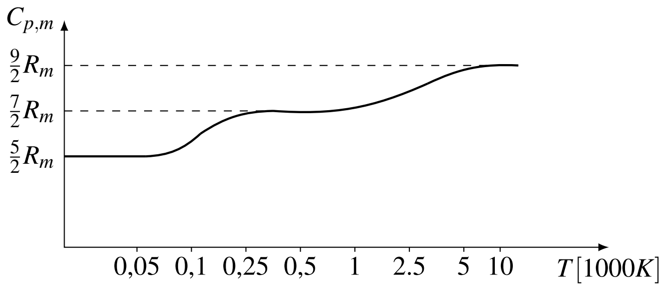
Die Exergie der Wärme (geschlossenes, stationäres System)

$$-\dot{W}_{ex} = \left(1 - \frac{T_u}{T_1}\right)\dot{Q}_1 = \eta_{th,C}\dot{Q}_1$$



Wärmekraftprozess Wärmepumpenprozess Kälteprozess

15 Wärmekapazität



$$C_{v,m} = \frac{1}{\kappa - 1}R_m \qquad C_{p,m} = \frac{\kappa}{\kappa - 1}r_m$$

$$c_v = \frac{1}{\kappa - 1}R_j \qquad c_p = \frac{\kappa}{\kappa - 1}R_j$$

$$\kappa = \frac{c_p}{c_v} \qquad R = c_p - c_v$$

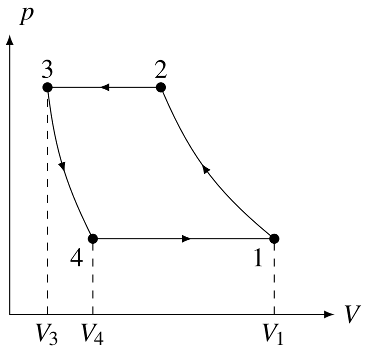
$$R = \frac{R_m}{M} \qquad R_m = 8,3143\left[\frac{kJ}{kmolK}\right]$$

$$C_{v,m} = \underbrace{3 + \frac{R_m}{2}}_{\text{Translatorisch}} + \underbrace{\frac{n_{\text{rot}}R_m}{2}}_{\text{Rotatorisch}} + \underbrace{R_M(3n_{\text{Atome}} - 3 - n_{rot})}_{\text{Vibratorisch}} + \underbrace{C_{v,m,Elektronenanregung}}_{\text{Relevant ab: } T\approx 10^4 K}$$

16 Technische Anwendung

adiabat ($c_p = const.$)	$W_{t,12} = mc_p(T_2 - T_1) = \frac{\kappa}{\kappa - 1}(p_2V_2 - p_1V_1)$	$Q_{12} = 0$
reversibel adiabat $\kappa = const.$	$W_{t,12} = \frac{\kappa}{\kappa - 1}(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right]$	$Q_{12} = 0$
irreversibel adiabat als Polytrope $n > \kappa; n, \kappa = const.$	$W_{t,12} = \frac{\kappa}{\kappa - 1}(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$	$Q_{12} = 0$
reversibel polytrop $n, \kappa = const.$	$W_{t,12} = \frac{n}{n-1}(p_2V_2 - p_1V_1)$ $= \frac{n}{n-1}mR(T_2 - T_1)$ $= \frac{n}{n-1}(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - 1\right]$	$Q_{12} = mc_n(T_2 - T_1)$ $= \frac{n-\kappa}{(n-1)(\kappa-1)}(p_1V_1)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}-1}\right]$ $c_n = \frac{n-\kappa}{n-1}cv$
isotherm	$W_{t,12} = (p_1V_1)\ln\left(\frac{p_2}{p_2}\right)$	$Q_{12} = -W_{t,12}$

16.1 Kolbenverdichter



$V1 =$ Maximales Zylindervolumen

$V2 =$ Volumen nach Verdichtung

$V3 =$

$V4 =$ Schädlicher Raum

$$\mu = \frac{V_1 - V_4}{V_1 - V3}, \qquad \varepsilon_S = \frac{V_3}{V_1 - V_3}$$

$$\mu = 1 - \varepsilon_S\left[\left(\frac{p_2}{p_1}\right)^{\frac{1}{n}} - 1\right]$$

$$W_{t,12} = \int_1^2 V\,dp$$

$$= \underbrace{p_2V_2}_{Ausschiebearbeit} - \underbrace{p_1V_1}_{Einschiebearbeit} - \int_1^2 p\,dV$$

$$= \frac{n}{n-1}p_1(V_1 - V_4)\left[\left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}} - \right]$$

Verdichter Wirkungsgrad

$$\eta_{sV} = \frac{w_{t,12,rev}}{w_{t,12}} = \frac{h_{2,rev} - h_1}{h_2 - h_1}$$

Verdichter wirkungsgrad (Ideales Gas, $c_p =$ const.)

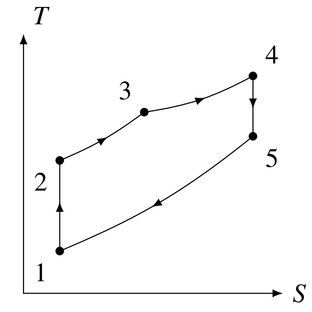
$$n_{sV} = \frac{T_{2,rev} - T_1}{T_2 - T_1}$$

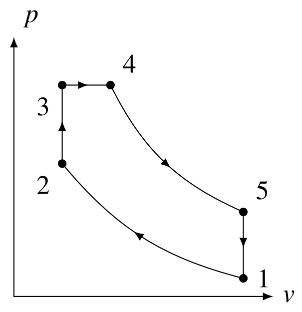
Technische Verlustarbeit

$$w_{t,Verl,12} = w_{t,12} - w_{t,12,rev} = h_2 - h_{2,rev}$$

$$= \int_{2,rev}^2 T|_{p_2=const.}\,ds$$

Seiliger Prozess

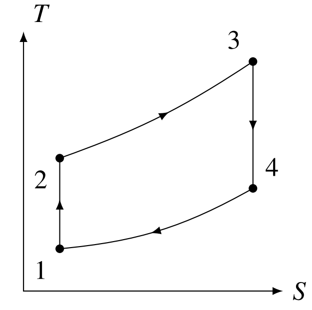


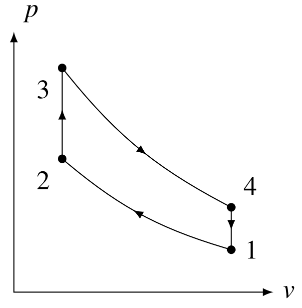


$$\eta_{th} = 1 - \frac{\varphi^{\kappa}\psi - 1}{\varepsilon^{\kappa-1}\left[\psi - 1 + \kappa\psi(\varphi - 1)\right]}$$

$$\varepsilon = \tfrac{v_1}{v_2} \qquad \psi = \tfrac{p3}{p2} \qquad \varphi = \tfrac{v_4}{v}$$

Otto Prozess

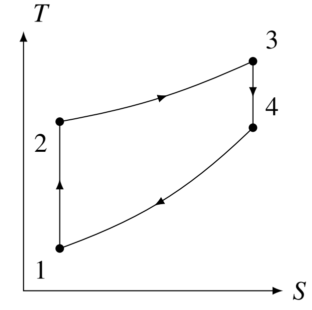


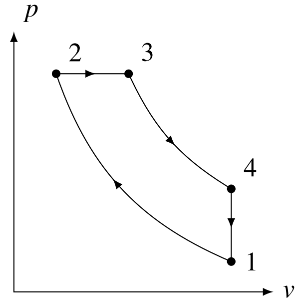


$$\eta_{th} = 1 - \frac{1}{\varepsilon^{\kappa-1}}$$

$$\varepsilon = \frac{v_1}{v_2}$$

Diesel Prozess

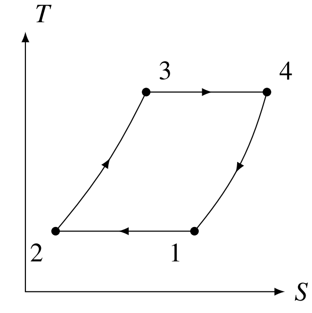


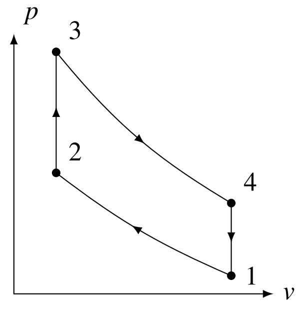


$$n_{th} = 1 - \frac{\varphi^{\kappa} - 1}{\varepsilon^{\kappa-1}\kappa(\varphi - 1)}$$

$$\varepsilon = \tfrac{v_1}{v_2} \qquad \varphi = \tfrac{v_4}{v}$$

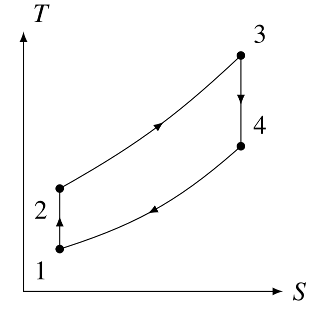
Stirling Prozess

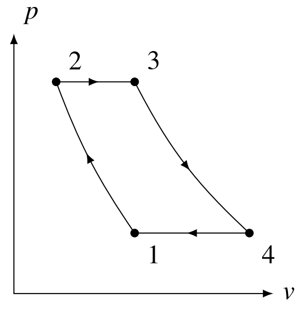




$$n_{th} = 1 - \frac{|q_{12}|}{q_{34}} = \frac{RT_1 \ln\left(\frac{v_1}{v_2}\right)}{RT_3 \ln\left(\frac{v_4}{v_3}\right)} = 1 - \frac{T_1}{T_3}$$

Joule Prozess

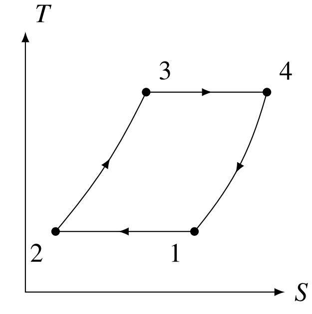


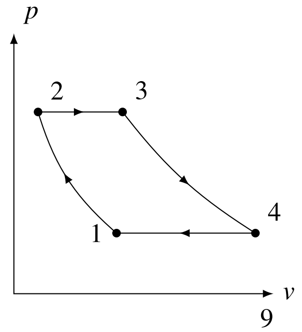


$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{p_1}{p_2}\right)^{\frac{\kappa-1}{\kappa}} = 1 - \left(\frac{1}{\pi}\right)^{\frac{\kappa-1}{\kappa}}$$

$$\pi = \tfrac{p_2}{p_1}$$

Ericsson Prozess





$$n_{th} 1 - \frac{|q_{12}|}{q_{34}} = \frac{RT_1 \ln\left(\frac{p_1}{p_2}\right)}{RT_3 \ln\left(\frac{p_4}{p_3}\right)} = 1 - \frac{T_1}{T_3}$$

Ideales Gas

	Isothermo	Isobare	Isochore	Isentrop	Polytrope
konstant:	T	p	v	$\delta q = 0$	pv^n
	-	-	-	$p_1 v_1^\kappa = p_2 v_2^\kappa$	$v_1^n = p_2 v_2^n$
	$p_1 p_2 = p_2 v_2$	$\frac{v_1}{v_2} = \frac{T_1}{T_2}$	$\frac{p_1}{T_1} = \frac{p_2}{T_2}$	$T_1 v_1^{\kappa-1} = T_2 v_2^{\kappa-1}$	$T_1 v_1^{n-1} = T_2 v_2^{n-1}$
	-	-		$\frac{T_1^{\frac{\kappa}{\kappa-1}}}{p_1} = \frac{T_2^{\frac{\kappa}{\kappa-1}}}{p_2}$	$\frac{T_1^{\frac{n}{n-1}}}{p_1} = \frac{T_2^{\frac{n}{n-1}}}{p_2}$
p, v	$p = \frac{p_1 v_1}{v}$	$p = p_1$	$v = v_1$	$p = \frac{p_1 v_1^\kappa}{v^\kappa}$	$p = \frac{p_1 v_1^n}{v^n}$
p, T	$p = \frac{p_1 v_1}{v}$	$p = p_1$	$p = \frac{p_1}{T_1} T$	$p = \frac{p_1}{T_1^{\frac{\kappa}{\kappa-1}}} T^{\frac{\kappa}{\kappa-1}}$	$p = \frac{p_1}{T_1^{\frac{n}{n-1}}} T^{\frac{n}{n-1}}$
v, T	$T = T_1$	$v = \frac{v_1}{T_1} T$	$v = v_1$	$T = \frac{T_1 v_1^{\kappa-1}}{v^{\kappa-1}}$	$T = \frac{T_1 v_1^{n-1}}{v^{n-1}}$
q_{12}	$= p_1 v_1 \ln \frac{p_1}{p_2}$	$= c_p (T_2 - T_1)$	$= c_v (T_2 - T_1)$	$= 0$	$= c_v \frac{n-\kappa}{n-1} (T_2 - T_1)$
$w_{V,12}$	$= -q_{12}$	$= -p_1 (v_2 - v_1)$	$= 0$	$= \frac{p_1 v_1}{k-1} \left[\left(\frac{v_1}{v_1} \right)^{\kappa-1} - 1 \right]$	$= \frac{p_1 v_1}{n-1} \left[\left(\frac{v_1}{v_2} \right)^{n-1} - 1 \right]$
$s_2 - s_1$	$s_2 - s_1 = R \ln \left(\frac{p_1}{p_2} \right)$	$= c_p \ln \left(\frac{T_2}{T_1} \right)$	$= c_v \ln \left(\frac{T_2}{T_1} \right)$	$= 0$	$= c_v \frac{n-\kappa}{n-1} \ln \left(\frac{T_2}{T_1} \right)$

Van-Der-Waals-Gas

	Isotherme	Isobare	Isochore	Isentrop
konst.	T	p	v	$\delta = 0$
	$(p_1 + \frac{a}{v^2})(v_1 - b) = (p_2 + \frac{a}{v^2})(v_2 - b)$	$\frac{RT_1}{v_1 - b} - \frac{a}{v_1^2} = \frac{RT_2}{v - b} - \frac{a}{v_2^2}$	$\frac{p_1 + \frac{a}{v_1^2}}{T_1} = \frac{p_2 + \frac{a}{v_1^2}}{T_2}$	$(p_1 + \frac{a}{v^2})(v_1 - b)^{\frac{c_v + R}{c_v}} = (p + \frac{a}{v^2})(v_2 - b)^{\frac{c_v + R}{c_v}}$, $T_1(v_1 - b)^{R/c_v} = T_2(v_2 - b)^{R/c_v}$
p, v	$p = (p + \frac{a}{v^2})\frac{v_u}{v - b} - \frac{a}{v^2}$	$p = p_1$	$v = v_1$	$p = -\frac{a}{v^2} + (p_1 + \frac{a}{v^2})\left(\frac{v_1 - b}{v_m}\right)^{\frac{v_v + R}{R}}$
p, T	$T = T_1$	$p = p_1$	$p = \frac{T}{T_1}(p_1 + \frac{a}{v^2}) - \frac{a}{v_1^2}$	$p = -\frac{a}{v^2} + (p_1 + \frac{a}{v^2})\left(\frac{T}{T_1}\right)^{\frac{c_v + R}{R}}$
v, T	$T = T_1$	$T = T_1 \frac{v - b}{v_1 - b} + \frac{a}{R}(v - b)\left(\frac{1}{v^2} - \frac{1}{v_1^2}\right)$	$v = v_1$	$T = T_1\left(\frac{v_1 - b}{v - b}\right)^{\frac{R}{c_v}}$
q_{12}	$= RT_1 \ln\left(\frac{v_2 - b}{v_1 - b}\right)$	$= \frac{a}{v_1} - \frac{a}{v_2} + c_v(T_2 - T_1) + p_1(v_2 - v_1)$	$= c_v(T_2 - T_1)$	$= 0$
$w_{V,12}$	$= -RT_1 \ln\left(\frac{v_2 - b}{v_1 - b}\right) + \frac{a}{v_1} - \frac{a}{v_2}$	$= -p_1(v_2 - v_1)$	$= 0$	$= \frac{a}{v_1} - \frac{a}{v_2} + c_v(T_2 - T_1)$
$s_2 - s_1$	$= R \ln\left(\frac{v_2 - b}{v_1 - b}\right)$	$= c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2 - b}{v_1 - b}\right)$	$= c_v \ln\left(\frac{T_2}{T_1}\right)$	$= 0$

p [bar]	h' [kJ/kg]	h'' [kJ/kg]	s' [kJ/(kgK)]	s'' [kJ/(kgK)]
0,01	29,3	2513,3	0,1058	8,9732
0,03	101,0	2544,7	0,3543	8,5754
0,06	151,4	2566,7	0,5207	8,3283
0,08	173,8	2576,3	0,5922	8,2266
0,10	191,7	2583,9	0,6489	8,1480
0,30	289,1	2624,4	0,9435	7,7657
0,50	340,4	2644,7	1,0906	7,5903
0,80	391,6	2664,3	1,2325	7,4300
1,00	417,4	2673,8	1,3022	7,3544
2,00	504,6	2704,6	1,5295	7,1212
3,00	561,3	2723,2	1,6711	6,9859
4,00	604,5	2736,5	1,7758	6,8902
6,00	670,2	2755,2	1,9301	6,7555
8,00	720,6	2768,0	2,0448	6,6594
10,00	762,2	2777,5	2,1372	6,5843
20,00	908,0	2800,6	2,4455	6,3422
30,00	1007,8	2805,5	2,6438	6,1890
50,00	1154,0	2794,6	2,9189	5,9735
70,00	1267,0	2771,1	3,1202	5,8113
100,00	1407,1	2725,6	3,3584	5,6155
130,00	1530,5	2662,8	3,5579	5,4338
150,00	1609,1	2610,1	3,6818	5,3109
170,00	1690,7	2547,3	3,8073	5,1784
200,00	1823,6	2415,6	4,0096	4,9371
210,00	1895,2	2335,2	4,1140	4,8024
220,00	1995,0	2224,4	4,2590	4,6230
221,20	2107,4	2107,4	4,4429	4,4429