# Thermodynamik Formelsammlung

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January 16, 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]
■**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
$\beta$ = Isobarer Ausdehnungskoeffizient[1/K]
$\gamma$ = Isochorer Spannungskoeffizeint[1/K]
$\delta_\mathbf{T}$ = Isothermer Drosselkoeffizient[m³/kg]
$\delta_\mathbf{h}$ = Isenthalper Drosselkoeffizient[Ks²m/kg]
$\varepsilon$ = Leistungsziffer[-]
$\varepsilon$ = Verdichtungsverhältnis[-]
$\eta_\mathbf{th}$ = Thermischer Wirkungsgrad[-]
$\eta_\mathbf{mech}$ = Mechanischer Wirkungsgrad[-]
$\kappa$ = Adiabaten- oder Isentropenexponent[-]
$\lambda$ = Reaktionslaufzahl[-]
$\mu_\mathbf{i}$ = Chemisches Potential[J/mol]
$\nu_\mathbf{i}$ = Stöchiometrische Koeffizienten[-]
$\xi_\mathbf{i}$ = Masseanteil[-]
$\pi$ = Druckverhältnis[-]
$\rho$ = Dichte[kg/m³]
$\tau$ = Temperaturverhältnis[-]
$\phi$ = Relative Feuchte[-]
$\phi$ = Einspritzverhältnis[-]
$\xi$ = Isothermer Kompressibilitätskoeffizient[m²/N]
■ = Dissipationsenergie[J]
$\psi$ = Spezifische Dissipationsenergie[J]
$\psi$ = Drucksteigerungsverhältnis[-]
$\psi_\mathbf{i}$ = Molanteil[-]

# 2 Grundbegriffe

Systeme

- Abgeschlossenes System - kein Stoff oder Energietransport
- Geschlossenes System - kein Stofftransport
- Adiabates System - kein $\Delta q$ , 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

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

# 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) |

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

# 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

$$pV = mRT$$
$$pv = RT$$
$$pV = nR_mT$$
$$\beta = \frac{1}{T}$$
$$\gamma = \frac{1}{T}$$
$$\chi = \frac{1}{p}$$
$$\beta = p\gamma\chi$$
$$R_m = 8,3143\left[\frac{kJ}{kmolK}\right]$$
$$R = c_p - c_v$$
$$R = \frac{R_m}{M}$$
$$U - U_0 = mc_v(T-T_0)$$
$$H - H_0 = mc_p(T-T_0) \quad \leftarrow \text{Für } c_p \text{ und } c_v \text{ const.}$$

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

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

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

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

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

# 9 Van-der-Waals

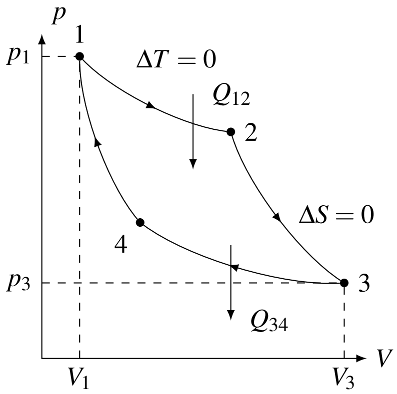
$$\left(p + \frac{a}{v^2}\right)(v-b) = RT$$
$$\left(\overline{p} + \frac{3}{\overline{v}^2}\right)(3\overline{v}-1) = 8\overline{T}$$
$$\overline{p} = \frac{p}{p_K}, \quad \overline{v} = \frac{v}{v_K}, \quad \overline{T} = \frac{T}{T_K}$$
$$p_K = \frac{a}{27b^2}, \quad T_K = \frac{8}{27}\frac{a}{b}\frac{1}{R},$$
$$a = 3p_Kv_K^2, \quad b = \frac{v_K}{3}, \quad \frac{p_Kv_K}{RT_K} = \frac{3}{8}$$
$$\beta = \frac{(v-b)Rv^2}{RTv^3 - 2a(v-b)^2}$$
$$\gamma = \frac{Rv^2}{RTv^2 - a(v-b)}$$
$$\chi = \frac{(v-b)^2v^2}{RTv^3 - 2a(v-b)^2}$$
$$du = \frac{a}{v^2}dv + c_v(T)dT$$
$$u - u_0 = \left(\frac{a}{v_0} - \frac{a}{v}\right) + \int_{T_0}^{T} c_v(\tilde{T})\,d\tilde{T}$$
$$u - u_0 = \left(\frac{a}{v_0} - \frac{a}{v}\right) + c_v(T-T_0) \leftarrow \text{für } c_v = \text{const.}$$
$$c_p - c_v = \frac{Tv\beta^2}{\chi}$$
$$s - s_0 = c_v\ln\left(\frac{T}{T_0}\right) + R\ln\left(\frac{v-b}{v_0-b}\right)$$

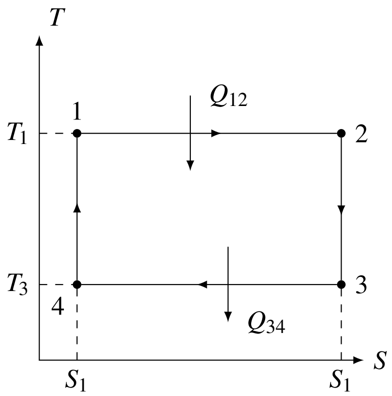
# 10 Carnot

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

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

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




# 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):

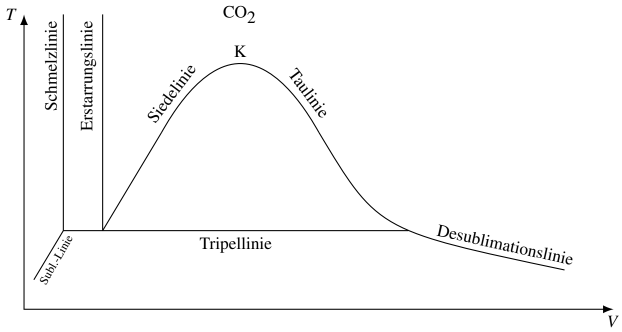
$$h + \frac{c^2}{2} + gz = \text{const.}$$

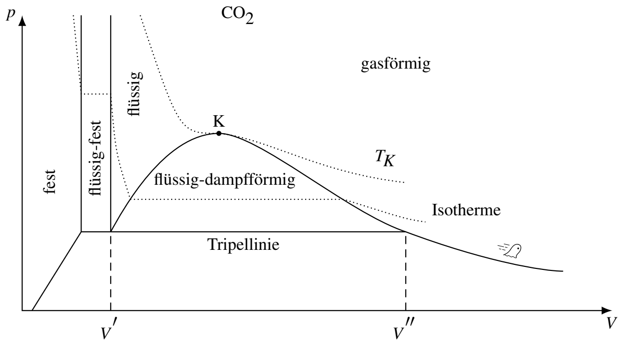
$$dh = 0$$

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

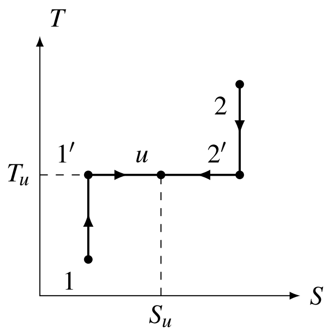
$$w_{V,12} = u_2 - u_1 = u_2' + x_2\left(u_2'' - u_2'\right) - u_1' - x_1\left(u_1'' - u_1'\right)$$

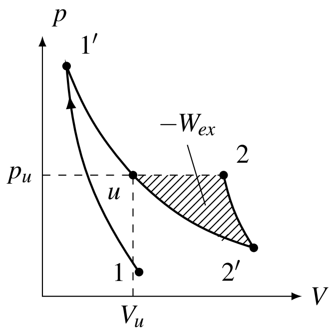
Entropieänderung wärend des Mischvorgangs

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

## 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

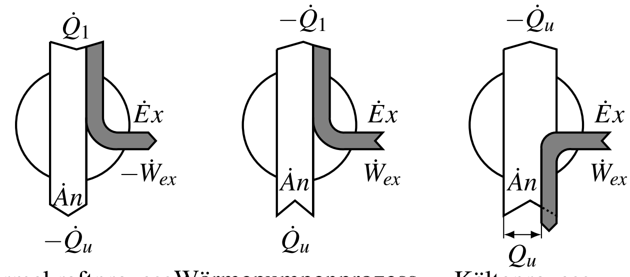
$$-W_{ex} = mc_v(T_1 - T_u) + p_u(V_1 - V_u) - T_u m\left(c_p \ln\left(\frac{T_1}{T_u}\right) - R_i \ln\left(\frac{p_1}{p_u}\right)\right)$$

Dampf/Luftdruckkammer

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

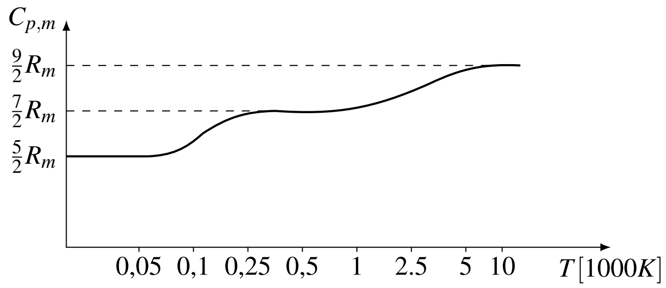
Die Exergie der Wärme (geschlossenes, stationäres System)

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




Wärmekraftprozess Wärmepumpenprozess Kälteprozess

## 15 Wärmekapazität



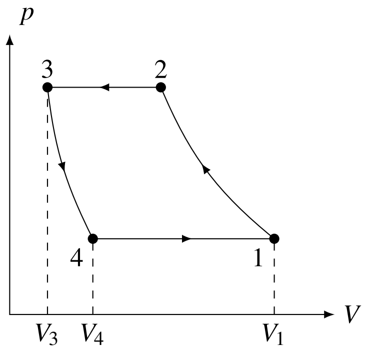

$$C_{v,m} = \frac{1}{\kappa - 1}R_m, \quad C_{p,m} = \frac{\kappa}{\kappa - 1}r_m$$
$$c_v = \frac{1}{\kappa - 1}R_j, \quad c_p = \frac{\kappa}{\kappa - 1}R_j$$
$$\kappa = \frac{c_p}{c_v}, \quad c_p - c_v = R$$

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

# 16 Technische Anwendung

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

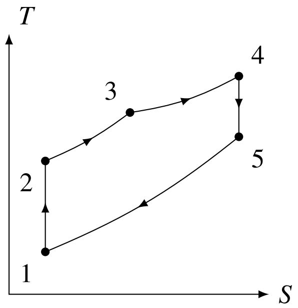
$$n_{sV} = \frac{T_{2,rev} - T_1}{T_2 - T_1}$$

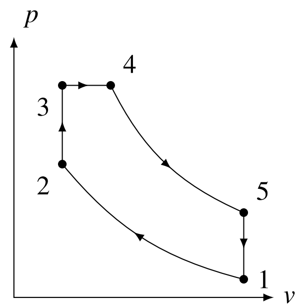
Technische Verlustarbeit

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

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

## Seiliger Prozess

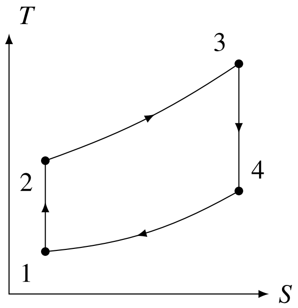


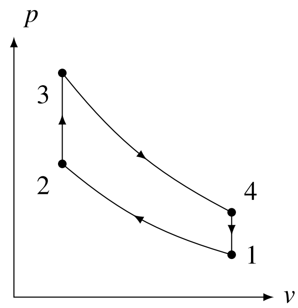




$$\eta_{th} = 1 - \frac{\varphi^{\kappa}\psi - 1}{\varepsilon^{\kappa-1}\left[\psi - 1 + \kappa\psi\left(\varphi - 1\right)\right]}$$

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

## Otto Prozess

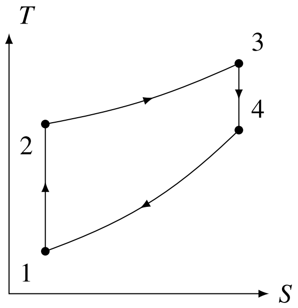


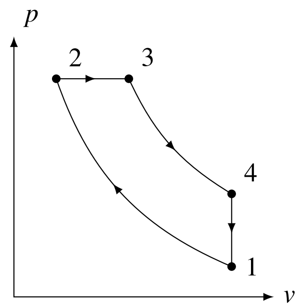




$$n_{th} = 1 - \frac{1}{\varepsilon^{\kappa-1}}$$

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

## Diesel Prozess

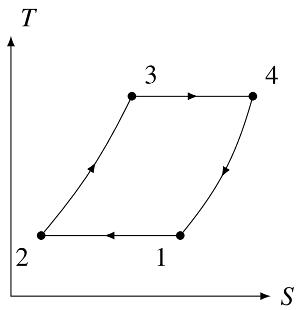


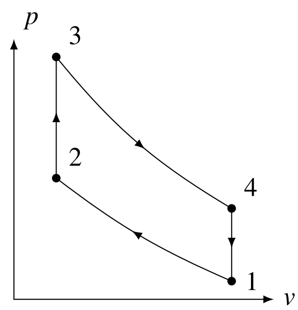




$$n_{th} = 1 - \frac{\varphi^{\kappa} - 1}{\varepsilon^{\kappa-1}\kappa(\varphi - 1)}$$

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

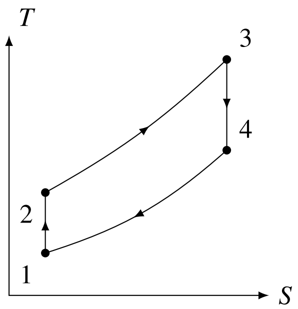
## Stirling Prozess

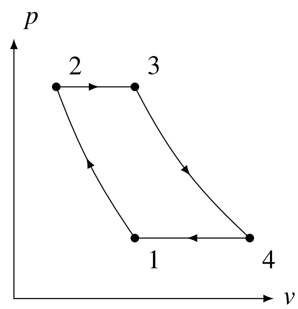



$$n_{th} 1 - \frac{|q_{12}|}{q_{34}} = \frac{RT_1 \ln\left(\frac{v_1}{v_2}\right)}{RT_3 \ln\left(\frac{v_4}{v_3}\right)} = 1 - \frac{T_1}{T_3}$$

## Joule Prozess

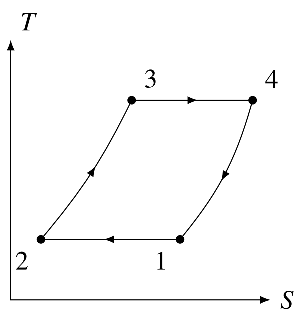


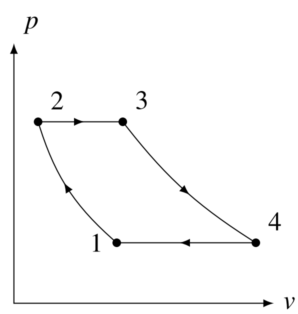




$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{p_1}{p_2}\right)^{\frac{\kappa-1}{\kappa}} = 1 - \left(\frac{1}{\pi}\right)^{\frac{\kappa-1}{\kappa}}$$

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

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

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 |