

# Thermodynamik Formelsammlung

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

## 1 Nomenklatur

|   |   |
|---|---|
| <b>A<sub>n</sub></b> = Anergie[J]                                   | <b>V</b> = Volumen[m <sup>3</sup> ]   |
| <b>c<sub>s</sub></b> = Schallgeschwindigkeit[m/s]                   | <b>v</b> = Spezifisches Volumen[m <sup>3</sup> /kg]                         |
| <b>c<sub>p</sub></b> = Spezifische Wärmekapazität dp = 0 [J/kg*K]   | <b>V<sub>m</sub></b> = Molares Volumen[m <sup>3</sup> /mol]                 |
| <b>c<sub>v</sub></b> = Spezifische Wärmekapazität dv = 0 [J/kg*K]   | <b>W</b> = Arbeit[J]  |
| <b>E</b> = Energie[J]   | <b>w</b> = Spezifische Arbeit[J/kg]   |
| <b>Ex</b> = - <b>W<sub>ex</sub></b> = Exergie[J]                    | <b>W<sub>v</sub></b> = Volumenänderungsarbeit[J]                            |
| <b>F</b> = Kraft[N]   | <b>W<sub>el</sub></b> = Elektrische Arbeit[J]                               |
| <b>F</b> = <b>U</b> - <b>TS</b> = Freie Energie[J]                  | <b>W<sub>w</sub></b> = Wellenarbeit[J]                                      |
| <b>f</b> = <b>u</b> - <b>Ts</b> = Spezifische freie Energie[J/kg]   | <b>W<sub>diss</sub></b> = Dissipationsarbeit[J]                             |
| <b>f</b> = Fugazität[Pa]  | <b>W<sub>t</sub></b> = Technische Arbeit[J]                                 |
| <b>G</b> = <b>H</b> - <b>TS</b> = Freie Enthalpie[J]                | <b>W<sub>virrev</sub></b> = Arbeitsverlust durch Irreversibilität[J]        |
| <b>g</b> = <b>h</b> - <b>Ts</b> = Spezifische freie Enthalpie[J/kg] | <b>x</b> = $\frac{m''}{m' + m''}$ = Dampfanteil[-]                          |
| <b>g</b> = Erdbeschleunigung[m/s <sup>2</sup> ]                     | <b>x</b> = $\frac{m_{H_2O}}{m_L}$ = Wassergehalt                            |
| <b>H</b> = <b>U</b> + <b>pV</b> = Enthalpie[J]                      | <b>Z</b> = Allgemeine extensive Zustandsgrößen[Z]                           |
| <b>h</b> = <b>u</b> + <b>pv</b> = Spezifische Enthalpie[J/kg]       | <b>z</b> = Allgemeine   |
| <b>ΔH<sub>g</sub></b> = Molare Reaktionsenthalpie                   | <b>β</b> = Isobarer Ausdehnungskoeffizient[1/K]                             |
| <b>K</b> = Konstante des Massenwirkungsgesetzes[-]                  | <b>γ</b> = Isochorer Spannungskoeffizient[1/K]                              |
| <b>M</b> = Molmasse[kg/mol]   | <b>δ<sub>T</sub></b> = Isothermer Drosselkoeffizient[m <sup>3</sup> /kg]    |
| <b>ṁ</b> = Massenstrom[kg/s]  | <b>δ<sub>h</sub></b> = Isenthalper Drosselkoeffizient[Ks <sup>2</sup> m/kg] |
| <b>m'</b> = Masse in der flüssigen Phase[kg]                        | <b>ε</b> = Leistungsziffer[-]   |
| <b>m''</b> = Masse in der gasförmigen Phase[kg]                     | <b>ε</b> = Verdichtungsverhältnis[-]  |
| <b>Ma</b> = <b>c</b> / <b>c<sub>s</sub></b> = Machzahl[-]           | <b>η<sub>th</sub></b> = Thermischer Wirkungsgrad[-]                         |
| <b>n</b> = <b>m</b> / <b>M</b> = Molzahl[mol]                       | <b>η<sub>mech</sub></b> = Mechanischer Wirkungsgrad[-]                      |
| <b>n</b> = Polytropenexponent[-]                                    | <b>κ</b> = Adiabaten- oder Isentropenexponent[-]                            |
| <b>P<sub>t</sub></b> = technische Leistung[W]                       | <b>λ</b> = Reaktionslaufzahl[-]   |
| <b>Q</b> = Wärme[J]   | <b>μ<sub>i</sub></b> = Chemisches Potential[J/mol]                          |
| <b>Q̇</b> = Wärmestrom[W]   | <b>v<sub>i</sub></b> = Stöchiometrische Koeffizienten[-]                    |
| <b>q</b> = Spezifische Wärme[J/kg]                                  | <b>ξ<sub>i</sub></b> = Masseanteil[-]                                       |
| <b>r</b> = Spezifische Verdampfungsenthalpie[J/kg]                  | <b>π</b> = Druckverhältnis[-]   |
| <b>R</b> = Gaskonstante[J/(kg K)]                                   | <b>ρ</b> = Dichte[kg/m <sup>3</sup> ]                                       |
| <b>R<sub>m</sub></b> = Universelle Gaskonstante[J/(mol K)]          | <b>τ</b> = Temperaturverhältnis[-]  |
| <b>S</b> = Entropie[J/K]  | <b>φ</b> = Relative Feuchte[-]  |
| <b>s</b> = Spezifische Entropie[J/(kg K)]                           | <b>φ</b> = Einspritzverhältnis[-]   |
| <b>T</b> = Temperatur[K]  | <b>ξ</b> = Isothermer Kompressibilitätskoeffizient[m <sup>2</sup> /N]       |
| <b>t</b> = Zeit[s]  | <b>Ψ</b> = Dissipationsenergie[J]   |
| <b>t</b> = Temperatur[°C]   | <b>ψ</b> = Spezifische Dissipationsenergie[J]                               |
| <b>T</b> = Sättigungstemperatur[K]                                  | <b>ψ</b> = Drucksteigerungsverhältnis[-]                                    |
| <b>U</b> = Innere Energie[J]  | <b>ψ<sub>i</sub></b> = Molanteil[-]   |
| <b>u</b> = Spezifische innere Energie [J/kg]                        |   |

## 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 wegunabhängig (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  $\rightarrow f(U, V, T) = 0$ ,  $U = U(V, T)$ ,  $u = u(v, T)$

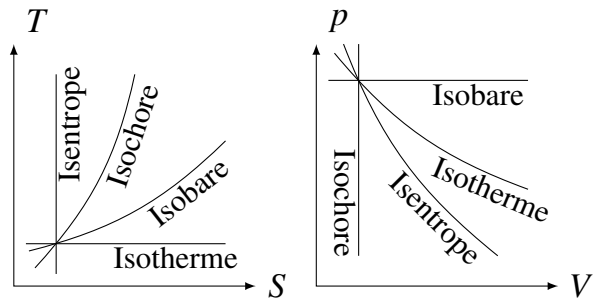
### Hauptsätze

- 0: Temperatur existiert, ihre Gleichheit ist notwendige Voraussetzung für das thermische Gleichgewicht von zwei Systemen.
- 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 existiert, bei dieser Temperatur ist die Entropie = 0

## 3 Basisformeln

$$\begin{aligned}
 H &= U + pV & dS &= \frac{Q_{rev}}{T} + S_{prod} \\
 dS &= \frac{\delta Q_{rev}}{T} & dS_{prod} &= \frac{\Psi}{T} \\
 F &= U - TS & \Psi &= \int_1^2 T dS_{prod} \\
 G &= H - ST & W_{ir} &= \frac{T_u}{T} \Psi \\
 W &= - \int p dV & W_{V,ir} &= T_U \cdot S_{prod} \\
 dU &= mc_v dT & p_1 &= p_a + \frac{\phi_1 - \phi_a}{\phi_b - \phi_a} (p_b - p_a) \\
 m &= \rho \cdot V
 \end{aligned}$$

## 4 Iso



## 5 Gibbs

$$\begin{aligned}
 dU &= T dS - p dV + \sum_{k=1}^K \mu_k dn_k \\
 dG &= -S dT + V dp + \sum_{k=1}^K \mu_k dn_k \\
 dH &= T dS + V dp + \sum_{k=1}^K \mu_k dn_k \\
 dF &= -S dT - p dV + \sum_{k=1}^K \mu_k dn_k \\
 dU &= \left( \frac{\partial U}{\partial S} \right)_V dS + \left( \frac{\partial U}{\partial V} \right)_S dV + \sum_{k=1}^K \left( \frac{\partial U}{\partial n_k} \right)_S dn_k
 \end{aligned}$$

## 6 Thermodynamische Beziehungen

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

## 7 Guggenheim

$$\begin{aligned}
 -S & \quad U & V & \quad U = U(S, V) \\
 H & & F & \quad H = H(S, p) \\
 -p & \quad G & T & \quad F = F(T, V) \\
 & & & \quad G = G(T, p)
 \end{aligned}$$

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

## 8 Maxwell

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

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

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

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

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

## 9 Ideales Gas

$$pV = mRT$$

$$pv = RT$$

$$pV = nR_m T$$

$$\beta = \frac{1}{T}$$

$$\gamma = \frac{1}{T}$$

$$\chi = \frac{1}{p}$$

$$\beta = p\gamma\chi$$

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

$$R = c_p - c_v$$

$$R = \frac{R_m}{M}$$

$$U - U_0 = mc_v(T - T_0)$$

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

$$s - s_0 = R \ln \left( \frac{v}{v_0} \right) + c_v \ln \left( \frac{T}{T_0} \right)$$

$$= c_v \ln \left( \frac{p}{p_0} \right) + c_p \ln \left( \frac{v}{v_0} \right)$$

$$= c_p \ln \left( \frac{T}{T_0} \right) - R \ln \left( \frac{p}{p_0} \right)$$

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

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

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

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

$$U_2 - U_1 = Q_{12} + W_{V,12}$$

## 10 Van-der-Waals

$$\left(p + \frac{a}{v^2}\right)(v-b) = RT$$

$$\left(\bar{p} + \frac{3}{\bar{v}^2}\right)(3\bar{v}-1) = 8\bar{T}$$

$$\bar{p} = \frac{p}{p_K}, \quad \bar{v} = \frac{v}{v_K}, \quad \bar{T} = \frac{T}{T_K}$$

$$p_K = \frac{a}{27b^2}, \quad T_K = \frac{8}{27} \frac{a}{b} \frac{1}{R},$$

$$a = 3p_K v_K^2, \quad b = \frac{v_K}{3}, \quad \frac{p_K v_K}{RT_K} = \frac{3}{8}$$

$$\beta = \frac{(v-b)Rv^2}{RTv^3 - 2a(v-b)^2}$$

$$\gamma = \frac{Rv^2}{RTv^2 - a(v-b)}$$

$$\chi = \frac{(v-b)^2 v^2}{RTv^3 - 2a(v-b)^2}$$

$$du = \frac{a}{v^2} dv + c_v(T) dT$$

$$u - u_0 = \left( \frac{a}{v_0} - \frac{a}{v} \right) + \int_{T_0}^T c_v(\tilde{T}) d\tilde{T}$$

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

$$c_p - c_v = \frac{Tv\beta^2}{\chi}$$

$$s - s_0 = c_v \ln \left( \frac{T}{T_0} \right) + R \ln \left( \frac{v-b}{v_0-b} \right)$$

$$h_2 - h_1 = \frac{1}{2}(p_2 - p_1) \left( \frac{1}{\rho_1} + \frac{1}{\rho_2} \right)$$

## 11 Drosselung



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

$$dh = 0, \quad T_1 = T_2$$

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

$$\delta_T = \left( \frac{\partial h}{\partial p} \right)_T$$

$$s_2 - s_1 = R \ln \left( \frac{v_2}{v_1} \right) = R \ln \left( \frac{p_1}{p_2} \right)$$

$$\mu_{J-T} = \left( \frac{\partial H}{\partial p} \right)_H \approx \frac{\frac{2a}{RT} - b}{c_{p,m}}$$

$$T_i = \frac{2a}{Rb}$$

## 12 Carnot

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

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

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



## 13 Gemische Idealer Gase

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

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

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

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

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

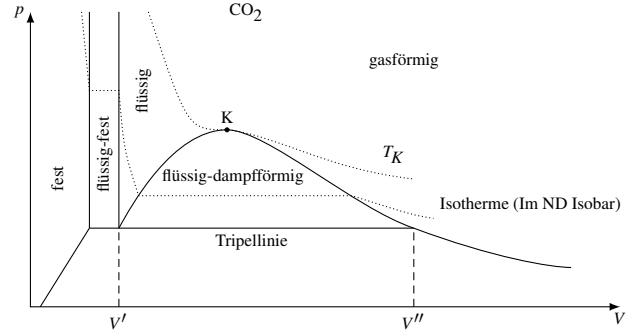
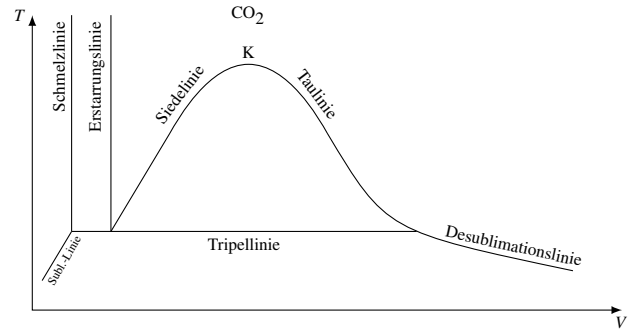
$$U_G = \sum_{k=1}^K U_k = \sum_{k=1}^K m_k u_k = \sum_{k=1}^K c_{vk} m_k T \leftarrow c_v = \text{const}$$

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

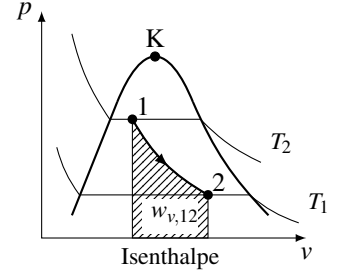
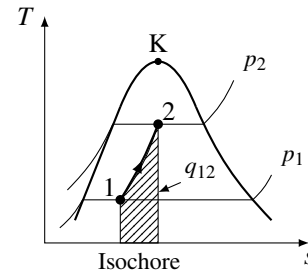
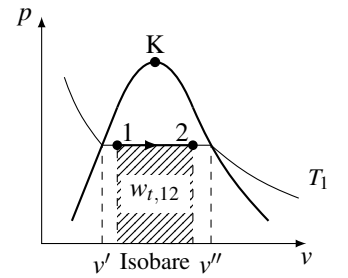
$$c_{vG} = \sum_{k=1}^K c_{vk} \xi_k, \quad c_{pG} = \sum_{k=1}^K c_{pk} \xi_k$$

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

## 14 Nassdampf



H<sub>2</sub>O



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

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

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

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

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

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

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

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

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

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

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

$$F = K + 2 - P$$

$$T' = T''$$

$$p' = p''$$

$$g' = g''$$

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

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

$$dg' = dg''$$

## 15 Realer Stoff im Nassdampfgebiet

Isobare Zustandsänderung

$$q_{12} = T(s_2 - s_1)$$

$$= T(s'' - s')(x_2 - x_1)$$

$$w_{V,12} = - \int_1^2 p dv$$

$$= -p(v_2 - v_1) = -p(v'' - v')(x_2 - x_1)$$

Isochore Zustandsänderung

$$q_{12} = u_2 - u_1 = u'_2 + x_2(u''_2 - u'_2) - u'_1 - x_1(u''_1 - u'_1)$$

Adiabate Zustandsänderung

$$w_{V,12} = u_2 - u_1 = u'_2 + x_2(u''_2 - u'_2) - u'_1 - x_1(u''_1 - u'_1)$$

Entropieänderung während des Mischvorgangs

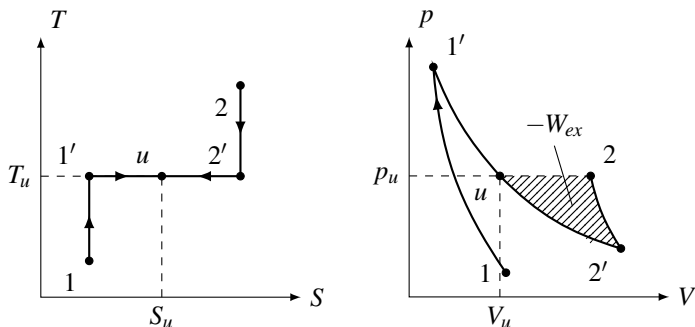
$$S_2 - S_1 = R_m \left( n \ln n - \sum_i n_i \ln n_i \right)$$

## 16 Maximale Arbeit und Exergie

Maximal nutzbare Arbeit  $\rightarrow$  isentrop, reibungsfrei

$1 \rightarrow 1'$ : isentrop auf  $T_u$

$1' \rightarrow u$ : isotherm auf  $u$



$$-W_{ex} = dh - T ds$$

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

Die Exergie der Enthalpie (offenes, 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

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

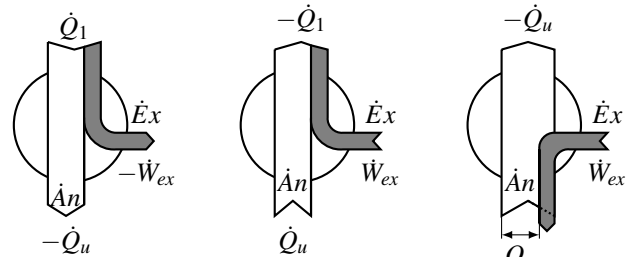
$$-W_{ex} = m \left[ c_p(T_1 - T_u) - T_u c_p \ln \left( \frac{T_1}{T_u} \right) \right] \leftarrow \text{isobar}$$

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)

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

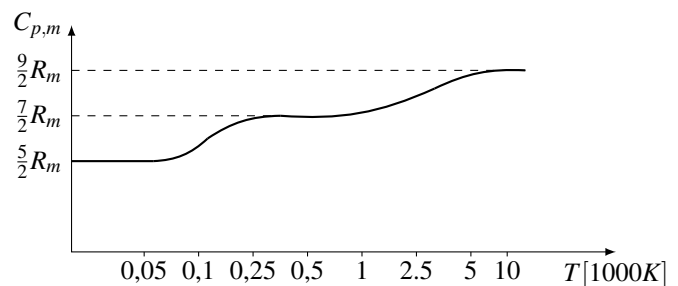


WärmeKraftprozess

Wärmepumpenprozess

Kälteprozess

## 17 Wärmekapazität



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

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

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

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

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

$$R = c_p - c_v$$

$$R = \frac{R_m}{M}$$

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

$$C_{m,v} = \frac{f}{2} R_m = \frac{f_{trans} + f_{rot} + f_{vib}}{2} R_m$$

$$C_{m,p} = \frac{f+2}{2} R$$

$$\kappa = \frac{f+2}{f}$$

$$f_{trans} = 3 \quad (\text{für die 3 Translatorischen Freiheitsgrade})$$

$$f_{rot} \in \{0, 2, 3\} \quad \{\text{Einatomig, Linear, Verzweigt}\}$$

$$f_{vib} = 2 \cdot l, \quad l = 1 \quad \text{Normalschwingungen der Atomkerne (Kann für komplexere Moleküle auch } > 1 \text{ sein.)}$$

## 18 Technische Anwendung

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

Thermischer Wirkungsgrad  $\eta_{th} = \frac{-w}{q_{zu}} = \frac{\text{Nutzen}}{\text{Aufwand}} = 1 - \frac{|q_{ab}|}{q_{zu}}$

Isentroper Verdichterwirkungsgrad  $\eta_{sv} = \frac{w_{t,12,rev}}{w_{t,12}} = \frac{h_{2,rev} - h_1}{h_2 - h_1} = \frac{T_{2,rev} - T_1}{T_2 - T_1}$   
ideales Gas

Isentroper Turbinenwirkungsgrad  $\eta_{sT} = \frac{w_{t,12}}{W_{t,12,rev}} = \frac{h_1 - h_2}{h_1 - h_{2,rev}} = \frac{T_1 - T_2}{T_1 - T_{2,rev}}$

Dampfkraftprozess Wirkungsgrad  $\eta_{th} = 1 - \frac{|q_{61}|}{q_{23} + q_{34} + q_{45}} = 1 - \frac{h_6 - h_1}{h_5 - h_2}$

Leistungszahl Kältemaschine  $\varepsilon_{K(A)} = \frac{q_{zu}}{w} = \frac{\dot{Q}_0}{\dot{W}}$

Leistungszahl Kaltdampfprozess  $\varepsilon_K = \frac{q_0}{|q| - q_0} = \frac{q_o}{w_t} = \frac{h_1 - h_6}{h_2 - h_1}$

Linkslaufender Carnotprozess  $\varepsilon_{carnot} = \frac{T_k}{T_H - T_K}$

Leistungszahl Wärmepumpe  $\varepsilon_{WP} = \frac{q}{|q| - q_0} = \frac{|q|}{w_t} = \frac{q_{ab}}{w} = \frac{h_2 - h_5}{h_2 - h_1} = 1 + \varepsilon_{K(A)}$

Kälteleistung Wärmepumpe  $\dot{Q}_0 = \dot{m}(h_2 - h_5)$

Leistungszahl Kaltluftprozess  $\varepsilon_K = \frac{1}{\left( \frac{p}{p_0} \right)^{\frac{\kappa-1}{\kappa}} - 1}$

Kälteleistung Kaltluftprozess  $\dot{Q}_0 = \dot{m}(h_1 - h_6)$

Arbeit der Enthalpie  $W_t = Q = mdh = mcpdT$

Verdichtungsverhältnis  $\varepsilon = v_1/v_2$

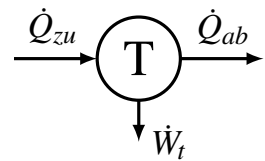
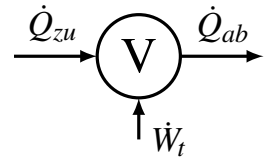
Drucksteigerungsverhältniss  $\psi = p_3/p_2$

Einspritzverhältnis  $\varphi = v_4/v_3$

Temperaturverhältnis  $\tau = T_3/T_1$

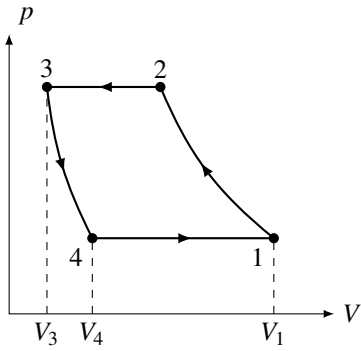
Verdrichtungsdruckverhältnis  $\pi = p_2/p_1$

für Joule-Prozess  $\pi_{opt} = \tau^{\frac{\kappa}{2(\kappa-1)}}$





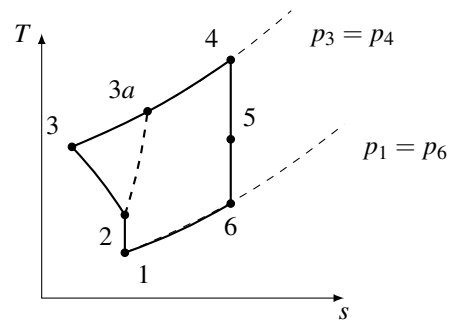
## 19 Kolbenverdichter



$$\mu = \frac{V_1 - V_4}{V_1 - V_3}, \quad \varepsilon_S = \frac{V_3}{V_1 - V_3}, \quad \mu = 1 - \varepsilon_S \left[ \left( \frac{p_2}{p_1} \right)^{\frac{1}{n}} - 1 \right]$$

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

## 20 Strahltriebwerk



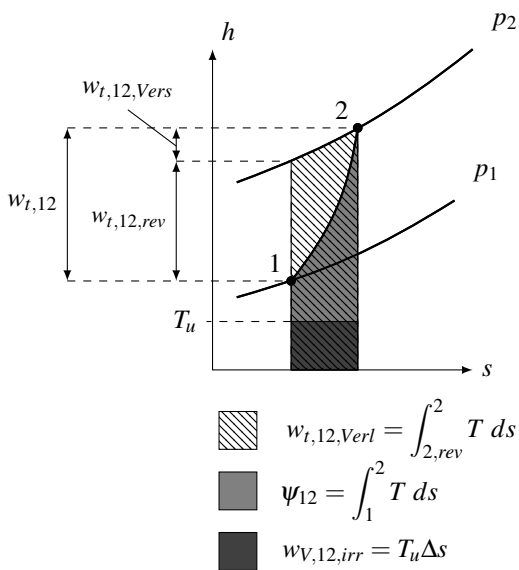
Anströmgeschwindigkeit:

$$\frac{1}{2} c_1^2 = c_p (T_2 - T_1)$$

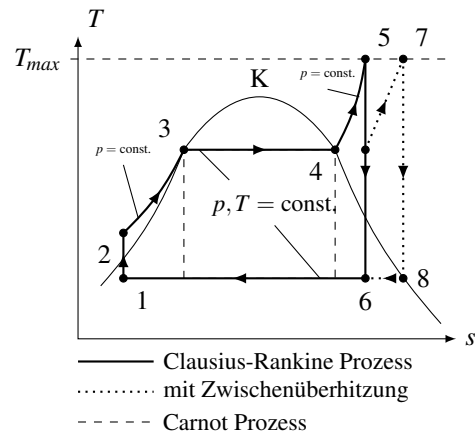
$$w_{2-3} = -w_{4-5} = c_p (T_3 - T_2)$$

$$\Delta E_{kin} = dH$$

## 21 Turboverdichter



## 22 Clausius-Rankine-Prozess

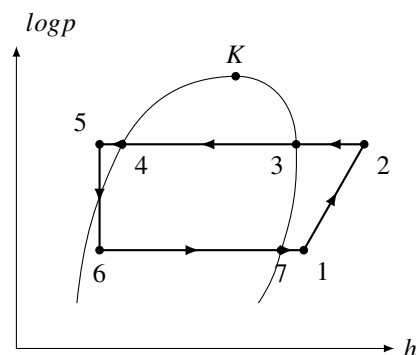
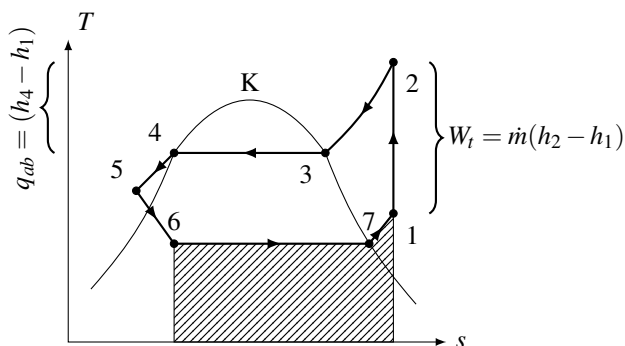


$$\eta_{th} = 1 - \frac{|q_{61}|}{q_{23} + q_{34} + q_{45}} = 1 - \frac{h_6 - h_1}{h_5 - h_2}$$

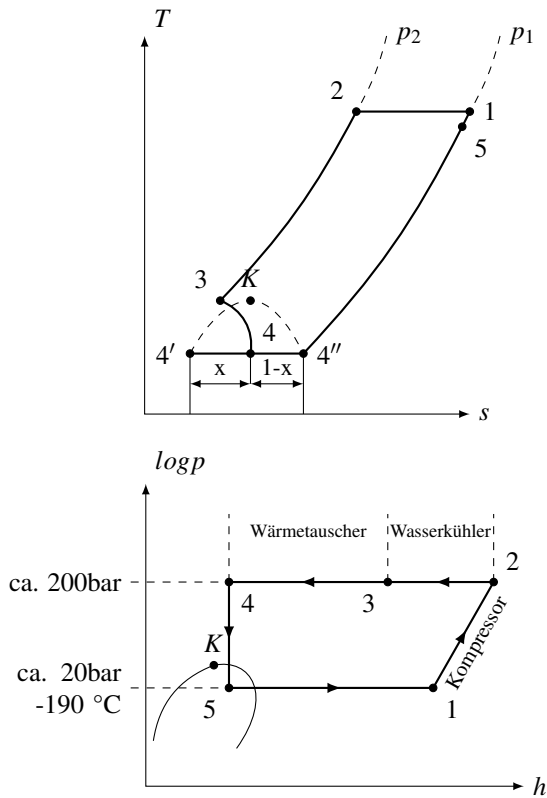
$$\eta_{th,Z} = 1 - \frac{|q_{81}|}{q_{23} + q_{34} + q_{45} + q_{67}}$$

$$\eta_{th,Z} = 1 - \frac{h_8 - h_1}{h_5 - h_2 + h_7 - h_6}$$

## 23 Kaltdampfprozess



## 24 Luftverflüssigung nach Linde



$$h_2 = (q-x)h_{4'} + xh_5$$

$$(1-x) = \frac{h_5 - h_2}{h_5 - h_{4'}} \leq \frac{h_1 - h_2}{h_1 - h_{4'}} \left[ \frac{\text{kg Flüssigkeit}}{\text{kg Ansaugluft}} \right]$$

## 25 Feuchte Luft

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

$$x = x_{D(ampf)} + x_{W(asser)} + x_{E(is)}$$

$$\phi = \frac{p_D}{p_s}$$

$$x_D = \frac{m_D}{m_L} = \frac{R_L}{R_D} \frac{p_D}{p_L} = \frac{R_L}{R_D} \frac{p_D}{p - p_D} = 0.622 \frac{p_D}{p - p_D}$$

$$x_s = \frac{m_{D,max}}{m_L} = 0.622 \frac{p_s}{p - p_s} \rightarrow \text{für } \phi = 1$$

$$p_s = \frac{x_s \cdot p}{0.622 + x_s}$$

$$x_s(t_{min}) = \frac{M_{H_2O}}{M_L} \frac{p_s^{min}(t_{min})}{p_1 - p_s^{min}(t_{min})}$$

$$p = p_L + p_D$$

$$\rho = \frac{p}{R_{ges}T} = \frac{1+x}{R_L + xR_D} \frac{p}{T}$$

$$R_{ges} = \frac{R_L + xR_D}{1+x}$$

$$h = \underbrace{c_{pL} \cdot t}_{\text{Luft}} + \underbrace{x_D(c_{pD}t + r_D)}_{\text{Dampf}} + \underbrace{x_W c_W \cdot t}_{\text{Wasser}} + \underbrace{x_E(c_E t - r_E)}_{\text{Eis}}$$

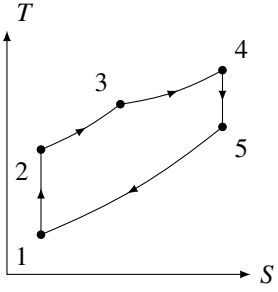
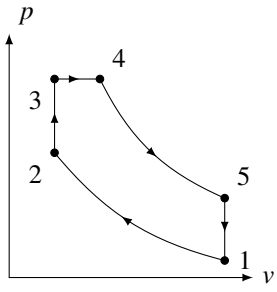
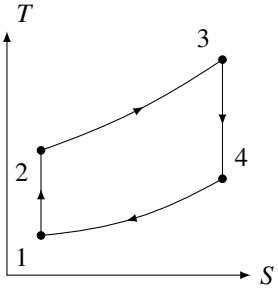
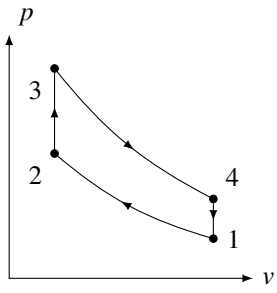
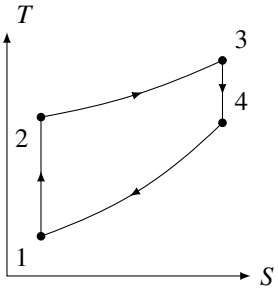
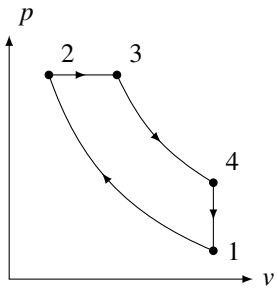
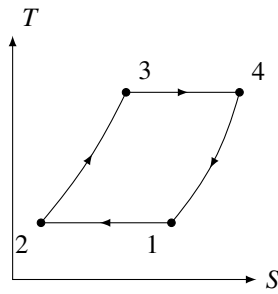
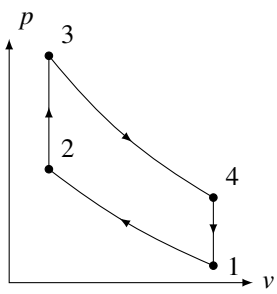
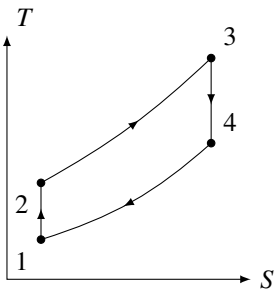
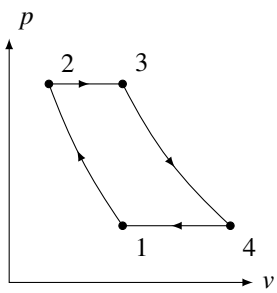
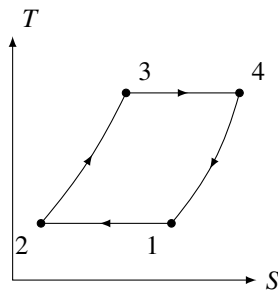
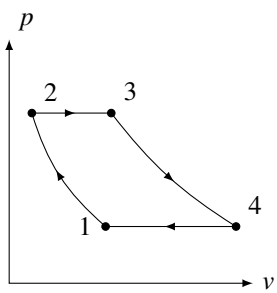
Schmelzentropie

$$s_E = \frac{r_E}{T}$$

Molare Verdampfungsenthalpie von Wasser (0 °C- 200 °C):

$$H_v = \left( 50,9 - 0,9298 \frac{T}{1000} - 65,19 \left( \frac{T}{1000} \right)^2 \right) \frac{\text{kJ}}{\text{mol}}$$

|                          |        |            |
|--------------------------|--------|------------|
| $M_L$                    | 28,96  | kg/ kmol   |
| $M_{H_2O}$               | 18,02  | kg/ kmol   |
| $R_L$                    | 0,287  | kJ/ (kg K) |
| $R_D$                    | 0,461  | kJ/ (kg K) |
| $c_{pL}$                 | 1,006  | kJ/ (kg K) |
| $c_{pD}$                 | 1,92   | kJ/ (kg K) |
| $c_W$                    | 4,182  | kJ/ (kg K) |
| $c_E$                    | 2,1    | kJ/ (kg K) |
| $r_D(0^\circ\text{C})$   | 2500   | kJ/ kg     |
| $r_D(20^\circ\text{C})$  | 2453,4 | kJ/ kg     |
| $r_D(100^\circ\text{C})$ | 2257   | kJ/ kg     |
| $r_E$                    | 334    | kJ/ kg     |
| $p_s(0^\circ\text{C})$   | 0,0061 | bar        |
| $p_s(10^\circ\text{C})$  | 0,0123 | bar        |
| $p_s(20^\circ\text{C})$  | 0,0234 | bar        |
| $p_s(100^\circ\text{C})$ | 1,0133 | bar        |

|   |   |  |   |
|---|---|--|---|
|    |    | <p> <math>1 \rightarrow 2</math>: isentrope Verdichtung<br/> <math>2 \rightarrow 3</math>: isochore Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isobare Wärmezufuhr<br/> <math>4 \rightarrow 5</math>: isentrope Entspannung<br/> <math>5 \rightarrow 1</math>: isochore Wärmeabfuhr         </p> | <p>Seiliger Prozess</p> $\eta_{th} = \frac{ q_{ab} }{q_{zu}} = 1 - \frac{u_5 - u_1}{u_3 - u_2 + h_4 - h_3}$ $\eta_{th} = 1 - \frac{\phi^\kappa \psi - 1}{\epsilon^{\kappa-1} [\psi - 1 + \kappa \psi (\phi - 1)]}$ $\epsilon = \frac{v_1}{v_2} \quad \psi = \frac{p_3}{p_2} \quad \phi = \frac{v_4}{v}$ |
|    |    | <p> <math>1 \rightarrow 2</math>: isentrope Verdichtung<br/> <math>2 \rightarrow 3</math>: isochore Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isentrope Entspannung<br/> <math>4 \rightarrow 1</math>: isochore Wärmeabfuhr         </p>  | <p>Otto Prozess</p> <p>Gleichraumverbrennung</p> $\eta_{th} = 1 - \frac{1}{\epsilon^{\kappa-1}}$ $\epsilon = \frac{v_1}{v_2} = \frac{v_4}{v_3}$   |
|   |   | <p> <math>1 \rightarrow 2</math>: isentrope Verdichtung<br/> <math>2 \rightarrow 3</math>: isobare Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isentrope Entspannung<br/> <math>4 \rightarrow 1</math>: isochore Wärmeabfuhr         </p>   | <p>Diesel Prozess</p> <p>Gleichdruckverbrennung</p> $\eta_{th} = 1 - \frac{\phi^\kappa - 1}{\epsilon^{\kappa-1} \kappa (\phi - 1)}$ $\epsilon = \frac{v_1}{v_2} \quad \phi = \frac{v_4}{v}$   |
|  |  | <p> <math>1 \rightarrow 2</math>: isotherme Verdichtung<br/> <math>2 \rightarrow 3</math>: isochore Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isotherme Entspannung<br/> <math>4 \rightarrow 1</math>: isobare Wärmeabfuhr         </p>   | <p>Stirling Prozess</p> $\eta_{th} = 1 - \frac{ q_{12} }{q_{34}} = 1 - \frac{T_1}{T_3}$ $\eta_{th} = \frac{RT_1 \ln\left(\frac{v_1}{v_2}\right)}{RT_3 \ln\left(\frac{v_4}{v_3}\right)}$   |
|  |  | <p> <math>1 \rightarrow 2</math>: isentrope Verdichtung<br/> <math>2 \rightarrow 3</math>: isobare Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isentrope Entspannung<br/> <math>4 \rightarrow 1</math>: isobare Wärmeabfuhr         </p>  | <p>Joule Prozess</p> $\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{p_1}{p_2}\right)^{\frac{\kappa-1}{\kappa}}$ $\eta_{th} = 1 - \left(\frac{1}{\pi}\right)^{\frac{\kappa-1}{\kappa}}$ $\pi = \frac{p_2}{p_1}$  |
|  |  | <p> <math>1 \rightarrow 2</math>: isotherme Verdichtung<br/> <math>2 \rightarrow 3</math>: isobare Wärmezufuhr<br/> <math>3 \rightarrow 4</math>: isotherme Entspannung<br/> <math>4 \rightarrow 1</math>: isobare Wärmeabfuhr         </p>  | <p>Ericsson Prozess</p> $\eta_{th} = 1 - \frac{ q_{12} }{q_{34}} = 1 - \frac{T_1}{T_3}$ $\eta_{th} = \frac{RT_1 \ln\left(\frac{p_1}{p_2}\right)}{RT_3 \ln\left(\frac{p_4}{p_3}\right)} = 1 - \frac{T_1}{T_3}$   |

# Ideales Gas

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

# Van-Der-Waals-Gas

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

## 26 Stoffwerte einiger Gase

| Bezeichnung      | Symbol      | Molmasse<br>[kg/kmol] | Gaskonstante<br>[J/(kg K)] | Dichte<br>[kg/m <sup>3</sup> ] | $c_p$<br>[J/(kg K)] | $c_v$<br>[J/(kg,K)] | $\kappa$ |
|------------------|-------------|-----------------------|----------------------------|--------------------------------|---------------------|---------------------|----------|
| Acetylen         | $C_2H_2$    | 26.038                | 319.3                      | 1.16                           | 1616                | 1278                | 1.26     |
| Ammoniak         | $NH_3$      | 17.031                | 488.2                      | 0.76                           | 2056                | 1526                | 1.35     |
| Argon            | $Ar$        | 39.948                | 208.1                      | 1.76                           | 519                 | 309                 | 1.68     |
| Äthan            | $C_2H_6$    | 30.070                | 276.5                      | 1.34                           | 1650                | 1355                | 1.22     |
| Butan            | $C_4H_{10}$ | 58.124                | 143.0                      | 2.67                           | 1599                | 1410                | 1.13     |
| Chlor            | $Cl_2$      | 56.108                | 117.3                      | 3.17                           | 473                 | 343                 | 1.38     |
| Chlorwasserstoff | $HCl$       | 70.906                | 228.0                      | 1.62                           | 795                 | 556                 | 1.43     |
| Helium           | $He$        | 4.003                 | 2077.0                     | 0.18                           | 5200                | 3124                | 1.66     |
| Kohlendioxid     | $CO_2$      | 44.010                | 188.9                      | 1.95                           | 816                 | 618                 | 1.32     |
| Kohlenmonoxid    | $CO$        | 28.010                | 296.8                      | 1.23                           | 1038                | 739                 | 1.40     |
| Luft             | –           | 28.964                | 287.1                      | 1.28                           | 1006                | 718                 | 1.40     |
| Methan           | $CH_4$      | 16.043                | 518.3                      | 0.71                           | 2165                | 1638                | 1.32     |
| Propan           | $C_3H_8$    | 44.097                | 188.5                      | 1.99                           | 1549                | 1331                | 1.16     |
| Sauerstoff       | $O_2$       | 31.999                | 259.8                      | 1.41                           | 909                 | 647                 | 1.40     |
| Stickstoff       | $N_2$       | 28.013                | 296.8                      | 1.23                           | 1038                | 739                 | 1.40     |
| Wasserstoff      | $H_2$       | 2.016                 | 4124.2                     | 0.09                           | 14050               | 9926                | 1.42     |
| Xenon            | $Xe$        | 131.300               | 63.3                       | 5.82                           | 159                 | 93                  | 1.71     |
| Ideales Gas      |             |                       | 8.3143[J/mol K]            |                                |                     |                     |          |

## 27 Stoffdaten einiger Stoffe

| Name         | chemische<br>Formel | Molmasse<br>[kg/kmol] | Normal-<br>Siedepunkt [°C] | kritische<br>Temperatur [°C] | kritischer<br>Druck [MPa] |
|--------------|---------------------|-----------------------|----------------------------|------------------------------|---------------------------|
| Wasserstoff  | $H_2$               | 2.02                  | -252.9                     | -240.0                       | 1.32                      |
| Helium       | $He$                | 4.00                  | -268.9                     | -268.0                       | 0.23                      |
| Ammoniak     | $NH_3$              | 17.03                 | -33.3                      | 132.3                        | 11.33                     |
| Wasser       | $H_2O$              | 18.02                 | 100.0                      | 373.9                        | 22.06                     |
| Luft         | 78%                 |                       |                            |                              |                           |
|              | $N_2$ 21%           | 28.96                 | -194.2                     | -140.4                       | 3.84                      |
|              | $O_2$ .1%Ar.+       |                       |                            |                              |                           |
| Kohlendioxid | $CO_2$              | 44.01                 | -78.4                      | 31.0                         | 7.38                      |
| Methan       | $CH_4$              | 16.04                 | -161.5                     | -82.6                        | 4.60                      |
| Äthan        | $C_2H_6$            | 30.07                 | -88.6                      | 32.2                         | 4.87                      |
| Propan       | $C_3H_8$            | 44.10                 | -42.1                      | 96.7                         | 4.25                      |
| R134a        | $CH_2FCF_3$         | 102.03                | -26.1                      | 101.1                        | 4.06                      |

## 28 Zahlenwerte feuchte Luft

| Bezeichnung                                | Formelzeichen     | Zahlenwert | Dimension  |
|--|-------------------|------------|------------|
| Molmasse der Luft                          | ML                | 28,96      | kg/ kmol   |
| Molmasse des Wassers                       | MH <sub>2</sub> O | 18,02      | kg/ kmol   |
| spezifische Gaskonstante der Luft          | RL                | 0,287      | kJ/ (kg K) |
| spezifische Gaskonstante des Dampfes       | RD                | 0,461      | kJ/ (kg K) |
| spezifische Wärmekapazität der Luft        | cpL               | 1,006      | kJ/ (kg K) |
| spezifische Wärmekapazität des Dampfes     | cpD               | 1,92       | kJ/ (kg K) |
| spezifische Wärmekapazität des Wassers     | cW                | 4,182      | kJ/ (kg K) |
| spezifische Wärmekapazität des Eises       | cE                | 2,1        | kJ/ (kg K) |
| Verdampfungsenthalpie des Wassers bei 0 °C | rD                | 2500       | kJ/ kg     |
| Schmelzenthalpie des Eises bei 0 °C        | rE                | 334        | kJ/ kg     |

## 29 Obskure Zusammenhänge

Aus Anhang B

$$dV = \left( \frac{\partial V}{\partial T} \right)_p dT + \left( \frac{\partial V}{\partial p} \right)_{T,n} dp + \sum_{k=1}^K \left( \frac{\partial V}{\partial n_k} \right)_{T,p} dn_k \quad (1)$$

$$dS = \left( \frac{nC_{p,m}}{T} \right) dT - \left( \frac{\partial V}{\partial T} \right)_{p,n} dp + \sum_{k=1}^K \left( \frac{\partial \mu_k}{\partial T} \right)_{p,n} dn_k \quad (2)$$

$$dU = \left[ nC_{p,m} - p \left( \frac{\partial V}{\partial T} \right)_{p,n} \right] dT - \left[ p \left( \frac{\partial V}{\partial p} \right)_{T,n} + T \left( \frac{\partial V}{\partial T} \right)_{p,n} \right] dp + \sum_{k=1}^K \left[ \mu_k - T \left( \frac{\partial \mu_k}{\partial T} \right)_{p,n} - p \left( \frac{\partial V}{\partial n_k} \right)_{T,p,n} \right] dn_k \quad (3)$$

$$dH = nC_{p,m}dT + \left[ VT \left( \frac{\partial V}{\partial T} \right)_{p,n} \right] + \sum_{k=1}^K \left[ \mu_k - T \left( \frac{\partial \mu_k}{\partial T} \right)_{p,n} \right] dn_k \quad (4)$$

$$dF = - \left[ S + p \left( \frac{\partial V}{\partial T} \right)_{p,n} \right] dT - p \left( \frac{\partial V}{\partial p} \right)_{T,n} dp + \sum_{k=1}^K \left[ \mu_k - p \left( \frac{\partial V}{\partial n_k} \right)_{T,p} \right] dn_k \quad (5)$$

$$\left( \frac{\partial C_{p,m}}{\partial p} \right)_{T,\psi_j} = T \frac{\partial}{\partial p} \left[ \left( \frac{\partial S_m}{\partial T} \right)_{p,\psi_j} \right]_{T,\psi_j} = T \frac{\partial}{\partial T} \left[ \left( \frac{\partial S_m}{\partial p} \right)_{T,\psi_j} \right]_{p,\psi_j} = -T \frac{\partial}{\partial T} \left[ \left( \frac{\partial V_m}{\partial T} \right)_{p,\psi_j} \right]_{p,\psi_j} = -T \left( \frac{\partial^2 V_m}{\partial T^2} \right)_{p,\psi_j} \quad (6)$$

$$C_{p,m} = (C_{p,m})_{\text{ideales Gas}} - T \int_0^p \left( \frac{\partial^2 V_m}{\partial T^2} \right)_{p,\psi_j} d\tilde{p} \quad (7)$$

$$C_{v,m} = (C_{v,m})_{\text{ideales Gas}} - T \int_0^{V_m} \left( \frac{\partial^2 p}{\partial T^2} \right)_{p,\psi_j} d\tilde{V} \quad (8)$$

$$(9)$$

## 30 Dinge, die man eigentlich wissen sollte

|                                 |                                   |   |   |  |
|---------------------------------|-----------------------------------|---|---|--|
| $10^1 = 1$                      |                                   |   |   |  |
| $10^1 = 10$                     | $10^{-1} = 0.1$                   | $1J = 1Ws = 1Nm = \frac{kg \cdot m^2}{s^2}$ | $E_{Feder} = \frac{1}{2}kx^2$                                   |  |
| $10^2 = 100$                    | $10^{-2} = 0.01$                  | $N = \frac{kgm}{s^2}$                       | $E_{pot} = mgz$   |  |
| $10^3 = 1000$                   | $10^{-4} = 0.001$                 | $E_{kin} = \frac{1}{2}mc^2$                 | $E_{Kondensator} = \frac{1}{2}C \left( \frac{Q_e}{C} \right)^2$ |  |
| $10^4 = 10\,000$                | $10^{-4} = 0.000\,1$              | $E_{rot} = \frac{1}{2}I\omega^2$            | $E_{Spule} = \frac{1}{2}LI^2$                                   |  |
| $10^5 = 100\,000$               | $10^{-5} = 0.000\,01$             |   | $E_{Elektrisch} = UA$   |  |
| $10^6 = 1000\,000$              | $10^{-6} = 0.000\,001$            |   |   |  |
| $10^7 = 10\,000\,000$           | $10^{-7} = 0.000\,000\,1$         |   |   |  |
| $10^8 = 100\,000\,000$          | $10^{-8} = 0.000\,000\,01$        |   |   |  |
| $10^9 = 1000\,000\,000$         | $10^{-9} = 0.000\,000\,001$       |   |   |  |
| $10^{10} = 10\,000\,000\,000$   | $10^{-10} = 0.000\,000\,000\,1$   |   |   |  |
| $10^{11} = 100\,000\,000\,000$  | $10^{-11} = 0.000\,000\,000\,01$  |   |   |  |
| $10^{12} = 1000\,000\,000\,000$ | $10^{-12} = 0.000\,000\,000\,001$ |   |   |  |

$$n = \frac{m}{M} = \text{Teichenanzahl} = \frac{\text{Masse}}{\text{Mol}}$$

|             |   |        |           |           |        |
|-------------|---|--------|-----------|-----------|--------|
|             |   | $m^3$  | $dm^3$    | $cm^3$    | $mm^3$ |
|             | Umfang  | $m^3$  | 1         | $10^3$    | $10^9$ |
|             | Fläche  | $dm^3$ | $10^{-3}$ | 1         | $10^3$ |
| Kreis:      | $u = 2r\pi$   | $cm^3$ | $10^{-6}$ | $10^{-3}$ | 1      |
| Kreissektor | $u = 2r + b$  | $mm^3$ | $10^{-9}$ | $10^{-6}$ | $10^3$ |
|             | $A = \frac{r^2\pi\alpha}{2\pi} = \frac{b \cdot r}{2}$ |        |           |           |        |

## 31 Eindimensionale Strömungsvorgänge

$$\begin{aligned}\chi &= \frac{1}{p} = -\frac{1}{V} \left( \frac{\partial V}{\partial p} \right)_T \\ c_S^2 &= \left( \frac{\partial p}{\partial \rho} \right)_S \\ c_S^2 &= \left( \frac{R}{c_v} + 1 \right) \left( v^2 \frac{RT}{(v-b)^2} \right) - \frac{2a}{v} \leftarrow VdW \\ c_S^2 &= \kappa RT \leftarrow ideal \\ Ma &= \frac{c}{c_S} \\ \frac{T_0}{T} &= 1 + \frac{\kappa-1}{2} \frac{c^2}{\kappa RT} = 1 + \frac{\kappa-1}{2} Ma^2 \\ \frac{p_0}{p} &= \left( \frac{T_0}{T} \right)^{\frac{\kappa}{\kappa-1}} = \left( 1 + \frac{\kappa-1}{2} Ma^2 \right)^{\frac{\kappa}{\kappa-1}} \\ \frac{\rho_0}{\rho} &= \left( \frac{T_0}{T} \right)^{\frac{\kappa-1}{\kappa}} = \left( 1 + \frac{\kappa-1}{2} Ma^2 \right)^{\frac{\kappa-1}{\kappa}} \\ \left( \frac{A}{A^*} \right)^2 &= \frac{1}{Ma^2} \left[ \frac{2}{\kappa+1} \left( 1 + \frac{\kappa-1}{2} Ma^2 \right) \right]^{\frac{\kappa+1}{\kappa-1}}\end{aligned}$$

$$h_2 - h_1 = \frac{1}{2}(p_2 - p_1) \left( \frac{1}{\rho_1} + \frac{1}{\rho_2} \right) = (p_2 - p_1) \frac{1}{2}(v_1 + v_2)$$

Stoßbeziehungen für ein ideales Gas

$$\begin{aligned}\frac{p_2}{p_1} &= \frac{2\kappa Ma^2 - (\kappa-1)}{\kappa+1} \\ \frac{\rho_2}{\rho_1} &= \frac{(\kappa+1)Ma^2}{2 + (\kappa-1)Ma^2} \\ \frac{T_2}{T_1} &= \frac{[2\kappa Ma^2 - (\kappa-1)][2 + (\kappa-1)Ma^2]}{(\kappa+1)^2} Ma^2 \\ Ma_2^2 &= \frac{(\kappa-1)(Ma_1^2 - 1) + (\kappa+1)}{2\kappa(Ma_1^2 - 1) + (\kappa+1)}\end{aligned}$$

Entropie über den senkrechten Verdichtungsstoß

$$\begin{aligned}s_2 - s_1 &= c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right) \\ &= c_p \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{p_2}{p_1} \right)\end{aligned}$$

## 32 Chemische Reaktionen

$$\begin{aligned}\frac{dn_1}{v_1} &= \frac{dn_2}{v_2} = \dots = d\lambda = .const \\ \sum_{k=1}^K \mu_k dn_k &= \sum_{k=1}^K \mu_k (v_k d\lambda) = \sum_{k=1}^K \mu_k v_k = 0 \\ \mu_i &= \left( \frac{\partial U}{\partial n_i} \right)_{S,V} = \left( \frac{\partial H}{\partial n_i} \right)_{S,p} = \left( \frac{\partial F}{\partial n_i} \right)_{T,V} = \left( \frac{\partial G}{\partial n_i} \right)_{T,p}\end{aligned}$$

$$\mu(p, T) = \mu(p^+, T) + R_m T \ln \left( \frac{p}{p^+} \right)$$

Massenwirkungsgesetz

$$\begin{aligned}\prod_{k=1}^K \psi_k^{v_k} &= \exp - \frac{1}{R_m T} \sum_{k=1}^K v_k \mu_{0k}(p, T) \\ &= \exp - \frac{1}{R_m T} \sum_{k=1}^K v_k G_{m,k}(p, T)\end{aligned}$$

Gleichgewichtskonstante

$$K(p, T) = \prod_{k=1}^K \psi_k^{v_k}$$

$$\begin{aligned}K(p_2, T) &= K(p_1, T) \left( \frac{p_1}{p_2} \right)^{\sum v_k} \\ \ln \left( \frac{K(p, T_2)}{K(p, T_1)} \right) &= \frac{\Delta H_R}{R_m} \left( \frac{1}{T_1} - \frac{1}{T_2} \right) = \frac{\Delta H_R}{R_m} \frac{T_2 - T_1}{T_1 T_2} \\ \Delta H_R &= \sum_{k=1}^K v_k H_{m,k}\end{aligned}$$