

Thermodynamik Formelsammlung

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January 24, 2020

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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

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

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

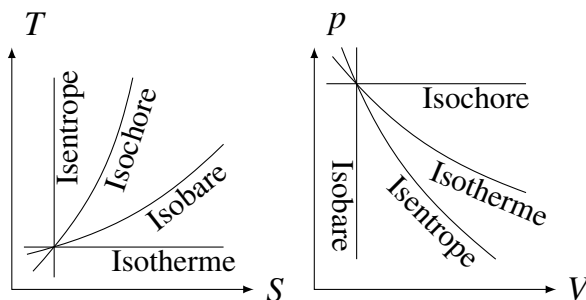
Hauptsätze

- 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

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

4 Iso



5 Gibbs

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

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

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

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

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

$$pV = mRT$$

$$pv = RT$$

$$pV = nR_m T$$

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

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

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

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

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

$$R = c_p - c_v$$

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

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

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

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

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

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

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

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

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

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

10 Van-der-Waals

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

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

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

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

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

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

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

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

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

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

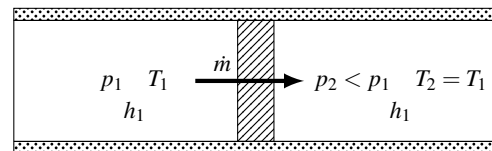
$$u - u_0 = \left(\frac{a}{v_0} - \frac{a}{v} \right) + c_v(T - T_0) \quad \leftarrow \text{für } c_v = \text{const.}$$

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

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

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

11 Adiabate Drosselung



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

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

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

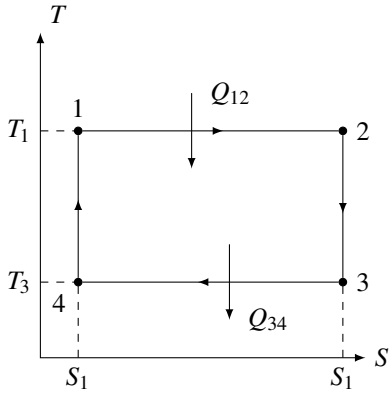
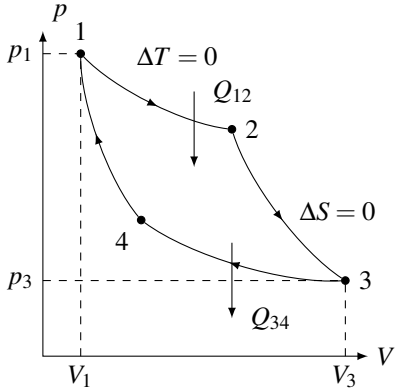
$$s_2 - s_1 = R \ln \left(\frac{v_2}{v_1} \right) = R \ln \left(\frac{p_1}{p_2} \right)$$

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

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

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

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

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

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

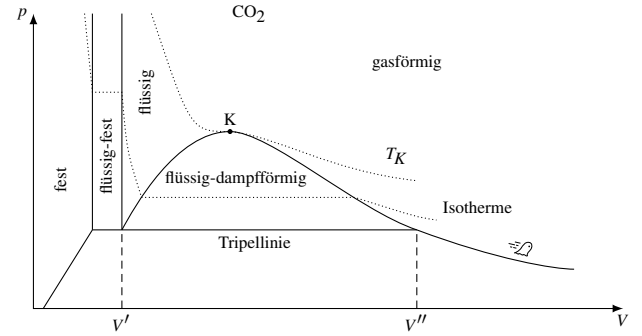
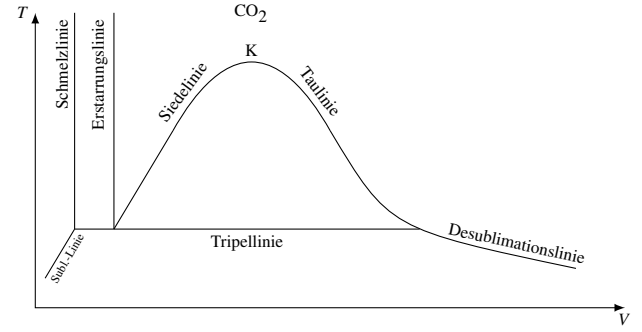
$$U_G = \sum_{k=1}^K U_k = \sum_{k=1}^K m_k u_k = \sum_{k=1}^K c_{vk} m_k T \leftarrow c_v = \text{const}$$

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

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

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

14 Nassdampf



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

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

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

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

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

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

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

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

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

$$T' = T''$$

$$p' = p''$$

$$g' = g''$$

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

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

$$dg' = dg''$$

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

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

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

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

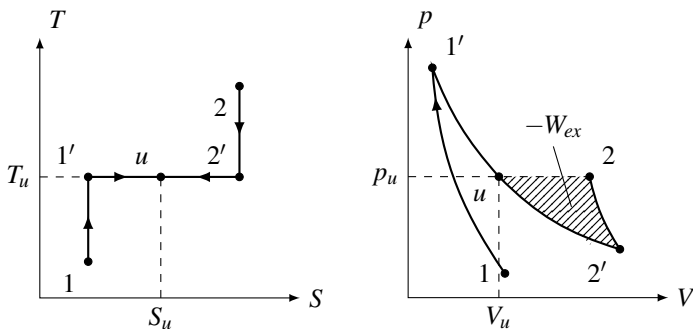
$$S_2 - S_1 = R_m \left(n \ln n - \sum_i n_i \ln n_i \right)$$

16 Maximale Arbeit und Exergie

Maximale 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 (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

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

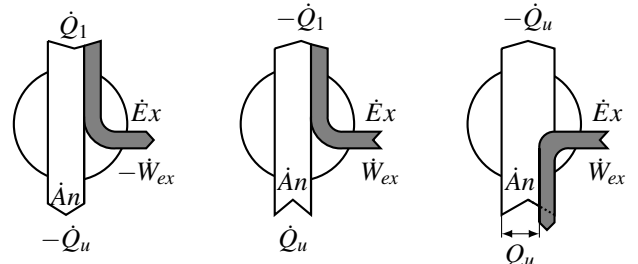
$$-W_{ex} = m \left[c_p (T_1 - T_u) - T_u c_p \ln \left(\frac{T_1}{T_u} \right) \right] \leftarrow \text{isobar}$$

Dampf/Luftdruckkammer

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

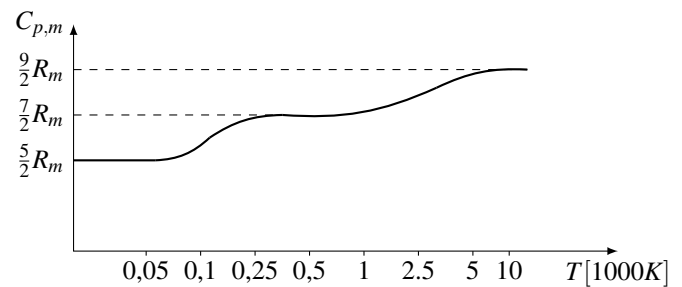
Die Exergie der Wärme (geschlossenes, stationäres System)

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



Wärmekraftprozess Wärmepumpenprozess Kälteprozess

17 Wärmekapazität



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

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

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

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

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

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

$$R = c_p - c_v$$

$$R_m = 8,3143 \left[\frac{\text{kJ}}{\text{kmol K}} \right]$$

$$C_{v,m} = \underbrace{3 + \frac{R_m}{2}}_{\text{Translatorisch}} + \underbrace{\frac{n_{\text{rot}} R_m}{2}}_{\text{Rotatorisch}} + \underbrace{R_m (3n_{\text{Atome}} - 3 - n_{\text{rot}})}_{\text{Vibratorisch}}$$

$$+ \underbrace{C_{v,m, \text{Elektronenanregung}}}_{\text{Relevant ab: } T \approx 10^4 \text{ K}}$$

18 Technische Anwendung

adiabat ($c_p = \text{const.}$)	$W_{t,12} = mc_p(T_2 - T_1) = \frac{\kappa}{\kappa - 1}(p_2V_2 - p_1V_1)$	$Q_{12} = 0$
reversibel adiabat $\kappa = \text{const.}$	$W_{t,12} = \frac{\kappa}{\kappa - 1}(p_1V_1) \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right]$	$Q_{12} = 0$
irreversibel adiabat als Polytrope $n > \kappa; n, \kappa = \text{const.}$	$W_{t,12} = \frac{\kappa}{\kappa - 1}(p_1V_1) \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$	$Q_{12} = 0$
reversibel polytrop $n, \kappa = \text{const.}$	$W_{t,12} = \frac{n}{n-1}(p_2V_2 - p_1V_1)$ $= \frac{n}{n-1}mR(T_2 - T_1)$ $= \frac{n}{n-1}(p_1V_1) \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$	$Q_{12} = mc_n(T_2 - T_1)$ $= \frac{n - \kappa}{(n-1)(\kappa-1)}(p_1V_1) \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$ $c_n = \frac{n - \kappa}{n-1}c_v$
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 $\eta_{sV} = \frac{w_{t,12,rev}}{w_{t,12}} = \frac{h_{2,rev} - h_1}{h_2 - h_1} = \frac{T_{2,rev} - T_1}{T_2 - T_1}$
idealer Fall

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

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

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

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

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

Verdichtungsverhältnis $\epsilon = \frac{v_1}{v_2}$

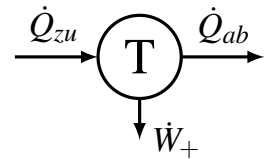
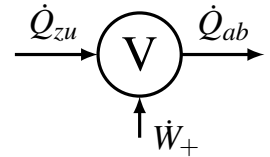
Drucksteigerungsverhältnis $\psi = \frac{p_3}{p_2}$

Einspritzverhältnis $\phi = \frac{v_4}{v_3}$

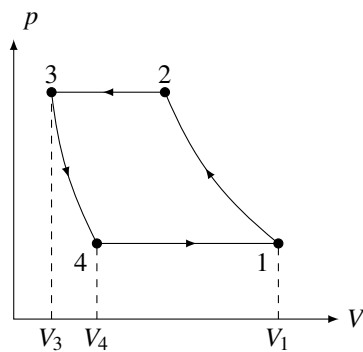
Temperaturverhältnis $\tau = \frac{T_3}{T_1}$

Verdrichtungsdruckverhältnis $\pi = \frac{p_2}{p_1}$

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



Kolbenverdichter



V_1 = Maximales Zylindervolumen

V_2 = Volumen nach Verdichtung

V_3 =

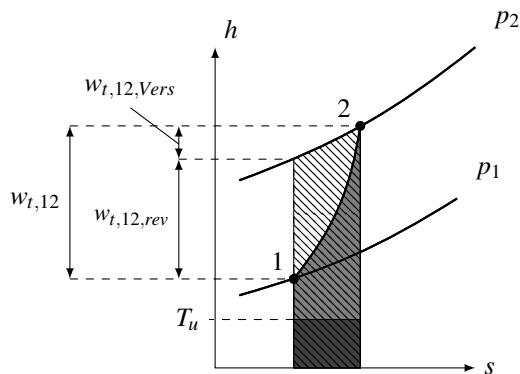
V_4 = Schädlicher Raum

$$\mu = \frac{V_1 - V_4}{V_1 - V_3}, \quad \epsilon_s = \frac{V_3}{V_1 - V_3}$$

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

$$\begin{aligned} W_{t,12} &= \int_1^2 p dV \\ &= \underbrace{p_2 V_2}_{\text{Ausschiebearbeit}} - \underbrace{p_1 V_1}_{\text{Einschiebearbeit}} - \int_1^2 p dV \\ &= \frac{n}{n-1} p_1 (V_1 - V_4) \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right] \end{aligned}$$

Turboverdichter



$$\text{hatched area} \quad w_{t,12,Verl} = \int_{2,rev}^2 T ds$$

$$\text{dark grey area} \quad \psi_{12} = \int_1^2 T ds$$

$$\text{black area} \quad w_{V,12,irr} = T_u \Delta s$$

Verdichter Wirkungsgrad

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

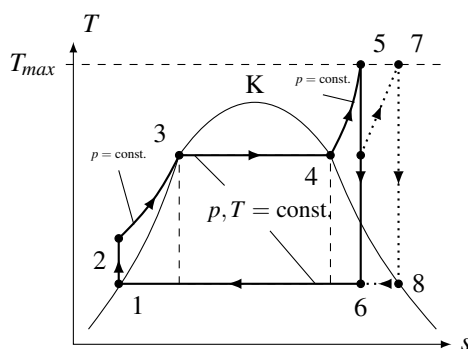
Verdichter wirkungsgrad (Ideales Gas, $c_p = \text{const.}$)

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

Technische Verlustarbeit

$$\begin{aligned} w_{t,Verl,12} &= w_{t,12} - w_{t,12,rev} = h_2 - h_{2,rev} \\ &= \int_{2,rev}^2 T|_{p_2=\text{const.}} ds \end{aligned}$$

19 Clausius-Rankine-Prozess



— Clausius-Rankine Prozess

..... mit Zwischenüberhitzung

----- Carnot Prozess

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

$$\eta_{th,Z} = 1 - \frac{|q_{81}|}{q_{23} + q_{34} + q_{45} + q_{67}} = 1 - \frac{h_8 - h_1}{h_5 - h_2 + h_7 - h_6}$$

20 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

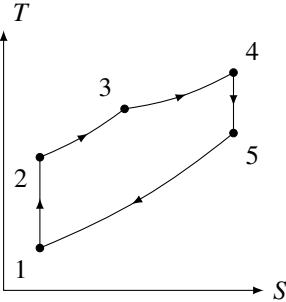
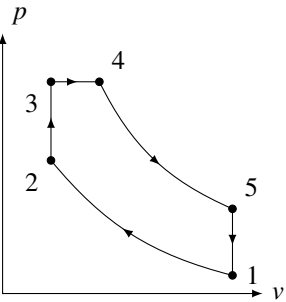
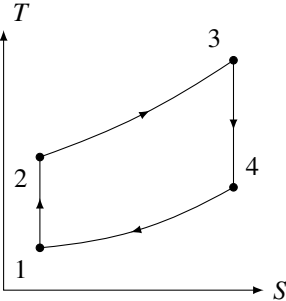
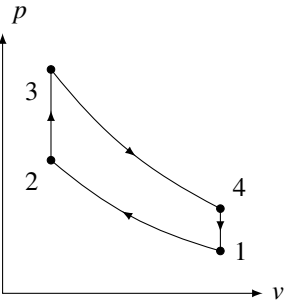
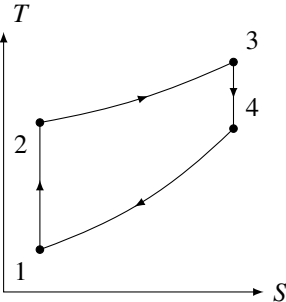
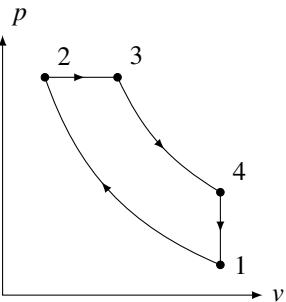
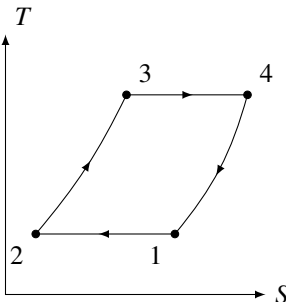
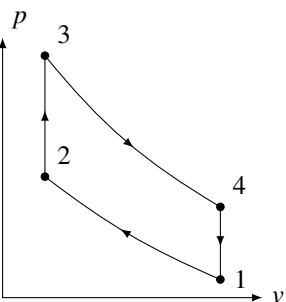
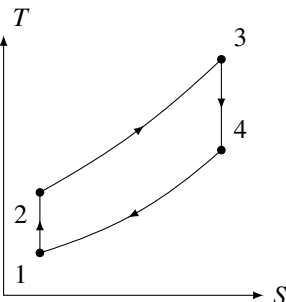
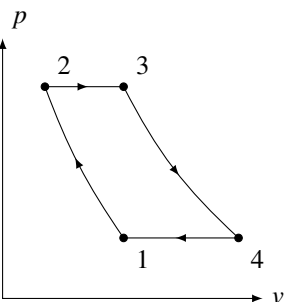
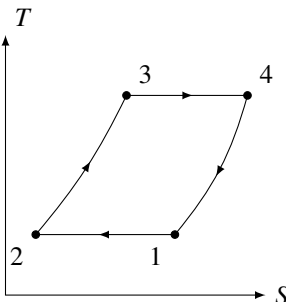
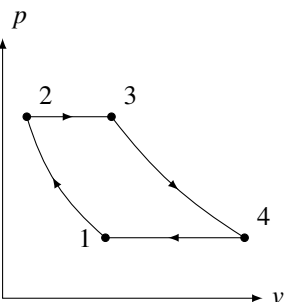
$$\begin{aligned}s_2 - s_1 &= c_v \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{v_2}{v_1} \right) \\ &= c_p \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{p_2}{p_1} \right)\end{aligned}$$

21 Feuchte Luft

$$\begin{aligned}x &= \frac{m_{H_2O}}{m_L} \\ x &= x_{D(ampf)} + x_{W(asser)} + x_{E(is)} \\ \phi &= \frac{p_D}{p_s} \\ x_D &= \frac{m_d}{m_L} = \frac{R_L}{R_D} \frac{p_D}{p_L} = \frac{R_L}{R_D} \frac{p_D}{p - p_D} = 0.622 \frac{p_D}{p - p_D} \\ x_s &= \frac{m_{D,max}}{m_L} = 0.622 \frac{p_s}{p - p_s} \rightarrow \text{für } \phi = 1 \\ \rho &= \frac{p}{R_{gesT}} = \frac{1+x}{R_L + xR_D} \frac{p}{T} \\ R_{ges} &= \frac{R_L + xR_D}{1+x} \\ h &= c_{pL}t + x_D(c_{pD}t + r_D) + x_W c_{Wt} + x_E(c_{Et} - r_E)\end{aligned}$$

22 Chemische Reaktionen

$$\begin{aligned}\frac{dn_1}{v_1} &= \frac{dn_2}{v_2} = \dots = d\lambda = .const \\ \sum_{k=1}^K \mu_k dn_k &= \sum_{k=1}^K \mu_k (v_k d\lambda) = \sum_{k=1}^K \mu_k v_k = 0 \\ \mu_i &= \left(\frac{\partial U}{\partial n_i} \right)_{S,V} = \left(\frac{\partial H}{\partial n_i} \right)_{S,p} = \left(\frac{\partial F}{\partial n_i} \right)_{T,V} = \left(\frac{\partial G}{\partial n_i} \right)_{T,p} \\ \mu(p, T) &= \mu(p^+, T) + R_m T \ln \left(\frac{p}{p^+} \right) \\ \text{Massenwirkungsgesetz} \\ \prod_{k=1}^K \psi_k^{v_k} &= \exp - \frac{1}{R_m T} \sum_{k=1}^K v_k \mu_{0k}(p, T) \\ &= \exp - \frac{1}{R_m T} \sum_{k=1}^K v_k G_{m,k}(p, T) \\ \text{Gleichgewichtskonstante} \\ K(p, T) &= \prod_{k=1}^K \psi_k^{v_k} \\ K(p_2, T) &= K(p_1, T) \left(\frac{p_1}{p_2} \right)^{\sum v_k} \\ \ln \left(\frac{K(p, T_2)}{K(p, T_1)} \right) &= \frac{\Delta H_R}{R_m} \left(\frac{1}{T_1} - \frac{1}{T_2} \right) = \frac{\Delta H_R}{R_m} \frac{T_2 - T_1}{T_1 T_2} \\ \Delta H_R &= \sum_{k=1}^K v_k H_{m,k}\end{aligned}$$

		<p>Seiliger Prozess</p> $\eta_{th} = \frac{ q_{ab} }{q_{zu}} = 1 - \frac{u_5 - u_1}{u_3 - u_2 + h_4 - h_3}$ $\eta_{th} = 1 - \frac{\phi^\kappa \psi - 1}{\varepsilon^{\kappa-1} [\psi - 1 + \kappa \psi (\phi - 1)]}$ $\varepsilon = \frac{v_1}{v_2} \quad \psi = \frac{p_3}{p_2} \quad \phi = \frac{v_4}{v}$
		<p>Otto Prozess</p> <p>Gleichraumverbrennung</p> $\eta_{th} = 1 - \frac{1}{\varepsilon^{\kappa-1}}$ $\varepsilon = \frac{v_1}{v_2}$
		<p>Diesel Prozess</p> <p>Gleichdruckverbrennung</p> $\eta_{th} = 1 - \frac{\phi^\kappa - 1}{\varepsilon^{\kappa-1} \kappa (\phi - 1)}$ $\varepsilon = \frac{v_1}{v_2} \quad \phi = \frac{v_4}{v}$
		<p>Stirling Prozess</p> $\eta_{th} = 1 - \frac{ q_{12} }{q_{34}} = \frac{RT_1 \ln \left(\frac{v_1}{v_2} \right)}{RT_3 \ln \left(\frac{v_4}{v_3} \right)} = 1 - \frac{T_1}{T_3}$
		<p>Joule Prozess</p> $\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{p_1}{p_2} \right)^{\frac{\kappa-1}{\kappa}} = 1 - \left(\frac{1}{\pi} \right)^{\frac{\kappa-1}{\kappa}}$ $\pi = \frac{p_2}{p_1}$
		<p>Ericsson Prozess</p> $\eta_{th} = 1 - \frac{ q_{12} }{q_{34}} = \frac{RT_1 \ln \left(\frac{p_1}{p_2} \right)}{RT_3 \ln \left(\frac{p_4}{p_3} \right)} = 1 - \frac{T_1}{T_3}$

Ideales Gas

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

Van-De-Waals-Gas

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

23 Stoffwerte einiger Gase

Bezeichnung	Symbol	Molmasse [kg/kmol]	Gaskonstante [J/(kg K)]	Dichte [kg/m ³]	c_p [J/(kg K)]	c_v [J/(kg,K)]	κ
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

24 Stoffdaten einiger Stoffe

Name Name	chemische Formel	Molmasse [kg/kmol]	Normal- siedepunkt [°C]	kritische Temperatur [°C]	kritischer 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

25 Zahlenwerte feuchte Luft

Bezeichnung	Formelzeichen	Zahlenwert	Dimension
Molmasse der Luft	ML	28,96	kg/ kmol
Molmasse des Wassers	MH ₂ 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

26 Obskure Zusammenhänge

$$\begin{aligned}
 dV &= \left(\frac{\partial V}{\partial T} \right)_p dT + \left(\frac{\partial V}{\partial p} \right)_{T,n} dp + \sum_{k=1}^K \left(\frac{\partial V}{\partial n_k} \right)_{T,p} dn_k \\
 dS &= \left(\frac{nC_{p,m}}{T} \right) dT - \left(\frac{\partial V}{\partial T} \right)_{p,n} dp + \sum_{k=1}^K \left(\frac{\partial \mu_k}{\partial T} \right)_{p,n} dn_k \\
 dU &= \left[nC_{p,m} - p \left(\frac{\partial V}{\partial T} \right)_{p,n} \right] dT - \left[p \left(\frac{\partial V}{\partial p} \right)_{T,n} + T \left(\frac{\partial V}{\partial T} \right)_{p,n} \right] dp + \sum_{k=1}^K \left[\mu_k - T \left(\frac{\partial \mu_k}{\partial T} \right)_{p,n} - p \left(\frac{\partial V}{\partial n_k} \right)_{T,p,n} \right] dn_k \\
 dH &= nC_{p,m} dT + \left[VT \left(\frac{\partial V}{\partial T} \right)_{p,n} \right] + \sum_{k=1}^K \left[\mu_k - T \left(\frac{\partial \mu_k}{\partial T} \right)_{p,n} \right] dn_k \\
 dF &= - \left[S + p \left(\frac{\partial V}{\partial T} \right)_{p,n} \right] dT - p \left(\frac{\partial V}{\partial p} \right)_{T,n} dp + \sum_{k=1}^K \left[\mu_k - p \left(\frac{\partial V}{\partial n_k} \right)_{T,p} \right] dn_k \\
 \left(\frac{\partial C_{p,m}}{\partial p} \right)_{T,\psi_j} &= T \frac{\partial}{\partial p} \left[\left(\frac{\partial S_m}{\partial T} \right)_{p,\psi_j} \right]_{T,\psi_j} = T \frac{\partial}{\partial T} \left[\left(\frac{\partial S_m}{\partial p} \right)_{T,\psi_j} \right]_{p,\psi_j} = -T \frac{\partial}{\partial T} \left[\left(\frac{\partial V_m}{\partial T} \right)_{p,\psi_j} \right]_{p,\psi_j} = -T \left(\frac{\partial^2 V_m}{\partial T^2} \right)_{p,\psi_j} \\
 C_{p,m} &= (C_{p,m})_{\text{ideales Gas}} - T \int_0^p \left(\frac{\partial^2 V_m}{\partial T^2} \right)_{p,\psi_j} d\tilde{p} \\
 C_{v,m} &= (C_{v,m})_{\text{ideales Gas}} - T \int_0^{V_m} \left(\frac{\partial^2 p}{\partial T^2} \right)_{p,\psi_j} d\tilde{V}
 \end{aligned}$$

27 Dinge die man eigentlich wissen sollte

$$1J = 1W = 1Nm$$

$$E_{kin} = \frac{1}{2}mc^2$$

$$E_{rot} = \frac{1}{2}I\omega^2$$

$$E_{Feder} = \frac{1}{2}kx^2$$

$$E_{pot} = mgz$$

$$E_{Kondensator} = \frac{1}{2}C \left(\frac{Q_e}{C} \right)^2$$

$$E_{Spule} = \frac{1}{2}LI^2$$

$$E_{Elektrisch} = UA$$

$$10^1 = 1$$

$$10^1 = 10$$

$$10^2 = 100$$

$$10^3 = 1000$$

$$10^4 = 10\,000$$

$$10^5 = 100\,000$$

$$10^6 = 1\,000\,000$$

$$10^7 = 10\,000\,000$$

$$10^8 = 100\,000\,000$$

$$10^9 = 1\,000\,000\,000$$

$$10^{10} = 10\,000\,000\,000$$

$$10^{11} = 100\,000\,000\,000$$

$$10^{12} = 1\,000\,000\,000\,000$$

$$10^{-1} = 0.1$$

$$10^{-2} = 0.01$$

$$10^{-4} = 0.001$$

$$10^{-4} = 0.000\,1$$

$$10^{-5} = 0.000\,01$$

$$10^{-6} = 0.000\,001$$

$$10^{-7} = 0.000\,000\,1$$

$$10^{-8} = 0.000\,000\,01$$

$$10^{-9} = 0.000\,000\,001$$

$$10^{-10} = 0.000\,000\,000\,1$$

$$10^{-11} = 0.000\,000\,000\,01$$

$$10^{-12} = 0.000\,000\,000\,001$$

$$m^2 \quad dm^2 \quad cm^2 \quad mm^2$$

$$1 \quad 10^2 \quad 10^4 \quad 10^6$$

$$10^{-2} \quad 1 \quad 10^2 \quad 10^4$$

$$10^{-4} \quad 10^{-2} \quad 1 \quad 10^2$$

$$10^{-6} \quad 10^{-4} \quad 10^2 \quad 1$$

$$m^3 \quad dm^3 \quad cm^3 \quad mm^3$$

$$1 \quad 10^3 \quad 10^6 \quad 10^9$$

$$10^{-3} \quad 1 \quad 10^3 \quad 10^6$$

$$10^{-6} \quad 10^{-3} \quad 1 \quad 10^3$$

$$10^{-9} \quad 10^{-6} \quad 10^3 \quad 1$$