

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

## 1 Nomenklatur

**A<sub>n</sub>** = Anergie[J]  
**c<sub>s</sub>** = Schallgeschwindigkeit[m/s]  
**c<sub>p</sub>** = Spezifische Wärmekapazität dp = 0 [J/kg\*K]  
**c<sub>v</sub>** = Spezifische Wärmekapazität dv = 0 [J/kg\*K]  
**E** = Energie[J]  
**Ex** = -**W<sub>ex</sub>** = Exergie[J]  
**F** = Kraft[N]  
**F** = **U** - **TS** = Freie Energie[J]  
**f** = **u** - **Ts** = Spezifische freie Energie[J/kg]  
**f** = Fugazität[Pa]  
**G** = **H** - **TS** = Freie Enthalpie[J]  
**g** = **h** - **Ts** = Spezifische freie Enthalpie[J/kg]  
**g** = Erdbeschleunigung[m/s²]  
**H** = **U** + **pV** = Enthalpie[J]  
**h** = **u** + **pv** = Spezifische Enthalpie[J/kg]  
**■Hg** = Molare Reaktionsenthalpie  
**K** = Konstante des Massenwirkungsgesetzes[-]  
**M** = Molmasse[kg/mol]  
**ṁ** = Massestrom[kg/s]  
**m'** = Masse in der flüssigen Phase[kg]  
**m''** = Masse in der gasförmigen Phase[kg]  
**Ma** = **c**/**c<sub>s</sub>** = Machzahl[-]  
**n** = **m**/**M** = Molzahl[mol]  
**n** = Polytropenexponent[-]  
**P<sub>t</sub>** = technische Leistung[W]  
**Q** = Wärme[J]  
**Q̇** = Wärmestrom[W]  
**q** = Spezifische Wärme[J/kg]  
**r** = Spezifische Verdampfungsenthalpie[J/kg]  
**R** = Gaskonstante[J/(kg K)]  
**R<sub>m</sub>** = Universelle Gaskonstante[J/(mol K)]  
**S** = Entropie[J/K]  
**s** = Spezifische Entropie[J/(kg K)]  
**T** = Temperatur[K]  
**t** = Zeit[s]  
**t** = Temperatur[°C]  
**T** = Sättigungstemperatur[K]  
**U** = Innere Energie[J]  
**u** = Spezifische innere Energie [J/kg]

**V** = Volumen[m³]  
**v** = Spezifisches Volumen[m³/kg]  
**V<sub>m</sub>** = Molares Volumen[m³/mol]  
**W** = Arbeit[J]  
**w** = Spezifische Arbeit[J/kg]  
**W<sub>v</sub>** = Volumenänderungsarbeit[J]  
**W<sub>el</sub>** = Elektrische Arbeit[J]  
**W<sub>w</sub>** = Wellenarbeit[J]  
**W<sub>diss</sub>** = Dissipationsarbeit[J]  
**W<sub>t</sub>** = Technische Arbeit[J]  
**W<sub>virrev</sub>** = Arbeitsverlust durch Irreversibilität[J]  
**x** =  $\frac{m''}{m' + m''}$  = Dampfanteil[-]  
**x** =  $\frac{m_{H_2O}}{m_L}$  = Wassergehalt  
**Z** = Allgemeine extensive Zustandsgrößen[Z]  
**z** = Allgemeine  
**β** = Isobarer Ausdehnungskoeffizient[1/K]  
**γ** = Isochorer Spannungskoeffizient[1/K]  
**δ<sub>T</sub>** = Isothermer Drosselkoeffizient[m³/kg]  
**δ<sub>h</sub>** = Isenthalper Drosselkoeffizient[Ks²m/kg]  
**ε** = Leistungsziffer[-]  
**ε** = Verdichtungsverhältnis[-]  
**η<sub>th</sub>** = Thermischer Wirkungsgrad[-]  
**η<sub>mech</sub>** = Mechanischer Wirkungsgrad[-]  
**κ** = Adiabaten- oder Isentropenexponent[-]  
**λ** = Reaktionslaufzahl[-]  
**μ<sub>i</sub>** = Chemisches Potential[J/mol]  
**v<sub>i</sub>** = Stöchiometrische Koeffizienten[-]  
**ξ<sub>i</sub>** = Masseanteil[-]  
**π** = Druckverhältnis[-]  
**ρ** = Dichte[kg/m³]  
**τ** = Temperaturverhältnis[-]  
**φ** = Relative Feuchte[-]  
**φ** = Einspritzverhältnis[-]  
**ξ** = Isothermer Kompressibilitätskoeffizient[m²/N]  
**■** = Dissipationsenergie[J]  
**ψ** = Spezifische Dissipationsenergie[J]  
**ψ** = Drucksteigerungsverhältnis[-]  
**ψ<sub>i</sub>** = Molanteil[-]

## 2 Grundbegriffe

### Systeme

- Abgeschlossenes System - kein Stoff oder Energietransport
- Geschlossenes System - kein Stofftransport
- Adiabates System - kein Wärmetransport, aber asse 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)
- Intensive Zustandsgrößen sind unabhängig von der Masse des Systems (eg. Druck, Temperatur)
- Extensive Zustandsgrößen sind abhängig von der Masse des Systems (eg. Volumen, Masse)

### Zustandsgleichungen

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

## 3 Basisformeln

$$H = U + pV, \quad dS = \frac{\delta Q_{rev}}{T}$$

$$F = U - TS, \quad G = H - ST$$

$$W_{V,12} = - \int_1^2 p dV, \quad dS = \frac{Q_{rev}}{T} + S_{prod}$$

$$\Psi_{12} = \int_1^2 T dS_{prod}$$

## 4 Gibbs-Duhem

$$dU = Tds - pdV + \sum_{k=1}^K \mu_k dn_k$$

$$dG = -SdT + Vdp + \sum_{k=1}^K \mu_k dn_k$$

$$dH = TdS + Vdp + \sum_{k=1}^K \mu_k dn_k$$

$$dF = -SdT - pdV + \sum_{k=1}^K \mu_k dn_k$$

$$dU = \left( \frac{\partial U}{\partial S} \right)_V dS + \left( \frac{\partial U}{\partial V} \right)_S dV + \sum_{k=1}^K \left( \frac{\partial U}{\partial n_k} \right)_S dn_k$$

$$p_1 = p_a + \frac{\varphi_1 - \varphi_a}{\varphi_b - \varphi_a} (p_b - p_a)$$

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

## 5 Maxwell

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

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

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

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

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

## 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)

## 7 Thermodynamische Beziehungen

$$T = \left( \frac{\partial U}{\partial S} \right)_V \quad -S = \left( \frac{\partial F}{\partial T} \right)_V$$

$$T = \left( \frac{\partial H}{\partial S} \right)_p \quad -S = \left( \frac{\partial G}{\partial T} \right)_p$$

$$p = - \left( \frac{\partial U}{\partial V} \right)_S \quad -p = \left( \frac{\partial F}{\partial V} \right)_T$$

$$\mu = \left( \frac{\partial U}{\partial n} \right)_{S, V} \quad V = \left( \frac{\partial G}{\partial p} \right)_T$$

## 8 Ideales Gas

$$pV = mRT, \quad pv = RT, \quad pV = nR_m T$$

$$\beta = \frac{1}{T}, \quad \gamma = \frac{1}{T}, \quad \chi = \frac{1}{p}, \quad \beta = p\gamma\chi$$

$$R_m = 8,3143 \left[ \frac{kJ}{kmolK} \right], \quad R = c_p - c_v$$

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

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

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

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

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

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

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

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

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

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

## 9 Van-der-Waals

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

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

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

$$p_K = \frac{a}{27b^2}, \quad T_K = \frac{8}{27} \frac{a}{bR}, \quad \bar{v} = 3$$

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

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

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

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

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

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

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

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

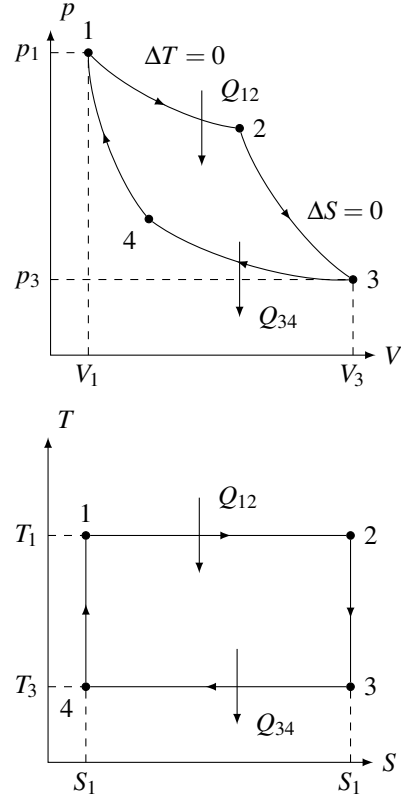
$$s - s_0 = c_v \ln \left( \frac{T}{T_0} \right) + R \ln \left( \frac{v - b}{v_0 - b} \right)$$

## 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

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

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

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

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

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

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

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

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

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

## 13 Realer Stoff im Nassdampfgebiet

Adiabate Drosselung (ideal):

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

$$dh = 0$$

Adiabate Drosselung (real):

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

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

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

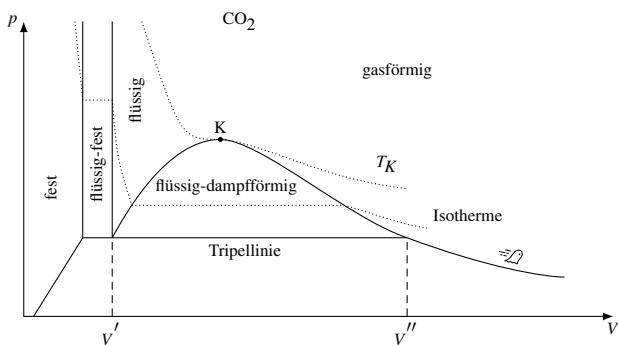
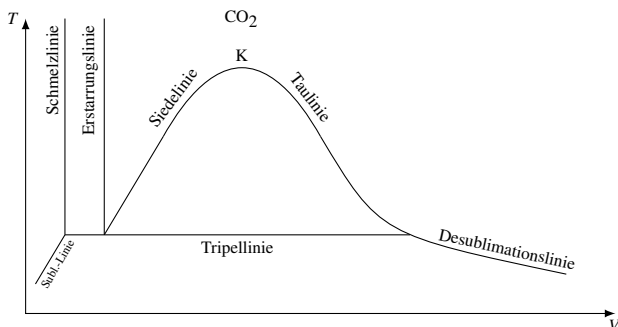
Adiabate Zustandsänderung

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

Entropieänderung während des Mischvorgangs

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

## 12 Nassdampf

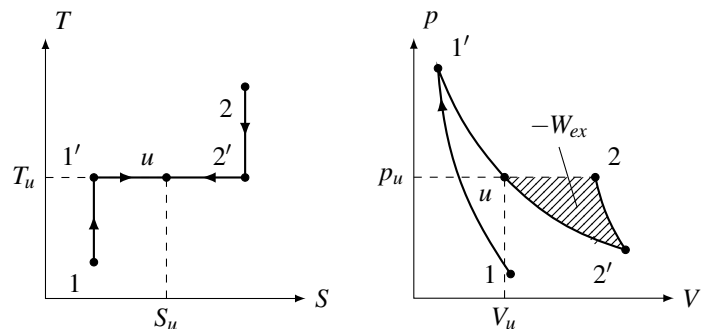


## 14 Maximale Arbeit und Exergie

Maximale nutzbare Arbeit → isentrop, reibungsfrei

1 → 1': isentrop auf  $T_u$

1' → u: isotherm auf  $u$



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

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

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

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

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

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

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

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

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

$$T' = T''$$

$$p' = p''$$

$$g' = g''$$

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

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

$$dg' = dg''$$

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

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

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

$$-W_{ex} = -(\dot{W}_t)_{rev} = -\frac{d}{dt} \left( U + m \left( \frac{c^2}{2} + gz \right) + p_u V - T_u S \right)$$

$$+ \sum_{j=1}^K \left( \dot{m}_j \left( h + \frac{c^2}{2} + gz - T_s \right) \right) + \sum_{l=1}^K \left( 1 - \frac{T_u}{T} \right) \dot{Q}_l$$

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)

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

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

Für Ideales Gas

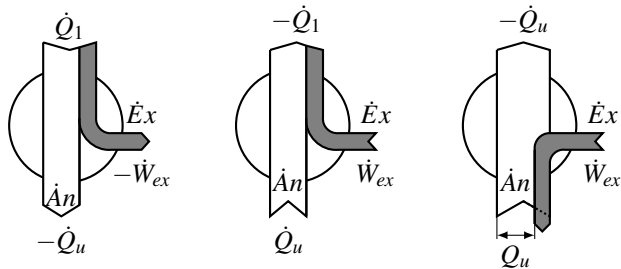
$$-W_{ex} = mc_v(T_1 - T_u) + p_u(V_1 - V_u) - T_u m \left( c_p \ln \left( \frac{T_1}{T_u} \right) - R_i \ln \left( \frac{p_1}{p_u} \right) \right)$$

## Dampf/Luftdruckkammer

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

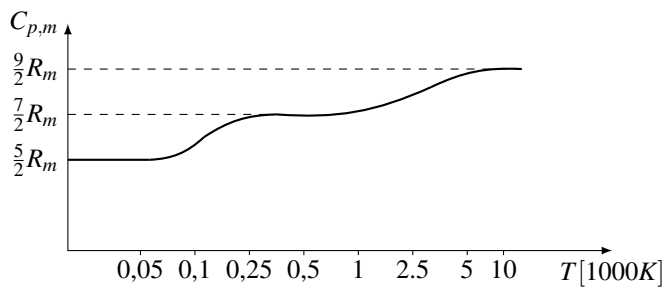
Die Exergie der Wärme (geschlossenes, stationäres System)

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



Wärmekraftprozess    Wärmepumpenprozess    Kälteprozess

## 15 Wärmekapazität



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

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

# Ideales Gas

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

# Van-Der-Waals-Gas

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