

Formelsammlung
Technische Verbrennung I

Kapitel 2 Thermodynamik von Verbrennungsprozessen

Molenbruch: $n_s = \sum_{i=1}^n n_i$

$$X_i = \frac{n_i}{n_s}$$

Massenbruch: $m_i = M_i n_i$

$$m = \sum_{i=1}^n m_i$$

$$Y_i = \frac{m_i}{m}$$

$$m = M n_s$$

$$M = \sum_{i=1}^n M_i X_i = \left[\sum_{i=1}^n \frac{Y_i}{M_i} \right]^{-1}$$

$$Y_i = \frac{M_i}{M} X_i$$

Massenbruch
der Elemente: $Z_j = \sum_{i=1}^n \frac{a_{ij} M_j}{M_i} Y_i$

$$Z_j = \frac{M_j}{M} \sum_{i=1}^n a_{ij} X_i$$

Konzentration: $C_i = \frac{n_i}{V}$

Volumenanteil: $v_i = \frac{V_i}{V} = X_i$

Gasgesetz: $p = \frac{\rho \mathcal{R} T}{M} = C_s \mathcal{R} T, \quad \mathcal{R} = 8.31451 \frac{\text{kJ}}{\text{kmol} \cdot \text{K}}$

stöchiometrischer
Koeffizient:

$$\nu_i = \nu_i'' - \nu_i'$$

$$0 = \sum_{i=1}^n \nu_{ik} [X_i]$$

Umsatzgleichung:

$$\frac{dn_i}{\nu_i} = \frac{dn_1}{\nu_1}, \quad \frac{dm_i}{\nu_i M_i} = \frac{dm_1}{\nu_1 M_1}, \quad \frac{dY_i}{\nu_i M_i} = \frac{dY_1}{\nu_1 M_1}$$

$$\frac{Y_{O_2} - Y_{O_2,u}}{\nu'_{O_2} M_{O_2}} = \frac{Y_B - Y_{B,u}}{\nu'_B M_B}$$

Mindestluftbedarf:

$$l_{min} = \frac{O_{min}}{Y_{O_2, Luft}}, \quad l_{min,m} = \frac{O_{min,m}}{X_{O_2, Luft}}$$

Luftzahl:

$$\lambda = \frac{l}{l_{min}} = \frac{l_m}{l_{min,m}}, \quad \phi = \frac{1}{\lambda}$$

Restsauerstoff:

$$n_{O_2, Rest} = (\lambda - 1) \frac{\nu'_{O_2}}{\nu'_B} n_{B,u}, \quad m_{O_2, Rest} = (\lambda - 1) \frac{\nu'_{O_2} M_{O_2}}{\nu'_B M_B} m_{B,u}$$

1. Hauptsatz der
Thermodynamik:

$$E = U + E_{kin} + E_{pot}$$

Innere Energie
und Enthalpie:

$$H = U + pV$$

$$U = \sum_{i=1}^n m_i u_i, \quad U = \sum_{i=1}^n n_i u_{i,m}$$

$$H = \sum_{i=1}^n m_i h_i, \quad H = \sum_{i=1}^n n_i h_{i,m}$$

$$c_v = \sum_{i=1}^n Y_i c_{vi}, \quad c_{v,m} = \sum_{i=1}^n X_i c_{vi,m}$$

$$c_p = \sum_{i=1}^n Y_i c_{pi}, \quad c_{p,m} = \sum_{i=1}^n X_i c_{pi,m}$$

Reaktionsenthalpie
und Heizwert:

$$h_u = \frac{(-\Delta h_m)}{\nu'_B M_B}$$

$$h_d = \Delta h_m = \sum_{i=1}^n \nu_i h_{i,m}$$

NASA-Polynome:

$$\frac{c_{p,m}}{\mathcal{R}} = a_1 + a_2 T/K + a_3 (T/K)^2 + a_4 (T/K)^3 + a_5 (T/K)^4$$

$$\frac{h_m}{\mathcal{R}T} = a_1 + a_2 \frac{T/K}{2} + a_3 \frac{(T/K)^2}{3} + a_4 \frac{(T/K)^3}{4} + a_5 \frac{(T/K)^4}{5} + \frac{a_6}{T/K}$$

$$\frac{s_m}{\mathcal{R}} = a_1 \ln(T/K) + a_2 T/K + a_3 \frac{(T/K)^2}{2} + a_4 \frac{(T/K)^3}{3} + a_5 \frac{(T/K)^4}{4} + a_7 + \ln \frac{p}{p_0}$$

adiabate

Flammentemperatur:
$$T_b = T_u + \frac{(-\Delta h_m)_{ref} Y_{B,u}}{c_p \nu'_B M_B}$$

chemisches

Gleichgewicht:
$$0 = \sum_{i=1}^n \nu_i \mu_i$$

Massenwirkungsgesetz:
$$K_{pk} = \prod_{i=1}^n \left(\frac{p_i}{p_0} \right)^{\nu_{ik}}$$

$$\pi_i(T) = \pi_{i,A} + \pi_{i,B} \ln T$$

$$K_p(T) = \exp \left(\frac{-\sum_{i=1}^n \nu_i \mu_i^0}{\mathcal{R}T} \right) = \exp \left(\frac{-\sum_{i=1}^n \nu_i h_{i,m,ref}}{\mathcal{R}T} \right) \exp \left(\sum_{i=1}^n \nu_i \pi_i \right)$$

$$K_{pk} = B_{pk} T^{n_{pk}} \exp \left(\frac{-\Delta h_{k,m,ref}}{\mathcal{R}T} \right) \quad (\text{Arrhenius-Ansatz})$$

$$B_{pk} = \exp \left(\sum_{i=1}^n \nu_{ik} \pi_{iA} \right)$$

$$n_{pk} = \sum_{i=1}^n \nu_{ik} \pi_{iB}$$

Kapitel 3 Reaktionskinetik homogener Gasreaktionen

chem. Reaktionsgeschw.:
$$\frac{dC_A}{dt} = -\nu'_A k_f C_A^{\nu'_A} C_B^{\nu'_B} + \nu'_A k_b C_C^{\nu'_C} C_D^{\nu'_D} = \nu_A w_f - \nu_A w_b = \nu_A w$$

$$k_i = B_i T^{n_i} \exp\left(-\frac{E_i}{RT}\right)$$

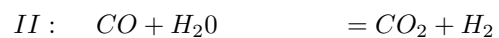
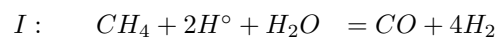
Konzentration inerter

Stoßpartner:
$$C_{M'} = \sum_{i=1}^n z_i C_i$$

Gleichgewichtskonstante:
$$K_C = \frac{k_f(T)}{k_b(T)}$$

chem. Produktionsdichte:
$$\dot{m}_i = M_i \sum_{k=1}^r \nu_{ik} w_k$$

reduzierter Methan-Mechanismus



Kapitel 4 Verbrennung in homogenen Systemen

Verbrennung bei
konst. Volumen:

$$\frac{du}{dt} = 0$$

Temperaturgleichung:
$$\rho c_v \frac{dT}{dt} = - \sum_{i=1}^n u_i M_i \sum_{k=1}^r \nu_{ik} w_k = - \sum_{i=1}^n u_i \dot{m}_i = - \sum_{k=1}^r \left(\sum_{i=1}^n M_i u_i \nu_{ik} \right) w_k$$

$$= \sum_{k=1}^r (-\Delta u_{k,m}) w_k$$

adiabate therm.
Explosion:

$$w = B \left(\frac{\rho Y_B}{M_B} \right) \left(\frac{\rho Y_{O_2}}{M_{O_2}} \right) \exp \left(-\frac{E}{\mathcal{R}T} \right)$$

Zündverzugszeit:

$$t_i = \frac{\mathcal{R}T_0^2}{E} \frac{c_v}{(-\Delta u_m) B \rho} \left(\frac{M_B}{Y_{B,0}} \right) \left(\frac{M_{O_2}}{Y_{O_2,0}} \right) \exp \left(\frac{E}{\mathcal{R}T_0} \right)$$

$$\frac{t_{i,q}}{t_i} = \int_0^\infty \frac{dz}{\exp(z) - \alpha z}, \quad \alpha = \frac{t_i}{t_q}$$

Reaktorgleichungen:

$$\frac{dY}{dt} = 1 - Y - Da Y \exp \left(-\frac{E}{T} \right)$$

$$\frac{dT}{dt} = 1 - T + Q Da Y \exp \left(-\frac{E}{T} \right)$$

$$Y^* = \frac{Y}{Y_u}, \quad Da = \frac{t_v}{t_r}, \quad E^* = \frac{E}{\mathcal{R}T_u}, \quad T^* = \frac{T}{T_u}, \quad t^* = \frac{t}{t_v},$$

$$Q^* = \frac{(-\Delta h_m) Y_u}{c_p M T_u}$$

Kapitel 6 Laminare Vormischflammen

Brennstoff-Luft-Verhältnis:
$$\phi = \frac{Z}{1-Z} \frac{1-Z_{st}}{Z_{st}}$$

$$T_b = aT_u + b + c\phi + d\phi^2 + e\phi^3$$

Approximationsformel:
$$s_L = Y_{B,u}^m A(T_0) \frac{T_u}{T_0} \left(\frac{T_b - T_0}{T_b - T_u} \right)^n, \quad \phi \leq 1$$

$$A(T_0) = F \exp(-G/T_0)$$

$$T_0 = -\frac{\tilde{E}}{\ln(p/B)}$$

Zeldovich-Zahl:
$$Ze = n \left(\frac{T_b - T_u}{T_b - T_0} - 1 \right) = \frac{E}{\mathcal{R}} \frac{T_b - T_u}{T_b^2}$$

Flammendicke:
$$l_F = \frac{D}{s_L} = \frac{\lambda_b}{c_p \rho_u s_L}$$

Flammenzeit:
$$t_F = \frac{l_F}{s_L}$$

chem. Flammenzeit:
$$t_c = \frac{\rho_u E^2 (T_b - T_u)^2}{2B \rho_b^2 (\mathcal{R} T_b^2)^2 S} \exp\left(\frac{E}{\mathcal{R} T_b}\right)$$

$$s_L = \sqrt{\frac{D}{t_c}}$$

Brennstoff	B [bar]	\tilde{E} [K]	F [cm/s]	G [K]	m	n
CH ₄	$3,1557 \times 10^8$	23873,0	$2,21760 \times 10^1$	-6444,27	0,565175	2,5158
C ₂ H ₂	$5,6834 \times 10^4$	11344,4	$3,77466 \times 10^4$	1032,36	0,907619	2,5874
C ₂ H ₄	$3,7036 \times 10^5$	14368,7	$9,97890 \times 10^3$	263,23	0,771333	2,3998
C ₂ H ₆	$4,3203 \times 10^6$	18859,0	$1,90041 \times 10^3$	-506,97	0,431345	2,1804
C ₃ H ₈	$2,2501 \times 10^6$	17223,5	$1,27489 \times 10^3$	-1324,78	0,582214	2,3970
CH ₃ OH	$2,1100 \times 10^6$	17657,5	$9,99557 \times 10^3$	1088,85	0,91	2,263
<i>n</i> -C ₇ H ₁₆	$1,7000 \times 10^6$	17508,0	$7,95600 \times 10^3$	912,00	0,52	2,30
<i>i</i> -C ₈ H ₁₈	$3,8000 \times 10^7$	20906,0	$2,92600 \times 10^3$	-25,60	0,5578	2,5214

Table 1: Koeffizienten zur Berechnung der laminaren Brenngeschwindigkeit für magere bis stöchiometrische Gemische

Brennstoff	a	b [K]	c [K]	d [K]	e [K]	Le
CH ₄	0,627	1270,15	-2449,0	6776	-3556	0,91
C ₂ H ₂	0,52	1646,0	-2965,0	8187	-4160	1,68
C ₂ H ₄	0,44	602,0	880,0	2686	-1891	1,21
C ₂ H ₆	0,526	1437,0	-2967,0	7538	-3873	1,32
C ₃ H ₈	0,53	1434,0	-2952,0	7518	-3856	1,63
CH ₃ OH	0,77	1260,0	-2449,0	6797	-3594	1,68
<i>n</i> -C ₇ H ₁₆	0,49	758,7	-277,8	4269	-2642	2,056
<i>i</i> -C ₈ H ₁₈	0,61	936,0	-1127,0	5326	-3044	2,55

Table 2: Koeffizienten zur Berechnung der adiabaten Flammentemperatur sowie Zahlenwerte für die Lewis-Zahl

Kapitel 7 Laminare Diffusionsflammen

Mischungsbruch:

$$Z = \frac{\dot{m}_1}{\dot{m}_1 + \dot{m}_2}$$

\dot{m}_1 Brenngasstrom

\dot{m}_2 Oxidatorstrom

$$Y_{B,u} = Y_{B,1}Z$$

$$Y_{O_2,u} = Y_{O_2,2}(1 - Z)$$

$$Z_{st} = \left[1 + \nu \frac{Y_{B,1}}{Y_{O_2,2}} \right]^{-1} = \left[1 + \frac{\nu'_{O_2} M_{O_2} Y_{B,1}}{\nu'_B M_B Y_{O_2,2}} \right]^{-1}$$

$$\lambda = \frac{Z_{st} (1 - Z)}{Z (1 - Z_{st})}$$

adiabate Flammentemperatur: $T_b(Z) = T_u(Z) + \frac{(-\Delta h_m)_{ref} Y_{B,1}}{c_p \nu'_B M_B} Z, \quad 0 \leq Z \leq Z_{st}$

$$T_u(Z) = T_2 + Z(T_1 - T_2)$$

Burke-Schumann-Lösung: $T(Z) = T_u(Z) + \frac{Z}{Z_{st}} [T_{st} - T_u(Z_{st})], \quad 0 \leq Z \leq Z_{st}$

$$T(Z) = T_u(Z) + \frac{1 - Z}{1 - Z_{st}} [T_{st} - T_u(Z_{st})], \quad Z_{st} \leq Z \leq 1$$