Toegepaste energieleer

Formulebladen

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Energievormen

materiegebonden energievormen

kinetische energie	$E_\mathrm{k} = \frac{1}{2} m v^2$ [J]	[2.1]
potentiële energie	$E_\mathrm{p} = m g z$ [J]	[2.3]
inwendige energie	$U = m c_\mathrm{V} T$ [J]	[2.4]
kernenergie	$E_\mathrm{kern} = m c^2$ [J]	[2.5]
chemische energie	$H_\mathrm{ch} = m_\mathrm{br} h_0$ [J]	[2.6]

arbeid

	$W = \int F \mathrm{d}s$ [J]	[2.7]
	$W = \int P \mathrm{d}t$ [J]	[2.14]
volumearbeid bij een fluïdum	$W = \int p \mathrm{d}V$ [2.9] met $F = pA$ [N]	[2.8]
technische arbeid bij een fluïdum	$W_\mathrm{t} = -\int V \mathrm{d}p$ [J]	[7.6]
	$W_t = nW$	[7.29]
roterende beweging	$W = \int M \mathrm{d}\alpha$ [2.11] met $M = F \times R$ [Nm]	[2.10]
elektrische arbeid	$W = U q$	[2.12]

vermogen

	$P = \lim\limits_{\Delta t \to 0} \frac{\Delta W}{\Delta t} = \frac{\mathrm{d}W}{\mathrm{d}t}$ [W]	[2.13]
	$P = \Phi_\mathrm{m} w$ [W]	[2.35]
rechtlijnige beweging	$P = Fv$	[2.15]
roterende beweging	$P = M\omega$ [2.16] met $\omega = \frac{2\pi n}{60}$	[2.17]
elektrisch vermogen	$P = UI$	[2.18]

warmte

	$Q = \int \Phi_\mathrm{w} \mathrm{d}t$ [J]	[2.20]
	$Q = \int m c(T) \mathrm{d}T$ [J]	[3.3]
	$Q = \int T \mathrm{d}S$ [J]	[8.23]

warmtestroom

$\Phi_w = \frac{dQ}{dt}$ [W] [2.19]

$\Phi_w = \Phi_m q$ [W] [2.36]

convectieve warmteoverdracht $\Phi_w = \alpha_c A \Delta T$ [2.23]

uitgezonden straling door een oppervlak $\Phi_w = \varepsilon A \sigma T^4$ [2.24]

warmtestraling tussen twee oppervlakken $\Phi_{w,12} = \varepsilon_1 \cdot \Psi_{12} A_1 \sigma (T_1^4 - T_2^4)$ [2.25] of

$\Phi_{w,12} = \alpha_s A_1 (T_1 - T_2)$ [2.27]

warmtestroomdichtheid

$\varphi_w = \frac{\Phi_w}{A}$ [W/m^2] [2.21]

warmtegeleiding $\varphi_w = -\lambda \frac{dT}{dx}$ [2.22]

specifieke energie

$e = \frac{E}{m}$ [J/kg] [2.29]

Toestandsgrootheden

dichtheid	$\rho = \frac{m}{V}$ [kg/m^3]	[3.1]
enthalpie	$H = U + pV$ [J]	[3.9]

entropieverandering bij omkeerbaar proces

$dS = \frac{dQ}{T}$ [J/K] [8.21] $\Rightarrow$ $\Delta S_{omk} = \int \frac{dQ}{T}$ [8.8]

specifieke entropieveranderingen geldig voor zowel omkeerbaar als niet-omkeerbaar proces

	Toestands-verandering	Specifieke entropieverandering	Vergelijking
Algemeen		$\Delta s = c \ln\left(\frac{T_2}{T_1}\right)$	[8.9]
Ideaal gas	Isobaar	$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) = c_p \ln\left(\frac{v_2}{v_1}\right)$	[8.10]
	Isochoor	$\Delta s = c_V \ln\left(\frac{T_2}{T_1}\right) = c_V \ln\left(\frac{p_2}{p_1}\right)$	[8.11]
	Isotherm	$\Delta s = R_s \ln\left(\frac{p_2}{p_1}\right) = R_s \ln\left(\frac{v_1}{v_2}\right)$	[8.12]
	Polytroop	$\Delta s = c_V \ln\left(\frac{T_2}{T_1}\right) + R_s \ln\left(\frac{v_2}{v_1}\right)$	[8.13]
		$\Delta s = c_V \ln\left(\frac{p_2}{p_1}\right) + c_p \ln\left(\frac{v_2}{v_1}\right)$	[8.14]
		$\Delta s = c_p \ln\left(\frac{T_2}{T_1}\right) + R_s \ln\left(\frac{p_1}{p_2}\right)$	[8.15]
Zuiver mengsel	Verdampen en condenseren	$\Delta s = \frac{\Delta x \cdot r}{T}$	[8.16]

gas

ideale gaswet	$\frac{pV}{T} = mR_s$ [J/K]	[3.20]
specifieke gasconstante	$R_s = c_p - c_V$ [J/kgK]	[5.4]

mengsels

enthalpie	$H_\mathrm{m} = \sum H_\mathrm{i}$ [J]	[3.28]
soortelijke warmte	$c_\mathrm{m} = \sum y_\mathrm{i} c_\mathrm{i}$ [J/kgK]	[3.30]
gemiddelde temperatuur	$T_\mathrm{m} = \dfrac{\sum m_\mathrm{i} c_\mathrm{i} T_\mathrm{i}}{\sum m_\mathrm{i} c_\mathrm{i}}$ [K]	[3.31]
ideale gaswet	$\dfrac{p_\mathrm{m} V_\mathrm{m}}{T_\mathrm{m}} = mR_\mathrm{s,m}$ [J/kgK]	[3.32]
mengseldruk	$p_\mathrm{m} = \sum_{\mathrm{i}=1}^{n} p_\mathrm{i}$ [Pa]	[3.33]
specifieke gasconstante	$R_\mathrm{s,m} = \sum_{\mathrm{i}=1}^{n} y_\mathrm{i} R_\mathrm{s,i}$ [J/kgK]	[3.34]

vloeistof-dampmengsel

specifieke enthalpie	$h = x \cdot h_\mathrm{d} - (1-x)h_\mathrm{vl}$ [J/kg]	[3.36]
	$h = \dfrac{s - s_\mathrm{vl}}{s_\mathrm{d} - s_\mathrm{vl}}(h_\mathrm{d} - h_\mathrm{vl}) + h_\mathrm{vl}$ [J/kg]	[9.1]

vloeistof

specifieke enthalpie	$h = h_\mathrm{vl} + v_\mathrm{vl} \cdot (p - p_\mathrm{vl})$ [J/kg]	[3.38]

vochtige lucht

absolute vochtigheid	$x = \dfrac{m_\mathrm{wd}}{m_\mathrm{dl}}$ [kg/kg]	[3.39]
	$x = \dfrac{0{,}622 p_\mathrm{wd}}{1{,}01325 \cdot 10^5 - p_\mathrm{wd}}$ [kg/kg]	[3.41]
specifieke enthalpie	$h_\mathrm{lucht} = \left(1{,}005 T_\mathrm{lucht} + x(2491 + 1{,}926 T_\mathrm{lucht})\right) \cdot 10^3$ [J/kgK]	[3.43]
maximale waterdampspanning	$p_\mathrm{wd,max} = 813 e^{\frac{T_\mathrm{lucht}}{17{,}6}} - 200$ [Pa]	[3.44]
natte boltemperatuur	$T_\mathrm{nb} = 27{,}8 \ln \dfrac{h_\mathrm{lucht} + 36000}{45500}$	[3.45]
relatieve vochtigheid	$\varphi = \dfrac{p_\mathrm{wd}}{p_{\mathrm{wd}_\mathrm{max}}} \cdot 100\%$	[3.46]
dichtheid	$\rho_\mathrm{lucht} = 219{,}6 \dfrac{x}{(T_\mathrm{lucht} + 273{,}15) \cdot (0{,}622 + x)}$	[3.47]

Algemene balansvergelijkingen

massabalans $\Phi_{\mathrm{m,in}} - \Phi_{\mathrm{m,uit}} + \Phi_{\mathrm{m,prod}} = \frac{\mathrm{d}m_{\mathrm{syst}}}{\mathrm{d}t}$ [kg/s] [4.5]

impulsbalans $\Phi_{\mathrm{m,in}} v_{\mathrm{in}} - \Phi_{\mathrm{m,uit}} v_{\mathrm{uit}} + \sum F = \frac{\mathrm{d}(mv)_{\mathrm{syst}}}{\mathrm{d}t}$ [N] [4.6]

impulsmomentbalans $\Phi_{\mathrm{m,in}} v_{\mathrm{in}} x R_{\mathrm{in}} - \Phi_{\mathrm{m,uit}} v_{\mathrm{uit}} x R_{\mathrm{uit}} + \sum M = \frac{\mathrm{d}(mv \times R)_{\mathrm{syst}}}{\mathrm{d}t}$ [Nm] [4.7]

energiebalans $\Phi_{\mathrm{m,in}} e_{\mathrm{in}} - \Phi_{\mathrm{m,uit}} e_{\mathrm{uit}} + \Phi_{\mathrm{w}} + \Phi_{\mathrm{w,prod}} - P = \frac{\mathrm{d}E_{\mathrm{syst}}}{\mathrm{d}t}$ [W] [4.8]

Gesloten systemen

Eerste hoofdwet voor een gesloten systeem $Q = \Delta U + W$ [J] [5.2]

$\mathrm{d}Q = \mathrm{d}H - V\mathrm{d}p$ [J] [5.5]

$mc\mathrm{d}T = mc_{\mathrm{p}}\mathrm{d}T - V\mathrm{d}p$ [J] [5.6]

Kringprocessen

netto arbeid $W_{\mathrm{nt}} = \sum W = \sum Q$ [5.23]

specifieke netto arbeid $w_{\mathrm{nt}} = \frac{W_{\mathrm{nt}}}{m}$ [6.1]

specifiek netto vermogen $P_{\mathrm{nt}} = \Phi_{\mathrm{m}} w_{\mathrm{nt}}$ [6.2]

Open systemen

Eerste hoofdwet voor open systemen

$Q = \Delta H + \Delta E_{\mathrm{k}} + \Delta E_{\mathrm{p}} + W_{\mathrm{t}}$ [J] **[7.1]**

$Q = \Delta U + \Delta E_{\mathrm{k}} + \Delta E_{\mathrm{p}} + W$ [J] [7.2] met $W = W_{\mathrm{t}} + p_{\mathrm{uit}} V_{\mathrm{uit}} - p_{\mathrm{in}} V_{\mathrm{in}}$ [7.3]

$q = \Delta h + \Delta e_{\mathrm{k}} + \Delta e_{\mathrm{p}} + w_{\mathrm{t}}$ [J/kg] [7.4]

$\Phi_{\mathrm{w}} = \Phi_{\mathrm{m}}(\Delta h + \Delta e_{\mathrm{k}} + \Delta e_{\mathrm{p}}) + P_{\mathrm{t}}$ [W] [7.5]

Prestatiecoëfficiënten

$$\eta_{\mathrm{m}} = \frac{W_{\mathrm{af}}}{W_{\mathrm{toe}}} \quad [-] \tag*{[4.12]}$$

$$\mathrm{COP} = \frac{E_{\mathrm{nt}}}{E_{\mathrm{offers}}} \quad [-] \tag*{[4.14]}$$

$$\mathrm{PER} = \frac{E_{nt}}{E_{pr}} \quad [-] \tag*{[4.16]}$$

thermische rendementen

$$\eta_{\mathrm{th}} = \frac{W_{\mathrm{nt}}}{Q_{\mathrm{toe}}} \quad [-] \tag*{[4.13]}$$

$$\eta_{\mathrm{th}} = 1 - \frac{Q_{\mathrm{af}}}{Q_{\mathrm{toe}}} \tag*{[6.4]}$$

omkeerbaar proces $\eta_{\mathrm{th}} = 1 - \dfrac{T_{\mathrm{laag,gem}}}{T_{\mathrm{hoog,gem}}}$ [8.24]

$$\eta_{\mathrm{th,Carnot}} = 1 - \frac{T_{\mathrm{laag}}}{T_{\mathrm{hoog}}} \tag*{[6.5]}$$

$\eta_{\mathrm{th,Otto}} = 1 - \dfrac{1}{\varepsilon^{k-1}}$ [6.7] met $\varepsilon = \dfrac{V_{\mathrm{max}}}{V_{\mathrm{min}}}$ [6.6]

$$\eta_{\mathrm{th,Seiliger}} = 1 - \frac{1}{\varepsilon^{k-1}} \cdot \frac{a \cdot b^k - 1}{k \cdot a \cdot (b-1) + a - 1} \tag*{[6.8]}$$

$\eta_{\mathrm{th,Joule}} = \eta_{\mathrm{th,Brayton}} = 1 - \dfrac{1}{\pi^{\frac{k-1}{k}}}$ [6.11] met $\pi = \dfrac{p_{\mathrm{hoog}}}{p_{\mathrm{laag}}}$ [6.9]

optimale drukverhouding bij Jouleproces $\pi_{\mathrm{opt}} = \left(\dfrac{T_{\mathrm{hoog}}}{T_{\mathrm{laag}}}\right)^{\frac{k}{2(k-1)}}$ [6.13]

$$\eta_{\mathrm{th,Stirling}} = 1 - \frac{T_{\mathrm{laag}}}{T_{\mathrm{hoog}}} \tag*{[6.15]}$$

isentropische rendementen

turbine

$$\eta_{\text{is,turb}} = \frac{W_{\text{turb,werk}}}{W_{\text{turb,theor}}} = \frac{H_{\text{in}} - H_{\text{uit}}}{H_{\text{in}} - H_{\text{uit,omk}}} \qquad [8.1]$$

$$\eta_{\text{is,turb}} = \frac{h_{\text{in}} - h_{\text{uit}}}{h_{\text{in}} - h_{\text{uit,omk}}} \qquad [8.2]$$

$$\eta_{\text{is,turb}} = \frac{h_{\text{in}} - h_{\text{uit}}}{h_{\text{in}} - h_{\text{uit,omk}}} = \frac{c_{\text{p}}(T_{\text{in}} - T_{\text{uit}})}{c_{\text{p}}(T_{\text{in}} - T_{\text{uit,omk}})} = \frac{T_{\text{in}} - T_{\text{uit}}}{T_{\text{in}} - T_{\text{uit,omk}}} \qquad [8.3]$$

compressor

$$\eta_{\text{is,compr}} = \frac{W_{\text{compr,theor}}}{W_{\text{compr,werk}}} \qquad [8.4]$$

$$\eta_{\text{is,compr}} = \frac{h_{\text{uit,omk}} - h_{\text{in}}}{h_{\text{uit}} - h_{\text{in}}} \qquad [8.5]$$

$$\eta_{\text{is,compr}} = \frac{T_{\text{uit,omk}} - T_{\text{in}}}{T_{\text{uit}} - T_{\text{in}}} \qquad [8.6]$$

koudefactor

$$\varepsilon = \frac{q_{\text{toe}}}{w_{\text{nt}}} \quad [-] \qquad [6.16]$$

$$\varepsilon_{\text{Carnot}} = \frac{q_{\text{toe}}}{w_{\text{nt}}} = \frac{T_{\text{laag}}}{T_{\text{hoog}} - T_{\text{laag}}} \qquad [6.19]$$

$$\varepsilon_{\text{Joule}} = \frac{q_{\text{toe}}}{w_{\text{nt}}} = \frac{1}{\pi^{\frac{k-1}{k}} - 1} \qquad [6.21]$$

warmteproductiegetal

$$\varepsilon_{\text{w}} = \frac{q_{\text{af}}}{w_{\text{nt}}} \quad [-] \qquad [6.17]$$

$$\varepsilon_{\text{w}} = \varepsilon + 1 \qquad [6.18]$$

$$\varepsilon_{\text{w,Carnot}} = \frac{q_{\text{af}}}{w_{\text{nt}}} = \frac{T_{\text{hoog}}}{T_{\text{hoog}} - T_{\text{laag}}} \qquad [6.20]$$

Toestandsveranderingen

gassen

polytroop

$pV^n = C$ [5.7] of $\frac{p}{\rho^n} = C$ [5.7a]

$TV^{n-1} = C$ [5.8] of $\frac{T}{\rho^{n-1}} = C$ [5.8a]

$\frac{T^n}{p^{n-1}} = C$ [5.9]

en

$W = \frac{-1}{n-1}(p_2V_2 - p_1V_1)$ [J] [5.10]

of $W = \frac{-mR_s}{n-1}(T_2 - T_1)$ [5.11]

en

$Q = mc(T_2 - T_1)$ [J] [3.4]

met

$c = c_V - \frac{R_s}{n-1}$ [J/kgK] [5.12]

$n = \frac{c - c_p}{c - c_V}$ [–] [5.13]

$Q = \frac{k-n}{k-1}W$ [5.14]

isobaar

$p = C$

$n = 1$ en $c = c_p$

$W = p(V_2 - V_1)$ [5.15]

$Q = mc_p(T_2 - T_1)$ [5.16]

isochoor

$V = C$

$n = \infty$ en $c = c_V$

$$W = 0 \qquad [5.17]$$

$$Q = mc_V(T_2 - T_1) \qquad [5.18]$$

isentroop

$$pV^k = C \qquad [5.19]$$

$n = k$ en $c = 0$

$$k = \frac{c_p}{c_V} \qquad [5.20]$$

$$W = \frac{-1}{k-1}(p_2V_2 - p_1V_1) = -mc_V(T_2 - T_1) \qquad [5.21]$$

$$Q = 0 \qquad [5.22]$$

isotherm

$pV = C$

$n = 1$ en $c = \infty$

$$W = Q = mR_sT\ln\left(\frac{V_2}{V_1}\right) \qquad [5.23]$$

of

$$W = Q = -mR_sT\ln\left[\frac{p_2}{p_1}\right] \qquad [5.24]$$

Werktuigen en installatieonderdelen

pomp

algemeen

$P_{\text{pomp}} = \Phi_V \Delta p_{\text{pomp}}$ [W] [7.7]

$W_{\text{pomp}} = V \Delta p_{\text{pomp}}$ [J] [7.8]

$w_{\text{pomp}} = v \Delta p_{\text{pomp}}$ [J/kg] [7.9]

$w_{\text{pomp}} = h_{\text{uit}} - h_{\text{in}}$ [7.10]

centrifugaalpomp

$P = \Phi_m (c_{2,\text{tan}} \cdot u_2 - c_{1,\text{tan}} \cdot u_1)$ [10.16]

$\Phi_V = c_{2,\text{rad}} \cdot \pi \cdot D_2 \cdot b_2$ [10.17]

$$\Delta p_{\text{pomp}} = \rho \cdot u_2 \left(u_2 - \frac{\Phi_V}{\tan(\beta_2) \cdot 2\pi R_2 \cdot b_2} \right)$$ [10.18]

$\Phi_V = C \cdot n$ [10.19]

$\Delta p_{\text{pomp}} = C \cdot n^2$ [10.20]

$P_{\text{pomp}} = C \cdot n^3$ [10.21]

$\Phi_V = C \cdot D^3$ [10.22]

$\Delta p_{\text{pomp}} = C \cdot D^2$ [10.23]

$P_{\text{pomp}} = C \cdot D^5$ [10.24]

straalbuis

$v_{\text{uit}} = \sqrt{2(h_{\text{in}} - h_{\text{uit}})}$ [7.11]

smoorvoorziening

$h_{\text{uit}} = h_{\text{in}}$ [7.12]

warmtewisselaar

$\Phi_{m,k}\left(h_{k,uit}-h_{k,in}\right)=\Phi_{m,w}\left(h_{w,in}-h_{w,uit}\right)$ [7.14]

$\Phi_{m,k}c_{p,k}\left(T_{k,uit}-T_{k,in}\right)=\Phi_{m,w}c_{p,w}\left(T_{w,in}-T_{w,uit}\right)$ [7.15]

$\Phi_{w}=UA\Delta T_{gem} \quad \Rightarrow \quad A=\dfrac{\Phi_{w}}{U\Delta T_{gem}}$ [13.26] met $\Delta T_{gem}=\Delta T_{ln}=\dfrac{\Delta T_{a}-\Delta T_{b}}{\ln\dfrac{\Delta T_{a}}{\Delta T_{b}}}$ [13.27]

temperatuurrendement opwarmend fluïdum $\eta_{k}=\dfrac{T_{2u}-T_{2i}}{T_{1i}-T_{2i}}$ [13.28]

temperatuurrendement afkoelend fluïdum $\eta_{w}=\dfrac{T_{1i}-T_{1u}}{T_{1i}-T_{2i}}$ [13.29]

tegenstroomwarmtewisselaar

$\eta_{k}=\dfrac{1-e^{-x(1-y)}}{1-y\cdot e^{-x(1-y)}}$ [13.30] en $\eta_{w}=y\cdot\eta_{k}$ [13.31]

waarin $x=\dfrac{UA}{\Phi_{m2}c_{2}}$ [13.32] en $y=\dfrac{\Phi_{m2}c_{2}}{\Phi_{m1}c_{1}}$ [13.33]

gelijkstroomwarmtewisselaar

$\eta_{k}=\dfrac{1-e^{-x(1+y)}}{1+y}$ [13.34] en $\eta_{w}=y\cdot\eta_{k}$ [13.31]

verdampend medium $\eta_{w}=1-e^{-\frac{UA}{\Phi_{mw}c_{w}}}$ [13.37] en $\eta_{k}=0$ [13.36]

condenserend medium $\eta_{k}=1-e^{-x}$ [13.35] en $\eta_{w}=0$

ketel

$\Phi_{w,ketel}=\Phi_{m}(h_{uit}-h_{in})$ [7.16]

$q_{ketel}=h_{uit}-h_{in}$ [7.17]

waterturbine

$P_{wt}=-\Phi_{m}\Delta\left(\dfrac{1}{2}v^{2}\right)$ [7.18]

compressor

Toestands-verandering	Compressor-vermogen $P_{\text{compr}} =$	Compressor-arbeid $W_{\text{compr}} =$	Specifieke compressorarbeid $w_{\text{compr}} =$
Adiabaat	$\Phi_{\text{m}}(h_{\text{uit}} - h_{\text{in}})$ [7.19]	$H_{\text{uit}} - H_{\text{in}}$ [7.19a]	$h_{\text{uit}} - h_{\text{in}}$ [7.19b]
	$\Phi_{\text{m}} c_{\text{p}}(T_{\text{uit}} - T_{\text{in}})$ [7.20]	$mc_{\text{p}}(T_{\text{uit}} - T_{\text{in}})$ [7.20a]	$c_{\text{p}}(T_{\text{uit}} - T_{\text{in}})$ [7.20b]
Polytroop ideaal gas	$\frac{n}{n-1}\Phi_{\text{m}} R_{\text{s}}(T_{\text{uit}} - T_{\text{in}})$ [7.21]	$\frac{n}{n-1} mR_{\text{s}}(T_{\text{uit}} - T_{\text{in}})$ [7.21a]	$\frac{n}{n-1} R_{\text{s}}(T_{\text{uit}} - T_{\text{in}})$ [7.21b]
	$\frac{n}{n-1}(p_{\text{uit}}\Phi_{\text{V,uit}} - p_{\text{in}}\Phi_{\text{V,in}})$ [7.22]	$\frac{n}{n-1}(p_{\text{uit}}V_{\text{uit}} - p_{\text{in}}V_{\text{in}})$ [7.22a]	$\frac{n}{n-1}(p_{\text{uit}}v_{\text{uit}} - p_{\text{in}}v_{\text{in}})$ [7.22b]
	$\frac{n}{n-1}\Phi_{\text{m}} R_{\text{s}} T_{\text{in}}\left\{\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)^{\frac{n-1}{n}} - 1\right\}$ [7.23]	$\frac{n}{n-1} mR_{\text{s}} T_{\text{in}}\left\{\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)^{\frac{n-1}{n}} - 1\right\}$ [7.23a]	$\frac{n}{n-1} R_{\text{s}} T_{\text{in}}\left\{\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)^{\frac{n-1}{n}} - 1\right\}$ [7.23b]
Isotherm ideaal gas	$\Phi_{\text{m}} R_{\text{s}} T_{\text{in}} \ln\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)$ [7.24]	$mR_{\text{s}} T_{\text{in}} \ln\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)$ [7.24a]	$R_{\text{s}} T_{\text{in}} \ln\left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)$ [7.24b]

turbine

$$P_{\text{turb}} = \Phi_{\text{m}}(h_{\text{in}} - h_{\text{uit}}) \qquad [7.31]$$

$$w_{\text{turb}} = h_{\text{in}} - h_{\text{uit}} \qquad [7.31a]$$

$$P_{\text{turb}} = \frac{n}{n-1}\Phi_{\text{m}} R_{\text{s}} T_{\text{in}}\left\{1 - \left(\frac{p_{\text{uit}}}{p_{\text{in}}}\right)^{\frac{n-1}{n}}\right\} \qquad [7.32]$$

$$P_{\text{turb}} = \Phi_{\text{m}} R_{\text{s}} T_{\text{in}} \ln\left(\frac{p_{\text{in}}}{p_{\text{uit}}}\right) \qquad [7.33]$$

straalmotor

stuwkrachtvermogen $P_{\text{stuw}} = \Phi_{\text{m}}(v_{\text{uit}} - v_{\text{in}}) \cdot v_{\text{in}}$ [10.13]

voortstuwingsrendement $\eta_{\text{stuw}} = \dfrac{2 \cdot v_{\text{in}}}{v_{\text{uit}} + v_{\text{in}}}$ [10.14]

gasturbine

$$w_{\mathrm{nt}} = w_{\mathrm{turb}} - w_{\mathrm{compr}}$$

verbrandingskamer gasturbine

$$q_{\mathrm{verbrandingskamer}} = h_{\mathrm{uit}} - h_{\mathrm{in}}$$

verdamper

$$q_{\mathrm{verdamper}} = h_{\mathrm{uit}} - h_{\mathrm{in}}$$

condensor

$$q_{\mathrm{condensor}} = h_{\mathrm{in}} - h_{\mathrm{uit}}$$

Stromingsleer

volumestroom

$\Phi_V = \int_A v\,\mathrm{d}A$ [m^3/s] [10.4]

massabalans stationaire toestand

$\rho_{\mathrm{uit}} \cdot v_{\mathrm{uit}} \cdot A_{\mathrm{uit}} = \rho_{\mathrm{in}} \cdot v_{\mathrm{in}} \cdot A_{\mathrm{in}}$ [m^3/s] [10.1]

impulsbalans stationaire toestand

$\sum F = \Phi_m (v_{\mathrm{uit}} - v_{\mathrm{in}})$ [N] [10.11]

$\sum F = p_{\mathrm{in}} A_{\mathrm{in}} - p_{\mathrm{uit}} A_{\mathrm{uit}} + \sum F_{\mathrm{wand}}$ [N] [10.12]

impulsmomentbalans stationaire toestand

$\sum M = \Phi_m (v_{\mathrm{uit}} x R_{\mathrm{uit}} - v_{\mathrm{in}} x R_{\mathrm{in}})$ [Nm] [10.15]

energiebalans stationaire toestand

$h_{\mathrm{uit}} + \frac{1}{2} v_{\mathrm{uit}}^2 + g z_{\mathrm{uit}} = h_{\mathrm{in}} + \frac{1}{2} v_{\mathrm{in}}^2 + g z_{\mathrm{in}}$ [J/kgK] [10.2]

onsamendrukbaar

$\Phi_{V,\mathrm{uit}} = \Phi_{V,\mathrm{in}}$ [10.3a] of $\int_{A_{\mathrm{uit}}} v_{\mathrm{uit}}\,\mathrm{d}A_{\mathrm{uit}} = \int_{A_{\mathrm{in}}} v_{\mathrm{in}}\,\mathrm{d}A_{\mathrm{in}}$ [10.5]

constante snelheid $v_{\mathrm{uit}} A_{\mathrm{uit}} = v_{\mathrm{in}} A_{\mathrm{in}}$ [10.3]

stroming zonder wrijving

wet van Bernoulli $p_{\mathrm{uit}} + \frac{1}{2}\rho v_{\mathrm{uit}}^2 + \rho g z_{\mathrm{uit}} = p_{\mathrm{in}} + \frac{1}{2}\rho v_{\mathrm{in}}^2 + \rho g z_{\mathrm{in}}$ [N/m^2] [10.6]

stroming met wrijving

stroming in een buis

$p_{\mathrm{uit}} + \frac{1}{2}\rho v_{\mathrm{uit}}^2 + \rho g z_{\mathrm{uit}} + \Delta p_{\mathrm{w}} = p_{\mathrm{in}} + \frac{1}{2}\rho v_{\mathrm{in}}^2 + \rho g z_{\mathrm{in}}$ [12.1]

met $\Delta p_{\mathrm{w}} = \sum \zeta \frac{1}{2}\rho v^2$ [12.2] en weerstandscoëfficiënt $\zeta = \lambda \frac{l}{D}$ [12.4]

$\lambda = \frac{64}{Re}$ $(Re < 2300)$ [12.8]

$\frac{1}{\sqrt{\lambda}} = -0{,}86 \cdot \ln\left(\frac{\varepsilon}{3{,}7} + \frac{2{,}51}{Re\sqrt{\lambda}}\right)$ $(Re > 2300)$ [12.14]

waarin

relatieve wandruwheid $\varepsilon = \frac{e}{D}$ [–] [12.7] en

kengetal van Reynolds $Re = \frac{\rho \cdot v \cdot D_\mathrm{h}}{\eta}$ [–] [12.3] met

hydraulische diameter $D_\mathrm{hydr} = 4\frac{A}{O}$ [m] [12.5]

Wet van Poiseuille $\Delta p_\mathrm{w} = \frac{128 \cdot \eta \cdot l}{\pi \cdot D^4}\Phi_\mathrm{V}$ $(Re < 2300)$ [12.9]

stroming om een lichaam

drukverliezen $\Delta p_\mathrm{w} = C_\mathrm{w}\frac{1}{2}\rho \cdot v^2$ [12.18]

gasstroming

Wet van Bernoulli voor ideale gassen ($Ma < 0{,}25$ met $Ma = \frac{v}{a}$ [10.9])

$$\frac{k}{k-1}\frac{p_\mathrm{uit}}{\rho_\mathrm{uit}} + \frac{1}{2}v_\mathrm{uit}^2 + gz_\mathrm{uit} = \frac{k}{k-1}\frac{p_\mathrm{in}}{\rho_\mathrm{in}} + \frac{1}{2}v_\mathrm{in}^2 + gz_\mathrm{in} \qquad [11.1]$$

geluidsnelheid

algemeen $a = \sqrt{\frac{\mathrm{d}p}{\mathrm{d}\rho}}$ [11.2]

vaste stof en vloeistof $a = \sqrt{\frac{E}{\rho}}$ [11.3]

ideaal gas $a = \sqrt{k\frac{p}{\rho}} = \sqrt{kR_\mathrm{s}T}$ [11.4]

massastroom $\Phi_\mathrm{m} = A_2\sqrt{\frac{2k}{k-1}p_1\rho_1\left(\pi^{\frac{2}{k}} - \pi^{\frac{k+1}{k}}\right)}$ [11.5]

kritische drukverhouding $\pi_\mathrm{kr} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$ [11.6]

snelheid $v = \sqrt{\frac{2k}{k-1}\left(\frac{p_1}{\rho_2} - \frac{p}{\rho}\right)}$ [11.7]

Warmtebalansen

differentiële warmtebalansen

cartesiaanse coördinaten

$$\lambda\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right]+g=\rho\, c\frac{\partial T}{\partial t} \tag*{[13.2]}$$

cilindercoördinaten

$$\lambda\left[\frac{1}{r}\frac{\partial r\dfrac{\partial T}{\partial r}}{\partial r}+\frac{1}{r}\frac{\partial \dfrac{1}{r}\dfrac{\partial T}{\partial \varphi}}{\partial \varphi}+\frac{\partial^2 T}{\partial z^2}\right]+g=\rho\, c\frac{\partial T}{\partial t} \tag*{[13.3]}$$

bolcoördinaten

$$\lambda\left[\frac{1}{r}\frac{\partial^2 rT}{\partial r^2}+\frac{1}{r\sin\theta}\frac{\partial\left(\sin\theta\dfrac{\partial T}{\partial \theta}\right)}{\partial \theta}+\frac{1}{r^2\sin^2\theta}\frac{\partial^2 T}{\partial \varphi^2}\right]+g=\rho c\frac{\partial T}{\partial t} \tag*{[13.4]}$$

Stationaire warmtetransport

vlakke wanden

Vlakke wand met opgelegde oppervlaktetemperaturen

temperatuurverdeling $$T = T_{\text{opp},1} + \frac{T_{\text{opp},2} - T_{\text{opp},1}}{d} x$$ [13.11]

warmtestroomdichtheid $$\varphi_{\text{w}} = \frac{\lambda}{d}\left(T_{\text{opp},1} - T_{\text{opp},2}\right) \quad [\text{W/m}^2]$$ [13.12]

vlakke wand met opgelegde fluïdumtemperaturen

wand bestaat uit een materiaallaag

$$T = \frac{\left(\frac{1}{\alpha_2} + \frac{d - x}{\lambda}\right) T_{\text{fluïdum},1} + \left(\frac{x}{\lambda} + \frac{1}{\alpha_1}\right) T_{\text{fluïdum},2}}{\frac{1}{\alpha_1} + \frac{d}{\lambda} + \frac{1}{\alpha_2}}$$ [13.13] en

$$\varphi_{\text{w}} = \frac{T_{\text{fluïdum},1} - T_{\text{fluïdum},2}}{\frac{1}{\alpha_1} + \frac{d}{\lambda} + \frac{1}{\alpha_2}} \quad [\text{W/m}^2]$$ [13.14]

wand bestaat uit meerdere materiaallagen $$\varphi_w = \frac{T_{\text{fluïdum},1} - T_{\text{fluïdum},2}}{\frac{1}{\alpha_1} + \sum \frac{d}{\lambda} + \frac{1}{\alpha_2}}$$ [13.17]

$$\Phi_{\text{w}} = UA\Delta T_{\text{gem}} \quad \Rightarrow \quad A = \frac{\Phi_{\text{w}}}{U\Delta T_{\text{gem}}}$$ [13.26]

$$U = \frac{1}{\frac{1}{\alpha_1} + \sum \frac{d}{\lambda} + \frac{1}{\alpha_2}}$$ [13.18]

leidingen

leiding met opgelegde fluidumtemperaturen

$$\Phi_{\text{W}} = \frac{T_{\text{fluïdum,i}} - T_{\text{fluïdum,u}}}{R_{\text{tot}}}$$ [13.17a]

met $$R_{\text{tot}} = \frac{1}{\alpha_{\text{i}}} \cdot \frac{1}{2\pi R_1 l} + \sum_{\text{j}=1}^{\text{j}=n} \frac{1}{2\pi l \lambda} \ln \frac{R_{\text{j}+1}}{R_{\text{j}}} + \frac{1}{\alpha_{\text{u}}} \cdot \frac{1}{2\pi R_{\text{n}+1} l}$$ [13.25]

Instationair warmtetransport

Uniforme temperatuur

$$\frac{T - T_{\text{fluïdum}}}{T_{\text{t=0}} - T_{\text{fluïdum}}} = e^{-\frac{\alpha A_{\text{o}}}{\rho c V} t} \qquad [14.2] \qquad \left(Bi < 0{,}1 \text{ met } Bi = \frac{\alpha L_{\text{s}}}{\lambda} \; [14.1] \right)$$

$$\Phi_{\text{w}} = \alpha \cdot A_{\text{o}} \cdot (T_{\text{fluïdum}} - T_{\text{t=0}}) \cdot e^{-\frac{\alpha A_{\text{o}}}{\rho c V} t} \qquad [14.5]$$

halfoneindig medium

$$\frac{T - T_{\text{t=0}}}{T_{\text{fluïdum}} - T_{\text{t=0}}} = 1 - erf\left(\frac{x}{2\sqrt{at}} \right) \quad [14.6] \text{ met } erf(y) = \frac{2}{\sqrt{\pi}} \int_0^y e^{-x^2} \mathrm{d}x \qquad [14.7]$$

$$\varphi_{\text{w,opp}} = \frac{\lambda}{\sqrt{\pi \cdot a \cdot t}} (T_{\text{fluïdum}} - T_{\text{t=0}}) \quad [14.9] \text{ met } a = \frac{\lambda}{\rho c} \qquad [14.8]$$

Differentiemethode voor stationaire warmtetransport

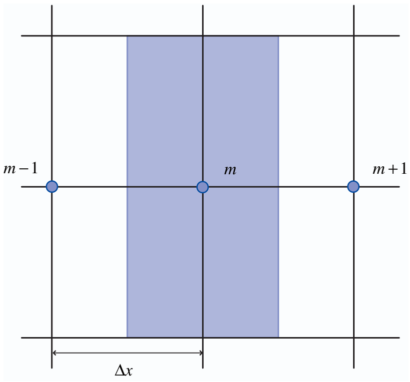
Eendimensionale modellen

inwendig knooppunt

$$T_{\mathrm{m-1}} - 2T_{\mathrm{m}} + T_{\mathrm{m+1}} = -\frac{g\Delta x^2}{\lambda} \qquad [13.38]$$

$$\Phi_{\mathrm{w,mm-1}} = \frac{T_{\mathrm{m}} - T_{\mathrm{m-1}}}{R_{\mathrm{m,m-1}}}$$

waarin: $R_{\mathrm{m,m-1}} = \dfrac{\Delta x}{\lambda A}$

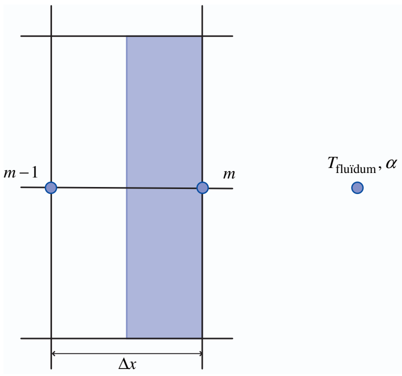


extern knooppunt

$$-\left(\alpha + \frac{\lambda}{\Delta x}\right)T_{\mathrm{m}} + \frac{\lambda}{\Delta x}T_{\mathrm{m-1}} = -\alpha T_{\text{fluïdum}} - g\frac{\Delta x}{2} \qquad [13.39]$$

Voor de warmtestroom van een knooppunt m naar een fluïdum kunnen we schrijven

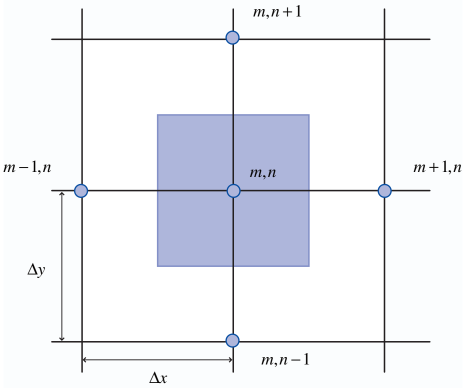
$$\Phi_{\text{w,mfluïdum}} = \frac{T_{\mathrm{m}} - T_{\text{fluïdum}}}{R_{\text{m,fluïdum}}} \quad \text{met} \quad R_{\text{m,fluïdum}} = \frac{1}{\alpha A}$$



Tweedimensionale modellen

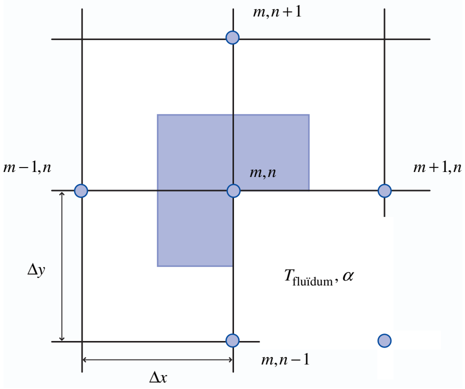
inwendig knooppunt

$$T_{\mathrm{m,n+1}}+T_{\mathrm{m,n-1}}+T_{\mathrm{m+1,n}}+T_{\mathrm{m-1,n}}-4T_{\mathrm{m,n}}=0 \qquad [13.42]$$



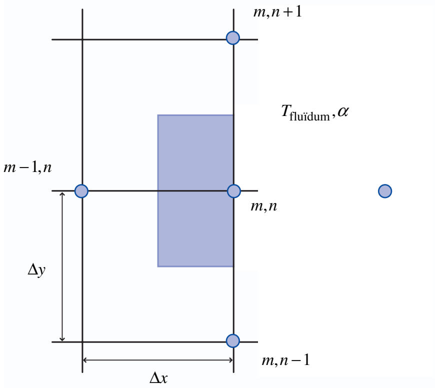
extern knooppunt op een intern hoekpunt met convectie naar de omgeving

$$2\left(T_{\mathrm{m-1,n}}+T_{\mathrm{m,n+1}}\right)+T_{\mathrm{m+1,n}}+T_{\mathrm{m,n-1}}+2BiT_{\mathrm{fluïdum}}-2\left(3+Bi\right)T_{\mathrm{m,n}}=0 \qquad [13.43]$$



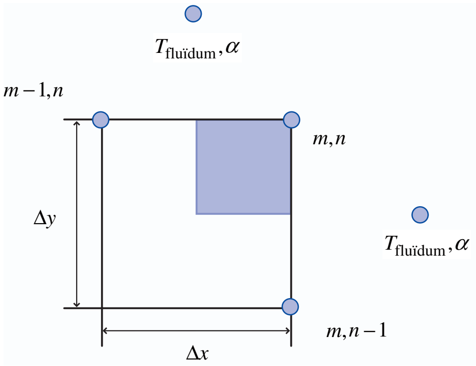
extern knooppunt op een vlak met convectie naar de omgeving

$$2T_{\mathrm{m-1,n}}+T_{\mathrm{m,n+1}}+T_{\mathrm{m,n-1}}+2BiT_{\mathrm{fluïdum}}-2(Bi+2)T_{\mathrm{m,n}}=0 \qquad [13.44]$$



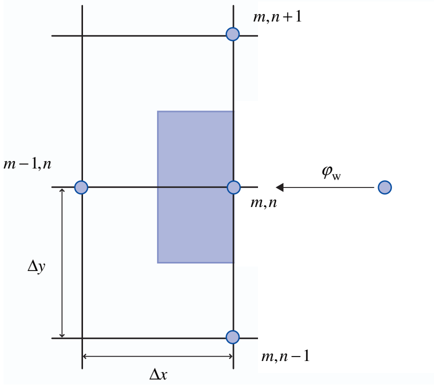
extern knooppunt op een extern hoekpunt met convectie naar de omgeving

$$T_{\mathrm{m,n-1}} + T_{\mathrm{m-1,n}} + 2BiT_{\mathrm{fluïdum}} - 2(Bi+1)T_{\mathrm{m,n}} = 0 \qquad [13.45]$$



extern knooppunt op een vlak met bekende externe warmtevoer vanuit de omgeving

$$2T_{\mathrm{m-1}} + T_{\mathrm{m,n+1}} + T_{\mathrm{m,n-1}} + \frac{2\Delta x}{\lambda}\varphi_{\mathrm{w}} - 4T_{\mathrm{m,n}} = 0 \qquad [13.46]$$

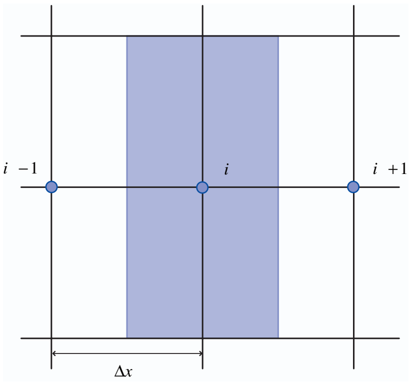


Differentiemethode voor instationaire warmtetransport

Eendimensionale modellen

intern knooppunt

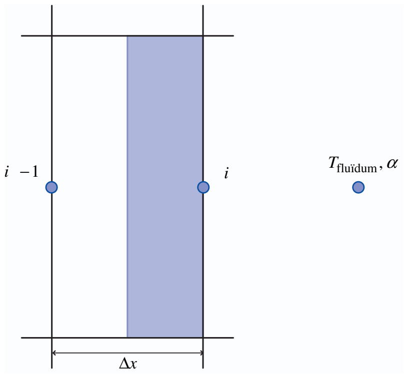
$$T_{\mathrm{i}}^{k+1} = FoT_{\mathrm{i-1}}^{k} + (1-2Fo)T_{\mathrm{i}}^{k} + FoT_{\mathrm{i+1}}^{k} \quad [14.10]$$



extern knooppunt

$$T_{\mathrm{i}}^{k+1} = 2FoBiT_{\mathrm{fluïdum}}^{k} + (1-2FoBi-2Fo)T_{\mathrm{i}}^{k} + 2FoT_{\mathrm{i+1}}^{k} \quad [14.11]$$

met: $$Fo = \frac{\lambda}{\rho c}\frac{\Delta t}{\Delta x^2} \quad [14.12]$$



Convectieve warmteoverdracht

gedwongen convectie

$Nu = f(Re, Pr)$ [15.1]

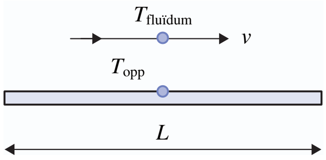
kengetal van Nusselt $Nu = \frac{\alpha_c L_s}{\lambda}$ [–] [15.2]

kengetal van Reynolds $Re = \frac{\rho \cdot v \cdot L_s}{\eta}$ [–] [15.3]

kengetal van Prandtl $Pr = \frac{\eta \cdot c_p}{\lambda}$ [–] [15.4]

Voor de stofeigenschappen moeten de eigenschappen bij de filmtemperatuur gehanteerd worden.

vlak oppervlak



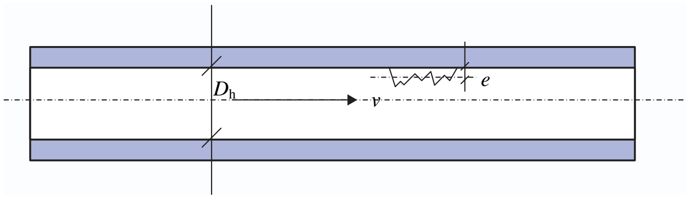
$Nu = 0{,}664 \cdot Re^{1/2} Pr^{1/3}$ [15.7]

geldig voor $Re < 5 \cdot 10^5$ en $Pr > 0{,}6$

$Nu = \left(0{,}037 \cdot Re^{4/5} - 871\right) \cdot Pr^{1/3}$ [15.8]

geldig voor $Pr < 60$ en $5 \cdot 10^5 < Re_L < 10^7$

in een rechte, cilindervormige buis



Bij een constante wandtemperatuur kunnen we hanteren

$Nu = 3{,}66$ [15.9] $(Re < 2300)$

en bij een constante warmtestroom

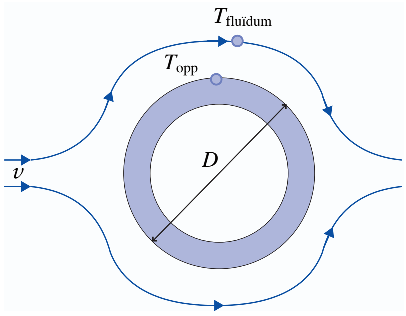
$Nu = 4{,}36$ [15.10] $(Re < 2300)$

In beide gevallen worden de stofeigenschappen bepaald bij de fluïdumtemperatuur.

$Nu = 0{,}023 \cdot Re^{0{,}8} Pr^{n}$ [15.11] $2300 < Re < 1{,}25 \cdot 10^{6}$ en $0{,}6 < Pr < 160$

met
$n = 0{,}4$ bij verwarming van het fluïdum
$n = 0{,}3$ bij koeling van het fluïdum

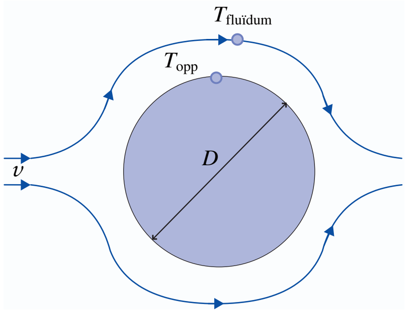
dwars op een rechte cilinder



$$Nu = 0{,}3 + \frac{0{,}62 \cdot Re^{1/2} Pr^{1/3}}{\left(1+\left(\frac{0{,}4}{Pr}\right)^{2/3}\right)^{1/4}} \left(1+\left(\frac{Re}{282000}\right)^{5/8}\right)^{4/5} \qquad [5.14]$$

geldig voor $100 < Re < 10^{7}$ en $Re \cdot Pr > 0{,}2$

bol



$$Nu = 2 + (0{,}4Re^{1/2} + 0{,}06Re^{2/3})Pr^{0{,}4} \left(\frac{\eta_{\text{fluïdum}}}{\eta_{\text{opp}}}\right)^{1/4} \qquad [5.16]$$

geldig voor $0{,}71 < Pr < 380$; $3{,}5 < Re < 76\,000$ en $1 < \frac{\eta_{\text{fluïdum}}}{\eta_{\text{opp}}} < 3{,}2$

Voor de stofeigenschappen moeten de eigenschappen bij de filmtemperatuur gehanteerd worden.

Convectieve warmteoverdracht

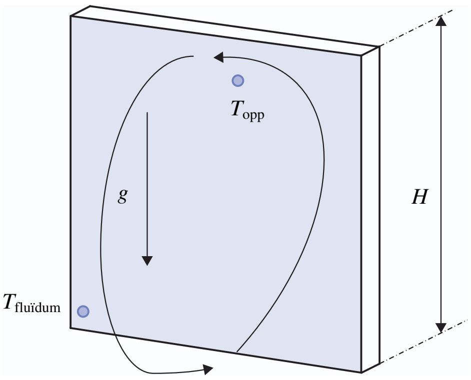
natuurlijke convectie

$Nu = f(Gr, Pr)$ [15.19]

kengetal van Grashof $Gr = \frac{\rho \cdot \Delta\rho g \cdot L^3}{\eta^2} = \frac{\beta \cdot \left|T_{\text{opp}} - T_{\text{fluidum}}\right| \cdot g \cdot L_s^3 \cdot \rho^2}{\eta^2}$ [15.20]

Voor de stofeigenschappen moeten de eigenschappen bij de filmtemperatuur gehanteerd worden.

verticaal, vlak oppervlak



$$Nu = \left(0{,}825 + \frac{0{,}387 \cdot Ra^{1/6}}{\left(1 + (0{,}492 / Pr)^{9/16}\right)^{8/17}}\right)^2 \quad [15.24]$$

geldig voor $10^{-1} < \text{Ra} < 10^{12}$

$Nu = 0{,}59 \cdot Ra^{1/4}$ [15.25] $(10^4 < Ra < 10^9)$

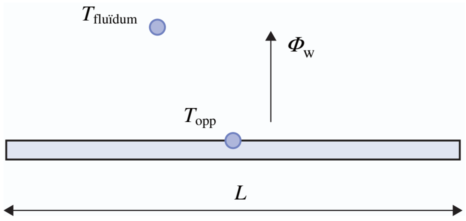
$Nu = 0{,}10 \cdot Ra^{1/3}$ [15.26] $(10^9 < Ra < 10^{13})$

horizontaal, vlak oppervlak
Bij horizontale oppervlakken wordt er onderscheid gemaakt tussen warmtestroom tegen de zwaartekracht in of met de zwaartekracht mee.

Warmtestroom naar beneden

$Nu = 0{,}27 \cdot Ra^{1/4}$ [15.29] $(10^5 < Ra < 10^{10})$

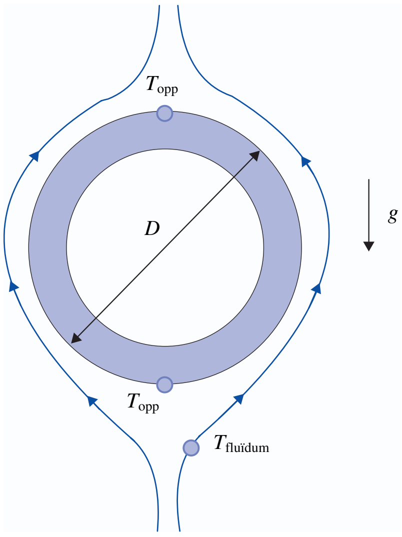
Warmtestroom naar boven



$Nu = 0{,}54 \cdot Ra^{1/4}$ [15.27] $(10^4 < Ra < 10^7)$

$Nu = 0{,}15 \cdot Ra^{1/3}$ [15.28] $Ra > 10^7$

horizontale cilinder

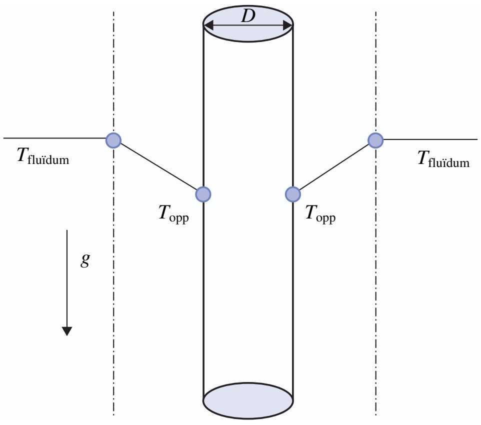


$$Nu = \left(0{,}6 + \frac{0{,}387 \cdot Ra^{1/6}}{\left(1 + (0{,}559 / Pr)^{9/16}\right)^{8/27}}\right)^2$$ [15.32] $(10^{-5} < Ra < 10^{13})$

$Nu = 0{,}48 \cdot Ra^{1/4}$ [15.33] $(10^4 < Ra < 10^7)$

$Nu = 0{,}125 \cdot Ra^{1/3}$ [15.34] $(10^7 < Ra > 10^{12})$

verticale cilinder



$$Nu = \left(0{,}825 + \frac{0{,}387 \cdot Ra^{1/6}}{\left(1 + (0{,}492 / Pr)^{9/16}\right)^{8/17}}\right)^2$$ [15.36]

wanneer $\frac{D}{L} \geq \frac{35}{Gr^{1/4}}$ [15.35]

geldig voor $10^{-1} < Ra < 10^{12}$

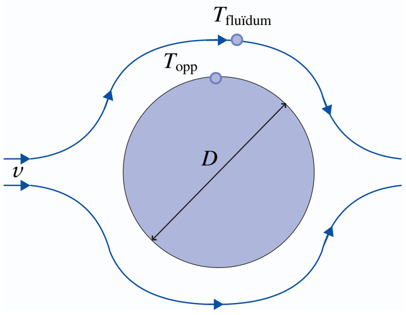
$Nu = 0{,}59 \cdot Ra^{1/4}$ [15.37] $(10^4 < Ra < 10^9)$

$Nu = 0{,}10 \cdot Ra^{1/3}$ [15.38] $(10^9 < Ra < 10$

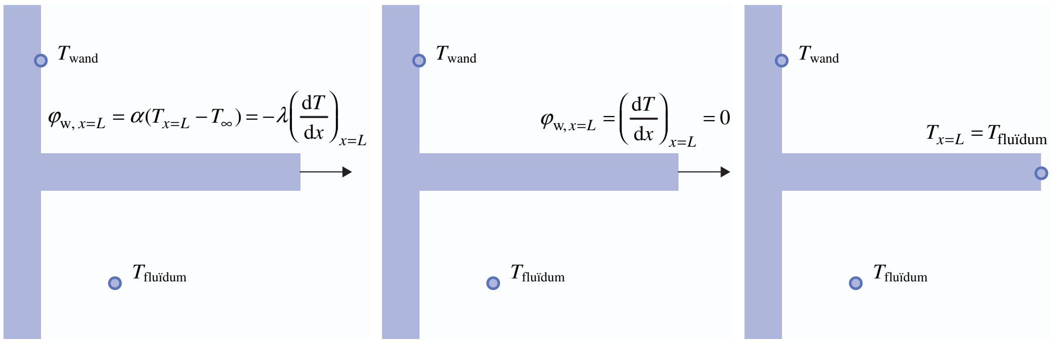
bol

$$Nu = 2 + \frac{0{,}589 \cdot Ra^{1/4}}{\left(1 + (0{,}469 / Pr)^{9/16}\right)^{4/9}}$$ [15.39]

$Ra < 10^{11}$
$Pr > 0{,}5$



Vinnen



Model A Model B Model C

Model	Tipvoorwaarde	Temperatuurverloop in vin	Warmtestroom van vin
A	Convectievoorwaarde $\alpha\theta_{x=L} = -\lambda\left(\frac{\mathrm{d}\theta}{\mathrm{d}x}\right)_{x=L}$	$\dfrac{\cosh m(L-x) + \left(\frac{\alpha}{m\lambda}\right)\sinh m(L-x)}{\cosh mL + \left(\frac{\alpha}{m\lambda}\right)\sinh mL}$ [15.40]	$M\dfrac{\sinh mL + \frac{\alpha}{m\lambda}\cosh mL}{\cosh mL + \frac{\alpha}{m\lambda}\sinh mL}$ [15.41]
B	Adiabatische randvoorwaarde $\left(\frac{\mathrm{d}T}{\mathrm{d}x}\right)_{x=L} = 0$	$\dfrac{\cosh m(L-x)}{\cosh mL}$ [15.42]	$M \tanh mL$ [15.43]
C	Oneindig lange vin $\theta_{x=L} = 0$	e^{-mx} [15.44]	M

Met $m = \sqrt{\frac{\alpha O}{\lambda A}}$ [15.45], $M = \sqrt{\alpha O \lambda A} \cdot \theta_{x=0}$ [15.46], $\theta = T - T_{\text{fluïdum}}$ en $\theta_{x=0} = T_{\text{wand}} - T_{\text{fluïdum}}$

vinrendement

$$\eta_{\text{vin}} = \frac{\Phi_{\text{w,vin}}}{\Phi_{\text{w,ideaal}}} \qquad [15.47]$$

waarin $\Phi_{\text{w,ideaal}} = \alpha O L \theta_{x=0}$ [15.48]

vaste doorsnede $\eta_{\text{vin}} = \dfrac{\tanh\left(mL_{\text{c}}\right)}{mL_{\text{c}}}$ [15.49]

vineffect

$$\varepsilon_{\text{vin}} = \frac{\Phi_{\text{w,vin}}}{\Phi_{\text{w,zonder vinnen}}}$$

vaste doorsnede $\varepsilon_{\text{vin}} = \sqrt{\frac{\lambda O}{\alpha A}} \tanh(mL)$ [15.52]

Straling

warmtevergelijkingen

$a + r + t = 1$ [16.3]

$E_z = \sigma \cdot T^4$ [16.5]

warmtestroom tussen twee grijze oppervlakken $\Phi_{\mathrm{w12,netto}} = \dfrac{\sigma \cdot A \cdot (T_1^4 - T_2^4)}{\dfrac{1}{\varepsilon_1} + \dfrac{1}{\varepsilon_2} - 1}$ [16.13]

zichtfactoren

$$F_{12} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\beta_1 \cdot \cos\beta_2}{\pi \cdot s^2} \, \mathrm{d}A_1 \mathrm{d}A_2 \qquad [16.19]$$

$$F_{12} \cdot A_1 = F_{21} \cdot A_2 \qquad [16.15]$$

som van de zichtfactoren van een oppervlak $\sum_{\mathrm{j}=1}^{\mathrm{j}=n} F_{\mathrm{ij}} = 1$ [16.16]

een door oppervlak 2 omsloten oppervlak 1 $F_{21} = \dfrac{A_1}{A_2}$ [16.17]

en $F_{22} = 1 - \dfrac{A_1}{A_2}$ [16.18]

netwerkmethode

netto warmtestroom van een oppervlak

$\Phi_{\mathrm{wi,netto}} = \dfrac{E_{\mathrm{z,i}} - J_{\mathrm{i}}}{R_{\mathrm{i}}}$ [16.27] met $R_{\mathrm{i}} = \dfrac{1 - \varepsilon_{\mathrm{i}}}{\varepsilon_{\mathrm{i}} \cdot A_{\mathrm{i}}}$ [16.28]

netto warmtestroom tussen twee oppervlakken

$\Phi_{\mathrm{wij,netto}} = \dfrac{J_{\mathrm{i}} - J_{\mathrm{j}}}{R_{\mathrm{ij}}}$ [16.29] met $R_{\mathrm{ij}} = \dfrac{1}{F_{\mathrm{ij}} \cdot A_{\mathrm{i}}}$ [16.30]