APPENDIX

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## APPENDIX 2

### LIST OF SYMBOLS

The following tables list the most important symbols used in the text, along with their meanings and their units. The last column of each table identifies the chapter in which the symbol was introduced.

Table S.1 Symbols using latin letters
Table S.2 Symbols using greek letters
Table S.3 Subscripts and superscripts

#### TABLE S.1: Symbols using latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Steffan-Boltzmann constant</td>
<td>$J \cdot m^{-3}K^{-4}$</td>
</tr>
<tr>
<td>$A$</td>
<td>Surface area, cross section</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$\dot{A}$</td>
<td>Rate of absorption of radiant energy per unit area</td>
<td>$W \cdot m^{-2}$</td>
</tr>
<tr>
<td>$a$</td>
<td>Absorptivity</td>
<td></td>
</tr>
<tr>
<td>$B$</td>
<td>Magnetic flux density</td>
<td>$T$</td>
</tr>
<tr>
<td>$c$</td>
<td>Speed of sound, speed of light</td>
<td>$m \cdot s^{-1}$</td>
</tr>
<tr>
<td>$c$, $c_V$</td>
<td>Specific temperature coefficient of energy</td>
<td>$J \cdot K^{-1}kg^{-1}$</td>
</tr>
<tr>
<td>$c_P$</td>
<td>Specific temperature coefficient of enthalpy</td>
<td>$J \cdot K^{-1}fg^{-1}$</td>
</tr>
<tr>
<td>$\tau_P$</td>
<td>Molar temperature coefficient of enthalpy</td>
<td>$J \cdot K^{-1}mole^{-1}$</td>
</tr>
<tr>
<td>$\tau_V$</td>
<td>Molar temperature coefficient of energy</td>
<td>$J \cdot K^{-1}mole^{-1}$</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Concentration</td>
<td>mole $\cdot m^{-3}$</td>
</tr>
<tr>
<td>$C$</td>
<td>Coulomb (unit of electrical charge)</td>
<td></td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitance (electrical)</td>
<td>$F$</td>
</tr>
<tr>
<td>$C$</td>
<td>Temperature coefficient of energy</td>
<td>$J \cdot K^{-1}$</td>
</tr>
<tr>
<td>$C$</td>
<td>Concentration ratio</td>
<td></td>
</tr>
<tr>
<td>$COP$</td>
<td>Coefficient of performance</td>
<td></td>
</tr>
<tr>
<td>$C_f$</td>
<td>Friction coefficient</td>
<td></td>
</tr>
<tr>
<td>$C_P$</td>
<td>Temperature coefficient of enthalpy</td>
<td>$J \cdot K^{-1}$</td>
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</tbody>
</table>
TABLE S.1: Symbols using latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_V$</td>
<td>Temperature coefficient of energy</td>
<td>J · K$^{-1}$</td>
</tr>
<tr>
<td>$C_V$</td>
<td>Hydraulic capacitance</td>
<td>m$^3$Pa$^{-1}$</td>
</tr>
<tr>
<td>$C'$</td>
<td>Momentum capacitance per length</td>
<td>kg · m$^{-3}$</td>
</tr>
<tr>
<td>$C^*$</td>
<td>Ratio of capacitance rates</td>
<td></td>
</tr>
<tr>
<td>$C_t$</td>
<td>Carnot (unit of heat—entropy)</td>
<td></td>
</tr>
<tr>
<td>$°C$</td>
<td>Degrees Celsius</td>
<td></td>
</tr>
<tr>
<td>$d_{ij}$</td>
<td>Components of the velocity gradient tensor (symmetric part)</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$D$</td>
<td>Diffusion constant</td>
<td>m$^2$s$^{-1}$</td>
</tr>
<tr>
<td>$e$</td>
<td>Specific energy</td>
<td>J · kg$^{-1}$</td>
</tr>
<tr>
<td>$\overline{\varepsilon}$</td>
<td>Molar energy</td>
<td>J · mole$^{-1}$</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy of system (energy content)</td>
<td>J</td>
</tr>
<tr>
<td>$E$</td>
<td>Young’s modulus</td>
<td>N · m$^{-2}$</td>
</tr>
<tr>
<td>$E_{chem}$</td>
<td>Energy exchanged (transported) in chemical process</td>
<td></td>
</tr>
<tr>
<td>$E_{el}$</td>
<td>Energy exchanged in electric process</td>
<td>J</td>
</tr>
<tr>
<td>$E_{mech}$</td>
<td>Energy exchanged in mechanical process</td>
<td>J</td>
</tr>
<tr>
<td>$E_{th}$</td>
<td>Energy exchanged in thermal process (heating and cooling)</td>
<td>J</td>
</tr>
<tr>
<td>$\mathbf{E}$</td>
<td>Electric flux density</td>
<td>V · m$^{-1}$</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Emissive power (rate of radiant energy emitted per unit area)</td>
<td>W · m$^{-2}$</td>
</tr>
<tr>
<td>$\varepsilon_b$</td>
<td>Emissive power of black body</td>
<td>W · m$^{-2}$</td>
</tr>
<tr>
<td>$f$</td>
<td>Degrees of freedom</td>
<td></td>
</tr>
<tr>
<td>$f_Q$</td>
<td>Specific source rate of quantity $Q$</td>
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</tr>
<tr>
<td>$F$</td>
<td>Force (flux of momentum)</td>
<td>N</td>
</tr>
<tr>
<td>$F_{12}$</td>
<td>Radiation shape factor</td>
<td></td>
</tr>
<tr>
<td>$F'$</td>
<td>Solar collector efficiency factor</td>
<td></td>
</tr>
<tr>
<td>$F_R$</td>
<td>Solar collector heat removal factor</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{F}$</td>
<td>Faraday’s constant</td>
<td>C · mole$^{-1}$</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational field strength</td>
<td>N · kg$^{-1}$</td>
</tr>
<tr>
<td>$G$</td>
<td>Gravitational constant</td>
<td>N · m$^2$kg$^{-2}$</td>
</tr>
<tr>
<td>$G$</td>
<td>Conductance</td>
<td></td>
</tr>
<tr>
<td>$G_E$</td>
<td>Energy conductance</td>
<td>W · K$^{-1}$</td>
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<tr>
<td>$G_S$</td>
<td>Entropy conductance</td>
<td>W · K$^{-2}$</td>
</tr>
<tr>
<td>$G_V$</td>
<td>Hydraulic conductance</td>
<td>m$^3$Pa$^{-1}$s$^{-1}$</td>
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<tr>
<td>$G$</td>
<td>Gibbs free energy</td>
<td>J</td>
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### TABLE S.1: Symbols using latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G$</td>
<td>Irradiance (rate of incident radiant energy per unit area)</td>
<td>W · m⁻²</td>
</tr>
<tr>
<td>$G_{sc}$</td>
<td>Solar constant</td>
<td>W · m⁻²</td>
</tr>
<tr>
<td>$h$</td>
<td>Height</td>
<td>m</td>
</tr>
<tr>
<td>$h$</td>
<td>Specific enthalpy</td>
<td>J/kg</td>
</tr>
<tr>
<td>$H$</td>
<td>Molar enthalpy</td>
<td>J · mole⁻¹</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck’s constant</td>
<td>J · s</td>
</tr>
<tr>
<td>$h$</td>
<td>Overall heat transfer coefficient with respect to energy</td>
<td>W · K⁻¹m⁻²</td>
</tr>
<tr>
<td>$h$</td>
<td>Convective heat transfer coefficient with respect to energy</td>
<td>W · K⁻¹m⁻²</td>
</tr>
<tr>
<td>$h_S$</td>
<td>Overall entropy transfer coefficient</td>
<td>W · K⁻²m⁻²</td>
</tr>
<tr>
<td>$H$</td>
<td>Enthalpy</td>
<td>J</td>
</tr>
<tr>
<td>$H$</td>
<td>Magnetic field strength</td>
<td>A · m⁻¹</td>
</tr>
<tr>
<td>$i_S$</td>
<td>Entropy intensity of radiation</td>
<td>W · K⁻¹m⁻²s⁻¹</td>
</tr>
<tr>
<td>$i_{SV}$</td>
<td>Spectral entropy intensity (with respect to frequency)</td>
<td>W · K⁻¹m⁻²s⁻¹sr⁻¹</td>
</tr>
<tr>
<td>$i_{SL}$</td>
<td>Spectral entropy intensity (with respect to wavelength)</td>
<td>W · K⁻¹m⁻²m⁻¹sr⁻¹</td>
</tr>
<tr>
<td>$i_E$</td>
<td>Energy intensity of radiation</td>
<td>W · m⁻²sr⁻¹</td>
</tr>
<tr>
<td>$i_{EV}$</td>
<td>Spectral energy intensity (with respect to frequency)</td>
<td>W · m⁻²s⁻¹sr⁻¹</td>
</tr>
<tr>
<td>$i_{EL}$</td>
<td>Spectral energy intensity (with respect to wavelength)</td>
<td>W · m⁻²m⁻¹sr⁻¹</td>
</tr>
<tr>
<td>$I$</td>
<td>Current; flux</td>
<td></td>
</tr>
<tr>
<td>$I_E$</td>
<td>Flux of energy</td>
<td>W</td>
</tr>
<tr>
<td>$I_L$</td>
<td>Flux of angular momentum</td>
<td>kg · m²s⁻²</td>
</tr>
<tr>
<td>$I_m$</td>
<td>Flux of gravitational mass</td>
<td>kg · s⁻¹</td>
</tr>
<tr>
<td>$I_{mag}$</td>
<td>Hertz magnetic current</td>
<td>A</td>
</tr>
<tr>
<td>$I_n$</td>
<td>Flux of amount of substance</td>
<td>mole · s⁻¹</td>
</tr>
<tr>
<td>$I_p$</td>
<td>Flux of momentum</td>
<td>N</td>
</tr>
<tr>
<td>$I_Q$</td>
<td>Flux of electrical charge</td>
<td>A</td>
</tr>
<tr>
<td>$I_S$</td>
<td>Flux of entropy</td>
<td>W · K⁻¹</td>
</tr>
<tr>
<td>$I_V$</td>
<td>Volume flux</td>
<td>m³s⁻¹</td>
</tr>
<tr>
<td>$J$</td>
<td>Joule (unit of energy)</td>
<td></td>
</tr>
<tr>
<td>$j$</td>
<td>Flux density</td>
<td></td>
</tr>
<tr>
<td>$j_E$</td>
<td>Energy flux density</td>
<td>W · m⁻²</td>
</tr>
</tbody>
</table>
### TABLE S.1: Symbols using latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
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<tbody>
<tr>
<td>$j_p$</td>
<td>Momentum flux density</td>
<td>$N \cdot m^{-2}$</td>
</tr>
<tr>
<td>$j_S$</td>
<td>Entropy flux density</td>
<td>$W \cdot K^{-1} \cdot m^{-2}$</td>
</tr>
<tr>
<td>$j_p$</td>
<td>Momentum current density tensor</td>
<td>$N \cdot m^{-2}$</td>
</tr>
<tr>
<td>$k$</td>
<td>Boltzmann’s constant</td>
<td>$J \cdot K^{-1}$</td>
</tr>
<tr>
<td>$k_E$</td>
<td>Thermal conductivity with respect to energy</td>
<td>$W \cdot K^{-1} \cdot m^{-1}$</td>
</tr>
<tr>
<td>$k_S$</td>
<td>Thermal conductivity with respect to entropy</td>
<td>$W \cdot K^{-2} \cdot m^{-1}$</td>
</tr>
<tr>
<td>$K$</td>
<td>Kelvin (unit of temperature)</td>
<td></td>
</tr>
<tr>
<td>$K$</td>
<td>See Greek letter kappa</td>
<td></td>
</tr>
<tr>
<td>$K_p$</td>
<td>Chemical equilibrium constant</td>
<td></td>
</tr>
<tr>
<td>$l$, $L$</td>
<td>Length</td>
<td>$m$</td>
</tr>
<tr>
<td>$l_f$, $l_v$</td>
<td>Specific entropy of fusion (vaporization)</td>
<td>$J \cdot K^{-1} \cdot kg^{-1}$</td>
</tr>
<tr>
<td>$l_f$, $l_v$</td>
<td>Molar latent entropy of fusion (vaporization)</td>
<td>$J \cdot K^{-1} \cdot mole^{-1}$</td>
</tr>
<tr>
<td>$L$</td>
<td>Electrical inductance</td>
<td>$H$</td>
</tr>
<tr>
<td>$L$</td>
<td>Luminosity of star</td>
<td>$W$</td>
</tr>
<tr>
<td>$L_V$</td>
<td>Hydraulic inductance</td>
<td>$Pa \cdot s^{-2} \cdot m^{3}$</td>
</tr>
<tr>
<td>$L'$</td>
<td>Momentum inductance per length</td>
<td>$N^{-1} \cdot m^{-2}$</td>
</tr>
<tr>
<td>$\mathcal{L}$</td>
<td>Loss of available power</td>
<td>$W$</td>
</tr>
<tr>
<td>$m$</td>
<td>Meter (unit of length)</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>Mass of a body</td>
<td>$kg$</td>
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<tr>
<td>$m_a$</td>
<td>Air mass</td>
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</tr>
<tr>
<td>mole</td>
<td>Unit of amount of substance</td>
<td></td>
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<tr>
<td>$M_0$</td>
<td>Molar mass</td>
<td>$kg \cdot mole^{-1}$</td>
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<tr>
<td>$n$</td>
<td>Amount of substance</td>
<td>$mole$</td>
</tr>
<tr>
<td>$n$</td>
<td>Unit normal vector on surface (directed outward)</td>
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<tr>
<td>$N_A$</td>
<td>Avogadro’s constant</td>
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<td>$N$</td>
<td>Newton (unit of momentum flux—force)</td>
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<td>$Nu$</td>
<td>Nusselt number</td>
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<tr>
<td>$NTU$</td>
<td>Number of transfer units</td>
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<tr>
<td>$p$</td>
<td>Momentum</td>
<td>$N \cdot s$</td>
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<td>Pressure</td>
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</tr>
<tr>
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<td>Power</td>
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<tr>
<td>$P_{av}$</td>
<td>Available power</td>
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<tr>
<td>$P_{diss}$</td>
<td>Rate of dissipation of energy</td>
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<tr>
<td>$Pa$</td>
<td>Pascal (unit of pressure)</td>
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</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number</td>
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<tr>
<td>$q$</td>
<td>Specific enthalpy of fusion</td>
<td>$J \cdot kg^{-1}$</td>
</tr>
</tbody>
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TABLE S.1: Symbols using latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( q_n )</td>
<td>Molar enthalpy of fusion</td>
<td>J · mole(^{-1} )</td>
</tr>
<tr>
<td>( Q )</td>
<td>Electrical charge</td>
<td>C</td>
</tr>
<tr>
<td>( Q )</td>
<td>Substancelike quantity</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( q )</td>
<td>Specific quantity</td>
<td>( \text{m} )</td>
</tr>
<tr>
<td>( r )</td>
<td>Radial variable</td>
<td>( \text{m} )</td>
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<tr>
<td>( r )</td>
<td>Specific enthalpy of vaporization</td>
<td>J · kg(^{-1} )</td>
</tr>
<tr>
<td>( r )</td>
<td>Specific rate of absorption of energy</td>
<td>W · kg(^{-1} )</td>
</tr>
<tr>
<td>( R )</td>
<td>Universal gas constant, ( 8.31 \text{ J/(K · mole)} )</td>
<td>J · K(^{-1} ) · mole(^{-1} )</td>
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<tr>
<td>( R )</td>
<td>Electrical resistance</td>
<td>( \Omega )</td>
</tr>
<tr>
<td>( R )</td>
<td>Radius</td>
<td>( \text{m} )</td>
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<tr>
<td>( Re )</td>
<td>Reynolds number</td>
<td>]</td>
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<tr>
<td>( R_E )</td>
<td>Thermal resistance with respect to energy</td>
<td>K · W(^{-1} )</td>
</tr>
<tr>
<td>( R_S )</td>
<td>Thermal resistance with respect to entropy</td>
<td>W(^{-1} ) · K(^2 )</td>
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<tr>
<td>( R_m )</td>
<td>Specific gas constant</td>
<td>J · K(^{-1} ) · kg(^{-1} )</td>
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<tr>
<td>( R_V )</td>
<td>Hydraulic resistance</td>
<td>Pa · s · m(^{-3} )</td>
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<tr>
<td>( s )</td>
<td>Second (unit of time)</td>
<td>( \text{s} )</td>
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<tr>
<td>( s )</td>
<td>Entropy per mass (specific entropy)</td>
<td>J · K(^{-1} ) · kg(^{-1} )</td>
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<tr>
<td>( \bar{s} )</td>
<td>Molar entropy</td>
<td>J · K(^{-1} ) · mole(^{-1} )</td>
</tr>
<tr>
<td>( S )</td>
<td>Entropy; entropy content of a body</td>
<td>J · K(^{-1} )</td>
</tr>
<tr>
<td>( S_e )</td>
<td>Entropy exchanged in a process</td>
<td>J · K(^{-1} )</td>
</tr>
<tr>
<td>( S_{gen} )</td>
<td>Amount of entropy produced in a system</td>
<td>J · K(^{-1} )</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>( \text{s} )</td>
</tr>
<tr>
<td>( T )</td>
<td>Ideal gas temperature, absolute temperature</td>
<td>K</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Conductive part of momentum current density tensor (stress tensor)</td>
<td>N · m(^{-2} )</td>
</tr>
<tr>
<td>( u )</td>
<td>Specific internal energy</td>
<td>J · kg(^{-1} )</td>
</tr>
<tr>
<td>( U )</td>
<td>Voltage</td>
<td>V</td>
</tr>
<tr>
<td>( U )</td>
<td>Internal energy</td>
<td>J</td>
</tr>
<tr>
<td>( U )</td>
<td>Overall heat transfer coefficient</td>
<td>W · K(^{-1} ) · m(^{-2} )</td>
</tr>
<tr>
<td>( U_{mag} )</td>
<td>Magnetic tension</td>
<td>V</td>
</tr>
<tr>
<td>( u )</td>
<td>Specific energy, internal energy per mass</td>
<td>J · kg(^{-1} )</td>
</tr>
<tr>
<td>( v )</td>
<td>Velocity</td>
<td>m · s(^{-1} )</td>
</tr>
<tr>
<td>( V )</td>
<td>Volume of a body</td>
<td>m(^3 )</td>
</tr>
<tr>
<td>( w )</td>
<td>Amount of precipitable water</td>
<td></td>
</tr>
</tbody>
</table>
### APPENDIX 2. LIST OF SYMBOLS

#### TABLE S.1: Symbols using Latin letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x$</td>
<td>Position variable</td>
<td>m</td>
</tr>
<tr>
<td>$x$</td>
<td>Quality</td>
<td></td>
</tr>
<tr>
<td>$y$</td>
<td>Mole fraction</td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical distance</td>
<td>m</td>
</tr>
<tr>
<td>$z$</td>
<td>Ionization number of atom</td>
<td></td>
</tr>
</tbody>
</table>

#### TABLE S.2: Symbols using Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Absorptivity (absorptance)</td>
<td>m²s⁻¹</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Peltier coefficient</td>
<td>J · K⁻¹ C⁻¹</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Thermal diffusivity</td>
<td></td>
</tr>
<tr>
<td>$\alpha_l$</td>
<td>Linear temperature coefficient of expansion</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>$\alpha_R$</td>
<td>Linear temperature coefficient of electrical resistance</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>$\alpha_V$</td>
<td>Temperature coefficient of expansion of volume</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>$\alpha_\mu$</td>
<td>Temperature coefficient of chemical potential</td>
<td>mole · K⁻¹</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Temperature coefficient of pressure</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>$\beta_E$</td>
<td>Scattering coefficient</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$\beta_\mu$</td>
<td>Pressure coefficient of chemical potential</td>
<td>mole · Pa⁻¹</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Adiabatic exponent, ratio of entropy capacities</td>
<td></td>
</tr>
<tr>
<td>$\gamma'$</td>
<td>Polytropic exponent</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Volume coefficient of thermal expansion</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Kronecker symbol</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Heat exchanger effectiveness</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Seebeck coefficient</td>
<td>V · K⁻¹</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>Carnot efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_\text{I}$</td>
<td>Thermal efficiency, first law efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_\text{II}$</td>
<td>Second law efficiency</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Celsius temperature</td>
<td>°C</td>
</tr>
</tbody>
</table>
### TABLE S.2: Symbols using Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>κ</td>
<td>Specific entropy capacitance</td>
<td>J · K−2kg−1</td>
</tr>
<tr>
<td>Κ</td>
<td>Molar entropy capacitance</td>
<td>J · K−2mole−1</td>
</tr>
<tr>
<td>κ</td>
<td>Bulk viscosity</td>
<td>Pa · s</td>
</tr>
<tr>
<td>κE</td>
<td>Absorption coefficient</td>
<td>m−1</td>
</tr>
<tr>
<td>κS</td>
<td>Adiabatic compressibility</td>
<td>Pa−1</td>
</tr>
<tr>
<td>κT</td>
<td>Isothermal compressibility</td>
<td>Pa−1</td>
</tr>
<tr>
<td>K</td>
<td>Entropy capacitance</td>
<td>J · K−2</td>
</tr>
<tr>
<td>K_V</td>
<td>Entropy capacitance at constant volume</td>
<td>J · K−2</td>
</tr>
<tr>
<td>K_P</td>
<td>Entropy capacitance at constant pressure</td>
<td>J · K−2</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength</td>
<td>m</td>
</tr>
<tr>
<td>λ_X</td>
<td>Lagrange multiplier for quantity X</td>
<td></td>
</tr>
<tr>
<td>Λ_V</td>
<td>Latent entropy with respect to volume</td>
<td>J · K−1m−3</td>
</tr>
<tr>
<td>Λ_P</td>
<td>Latent entropy with respect to pressure</td>
<td>J · K−1Pa−3</td>
</tr>
<tr>
<td>μ</td>
<td>Viscosity</td>
<td>Pa · s</td>
</tr>
<tr>
<td>μp</td>
<td>Chemical potential G = J · mole−1</td>
<td></td>
</tr>
<tr>
<td>μ</td>
<td>Attenuation coefficient</td>
<td>m−1</td>
</tr>
<tr>
<td>μ_o</td>
<td>Permeability constant</td>
<td>H · m−1</td>
</tr>
<tr>
<td>ν</td>
<td>Frequency</td>
<td>s−1</td>
</tr>
<tr>
<td>ν</td>
<td>Kinematic viscosity</td>
<td>m²s−1</td>
</tr>
<tr>
<td>ν</td>
<td>Stoichiometric coefficient</td>
<td></td>
</tr>
<tr>
<td>π</td>
<td>Volume density of rate of production</td>
<td></td>
</tr>
<tr>
<td>π_s</td>
<td>Volume density of rate of production of entropy</td>
<td>W · K−1m−3</td>
</tr>
<tr>
<td>Π</td>
<td>Rate of production</td>
<td></td>
</tr>
<tr>
<td>Π_n</td>
<td>Rate of production of amount of substance</td>
<td>mole · s−1</td>
</tr>
<tr>
<td>Π_s</td>
<td>Rate of production of entropy</td>
<td>W · K−1</td>
</tr>
<tr>
<td>ρ</td>
<td>Density (general)</td>
<td></td>
</tr>
<tr>
<td>ρ</td>
<td>Mass density of a body</td>
<td>kg · m−3</td>
</tr>
<tr>
<td>ρ_e</td>
<td>Reflectivity (reflectance)</td>
<td></td>
</tr>
<tr>
<td>ρ_E</td>
<td>Energy density</td>
<td>J · m−3</td>
</tr>
<tr>
<td>ρ_s</td>
<td>Density of entropy of body</td>
<td>J · K−1m−3</td>
</tr>
<tr>
<td>σ</td>
<td>Steffan-Boltzmann constant</td>
<td>W · m²K−4</td>
</tr>
<tr>
<td>σ</td>
<td>Volume density of source rate</td>
<td></td>
</tr>
<tr>
<td>σ_E</td>
<td>Volume density of source rate of energy</td>
<td>W · m−3</td>
</tr>
<tr>
<td>σ_s</td>
<td>Volume density of source rate of entropy</td>
<td>W · K−1m−3</td>
</tr>
<tr>
<td>Σ</td>
<td>Source rate</td>
<td></td>
</tr>
<tr>
<td>Σ_E</td>
<td>Source rate of energy</td>
<td>W</td>
</tr>
</tbody>
</table>
### TABLE S.2: Symbols using Greek letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>SI-units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Sigma_S$</td>
<td>Source rate of entropy</td>
<td>W·K$^{-1}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time constant</td>
<td>s</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Transmittance</td>
<td></td>
</tr>
<tr>
<td>$\tau$</td>
<td>Quantum of amount of substance</td>
<td>mole</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Relaxation time</td>
<td>s</td>
</tr>
<tr>
<td>$(\tau\alpha)$</td>
<td>Transmission-absorption product</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>Specific volume (inverse density)</td>
<td>m$^3$kg$^{-1}$</td>
</tr>
<tr>
<td>$\overline{\nu}$</td>
<td>Molar volume</td>
<td>m$^3$mole$^{-1}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>Potential</td>
<td></td>
</tr>
<tr>
<td>$\phi$</td>
<td>Relative humidity</td>
<td></td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Ohm (unit of electrical resistance)</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Humidity ratio</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE S.3: Subscripts and superscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Air</td>
</tr>
<tr>
<td>$a$</td>
<td>Ambient</td>
</tr>
<tr>
<td>$a$</td>
<td>average</td>
</tr>
<tr>
<td>$ad$</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>$av$</td>
<td>Available</td>
</tr>
<tr>
<td>$b$</td>
<td>Body</td>
</tr>
<tr>
<td>$b$</td>
<td>Beam</td>
</tr>
<tr>
<td>$b$</td>
<td>Blackbody</td>
</tr>
<tr>
<td>$c$</td>
<td>Carnot</td>
</tr>
<tr>
<td>$C$</td>
<td>Capacitive</td>
</tr>
<tr>
<td>$(c)$</td>
<td>Conductive (part of a) flux</td>
</tr>
<tr>
<td>$chem$</td>
<td>Chemical</td>
</tr>
<tr>
<td>$cond$</td>
<td>Conductive</td>
</tr>
<tr>
<td>$conv$</td>
<td>Convective</td>
</tr>
</tbody>
</table>
### TABLE S.3: Subscripts and superscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$, $diff$</td>
<td>Diffuse</td>
</tr>
<tr>
<td>$e$</td>
<td>Exchanged</td>
</tr>
<tr>
<td>$el$</td>
<td>Electrical</td>
</tr>
<tr>
<td>$eq$</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy, with respect to energy</td>
</tr>
<tr>
<td>$E$</td>
<td>Equilibrium</td>
</tr>
<tr>
<td>$EC$</td>
<td>Electro-chemical</td>
</tr>
<tr>
<td>$f$</td>
<td>Final</td>
</tr>
<tr>
<td>$f$</td>
<td>Fluid, solvent</td>
</tr>
<tr>
<td>$f$</td>
<td>Fusion</td>
</tr>
<tr>
<td>$f$</td>
<td>Formation</td>
</tr>
<tr>
<td>$g$</td>
<td>Gas, gaseous, vapor</td>
</tr>
<tr>
<td>$gen$</td>
<td>Generated</td>
</tr>
<tr>
<td>$grav$</td>
<td>Gravitation</td>
</tr>
<tr>
<td>$GC$</td>
<td>Gravito-chemical</td>
</tr>
<tr>
<td>$h$</td>
<td>Horizontal</td>
</tr>
<tr>
<td>$H$</td>
<td>High (high temperature, temperature of furnace...)</td>
</tr>
<tr>
<td>$hp$</td>
<td>Heat pump</td>
</tr>
<tr>
<td>$hydro$</td>
<td>Hydraulic</td>
</tr>
<tr>
<td>$i$</td>
<td>Initial</td>
</tr>
<tr>
<td>$in$</td>
<td>In, flowing inward</td>
</tr>
<tr>
<td>$kin$</td>
<td>Kinetic</td>
</tr>
<tr>
<td>$l$</td>
<td>Liquid</td>
</tr>
<tr>
<td>$l$</td>
<td>Linear</td>
</tr>
<tr>
<td>$L$</td>
<td>Angular momentum</td>
</tr>
<tr>
<td>$L$</td>
<td>Inductive</td>
</tr>
<tr>
<td>$L$</td>
<td>Low (low temperature, temperature of cooler...)</td>
</tr>
<tr>
<td>$m$</td>
<td>Mass</td>
</tr>
<tr>
<td>$m$</td>
<td>Mean</td>
</tr>
<tr>
<td>$mag$</td>
<td>Magnetic</td>
</tr>
<tr>
<td>$max$</td>
<td>Maximum</td>
</tr>
<tr>
<td>$mech$</td>
<td>Mechanical</td>
</tr>
<tr>
<td>$min$</td>
<td>Minimum</td>
</tr>
<tr>
<td>$net$</td>
<td>Sum, total (net current)</td>
</tr>
<tr>
<td>$o$, $0$</td>
<td>Reference point</td>
</tr>
<tr>
<td>$o$, $out$</td>
<td>Out, flowing outward</td>
</tr>
</tbody>
</table>
### TABLE S.3: Subscripts and superscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>Momentum, with respect to momentum</td>
</tr>
<tr>
<td>$p$</td>
<td>Absorber plate</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure, with respect to pressure, at constant pressure</td>
</tr>
<tr>
<td>$Q$</td>
<td>Charge</td>
</tr>
<tr>
<td>$Q$</td>
<td>With respect to quantity $Q$</td>
</tr>
<tr>
<td>$r$</td>
<td>Radiation</td>
</tr>
<tr>
<td>$rad$</td>
<td>Radiative</td>
</tr>
<tr>
<td>$refr$</td>
<td>Refrigerator</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistive, electrical resistance</td>
</tr>
<tr>
<td>$S$</td>
<td>Entropy, with respect to entropy</td>
</tr>
<tr>
<td>$s$</td>
<td>Surface</td>
</tr>
<tr>
<td>$s$</td>
<td>Sun, solar</td>
</tr>
<tr>
<td>$s$</td>
<td>Solid</td>
</tr>
<tr>
<td>$s$</td>
<td>Solute</td>
</tr>
<tr>
<td>$s$</td>
<td>Storage, store</td>
</tr>
<tr>
<td>$t$</td>
<td>Top</td>
</tr>
<tr>
<td>$th$</td>
<td>Thermal</td>
</tr>
<tr>
<td>$TE$</td>
<td>Thermo-electric</td>
</tr>
<tr>
<td>$v$</td>
<td>Vaporization, vapor</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume, hydraulic, with respect to volume, at constant volume</td>
</tr>
<tr>
<td>$wb$</td>
<td>Wet bulb</td>
</tr>
<tr>
<td>$x,y,z$</td>
<td>Spatial coordinates, with respect to spatial coordinate</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>With respect to wavelength</td>
</tr>
<tr>
<td>$\nu$</td>
<td>With respect to frequency</td>
</tr>
</tbody>
</table>
APPENDIX 3

GLOSSARY

The following short glossary is provided because the generalized version of thermodynamics presented in this book requires a generalization of and sometimes a change from usual terminology. Only the most important terms are included. Expressions in italics can be found elsewhere in the glossary.

**Amount of substance** Formal measure of an amount of substance as used in the sense of chemistry (the “number of moles”, the “number of particles”).

**Availability** The amount of energy that can be released (see release of energy) in the fall of entropy from points of high to points of low temperature. Quite generally, the amount of energy that can be released in the fall of a fluidlike quantity through a potential difference.

**Balance of energy** Application of the general law of balance to energy.

**Balance of entropy** Application of the general law of balance to entropy.

**Binding energy** Binding energy to the current of a fluidlike quantity which thereby is lifted from a lower to a higher potential. Same as using energy. Opposite of releasing energy.

**Caloric** Used as an alternative term for heat. The caloric theory of heat can be rendered formal and correct in a modern sense if it is accepted that caloric is not conserved (that it can be produced). In this case it turns out to be equivalent to the entropy of a body.

**Chemical driving force** The difference of the chemical potential.

**Chemical potential** The potential associated with processes which have to do with the change or the flow of amount of substance.

**Continuous processes** Processes which are spatially continuous, i.e. processes in which the variables change from point to point inside a body or a system.

**Constitutive relations** The laws which are not generic but differentiate between bodies and circumstances. (Generic laws see laws of balance)

**Current** Informal term for the phenomenon of the transport of a fluidlike quantity. Also used colloquially for the formal measure which is called flux.

**Current density** Formal measure of the local condition of a current. The flux is the surface integral of the current density. For a scalar fluidlike quantity, the current density is a vector.

**Density** Spatial density of a fluidlike quantity. The integral of the density of such a quantity over the volume of a system delivers the amount of the fluidlike quantity.
stored in the system.

**Dissipation rate** Rate at which energy is bound (see binding of energy) as the result of the production of entropy.

**Dissipative process** A process during which entropy has been produced, i.e. an irreversible process.

**Driving force** Informal term for the difference of a potential. The thermal driving force is the difference of the thermal potentials at two points in space, i.e. the difference of temperatures.

**Dynamics** A theory of dynamics requires the formulation of the laws of balance and the constitutive relations appropriate for a particular case. Models of dynamical processes rely upon the clear distinction between laws of balance and the constitutive relations.

**Energy** Quantity that accompanies all physical processes and takes the same role in all of them. Used to quantify the coupling of processes (releasing energy). Flows together with fluidlike quantities in conductive processes (energy carrier).

**Energy carrier** Fluidlike quantity (in conductive processes).

**Energy current** The amount of energy crossing the surface of a system in unit time as the result of a transport process. It must be distinguished from power.

**Entropy** Formal for a quantity of heat or caloric. Entropy is the fluidlike quantity of thermal processes and thus obeys a law of balance. It can be stored (see heat function), it can flow (entropy current), and it can be created (see production).

**Entropy current** Measure of the transfer of entropy across the surface of a system.

**Entropy production** The process of the production of entropy as the result of an irreversible process.

**Entropy production rate** The rate at which entropy is produced in an irreversible process.

**Exchanged quantity** The amount of a fluidlike quantity which has crossed the surface of a system together with a current in a certain interval of time. Formally equal to the integral of the flux over time.

**Extensive quantities** Quantities which scale with the size of a system are said to be extensive. The fluidlike quantities are a subset of the extensive quantities. An example of a non-fluidlike extensive quantity is provided by the volume.

**First law of thermodynamics** The law of balance of energy. It includes only rates of change of the energy content, energy currents, and energy source rates.

**Fluidlike quantities** Physical quantities which possess a density and a current density (and possibly source densities and production densities) are called fluidlike. Laws of balance can be written for them. They form a subset of the extensive quantities. The classical fluidlike quantities are momentum, angular momentum, entropy, charge, amount of substance, and (gravitational) mass.

**Flux** Formal measure of the amount of a fluidlike quantity crossing the surface of a system in unit time (informally, the same quantity is called a current). The flux is counted as positive for a current flowing out of the system.

**Flux density** The surface density of a flux. The surface integral of a flux density delivers the flux. Equivalent to current density.
Heat Informal term for entropy. Equivalent to caloric. (Commonly the energy exchanged in heating is called heat; this usage is not followed in this text.)

Heating The process of the transfer of heat (entropy) across the surface of a body excluding convective transports. The opposite process is cooling.

Heat capacity Used in the sense of entropy capacitance, i.e. as the derivative of the entropy function with respect to temperature. The usual “heat capacities” are called the temperature coefficients of energy and of enthalpy.

Heat function The formal expression of the assumption that a body contains a certain amount of heat, where the heat stored is a function of the independent variables describing the properties of the body. This heat function turns out to be equivalent to the entropy of the body.

Hotness The hotness manifold is the primitive concept for describing the ordering of bodies according to the sensation of how hot they are. The numerical measure of the hotness is the temperature.

Intensive quantities The quantities which remain the same if a body is divided into parts. A subset of the intensive quantities are the potentials.

Irreversible process A process which leads to the production of entropy.

Irreversibility Opposite of reversibility. The condition of irreversibility means that entropy is produced during a process.

Law of balance The formal relation which holds for the rate of change of the fluid-like quantity of a body and its currents (and possibly its source rates and production rates).

Level Informal term for potential. Levels are the conjugate quantities (conjugate with respect to energy) of the fluidlike quantities.

Minimization of entropy production Minimizing irreversibility is achieved by minimizing the rate of production of entropy.

Potential Formal term for the quantities which take the role of physical levels, otherwise known as the intensive quantities. There is a potential associated with each of the fluidlike quantities. The classical potentials are velocity (for momentum), angular velocity (for angular momentum), temperature (for entropy), the electrical potential (for charge), the chemical potential (for amount of substance), and the gravitational potential (for gravitational mass).

Potential difference Difference of potential at two points in space.

Power The rate of release of energy or the rate of binding of energy. Power is associated with an internal process as opposed to an external process (i.e. a transport process which is quantified by energy currents).

Power of heat Colloquial for the power associated with the fall of entropy from points of higher to points of lower temperature. This is Carnot’s puissance du feu. Integrating the power of heat over time delivers the availability.

Production Informal term for the phenomenon of production of a fluidlike quantity. A quantity which is produced can accumulate inside a system even without being transported into the system. Production (or destruction) is associated with nonconservation of a quantity.

Production rate Formal measure of the production of a fluidlike quantity. It describes
the amount of the quantity produced inside a system per unit time. A negative production rate means the quantity is destroyed.

**Production (rate) density** The spacial density of the production rate. Its volume integral delivers the production rate.

**Releasing energy** Release of energy when the current of a fluidlike quantity goes from higher to lower potential. Opposite of binding of energy.

**Reversibility** The condition of reversibility means that there is no entropy production during a process.

**Second law of thermodynamics** The law of balance of entropy. (Historically, it is not clear what to call the Second law of thermodynamics; in traditional thermodynamics, we find countless forms of the Second law. Here, the simplest and—for us—most useful choice has been made.)

**Source** Informal for processes as by which a fluidlike quantity is transferred into a system without having to cross the surface of the systems. This happens as the result of the interaction of bodies and fields.

**Source rate** Formal measure of a source of a fluidlike quantity. It determines the amount of the quantity delivered to the system per unit time.

**Source (rate) density** The spatial density of the source rate. Its volume integral delivers the source rate.

**Superconducting process** A transport process of a fluidlike quantity which does not require a driving force.

**Temperature** Measure of the hotness of a body. Temperature is like the coordinate on the hotness manifold. Temperature serves the role of the thermal potential.

**Temperature coefficient of energy** The derivative of the energy with respect to temperature at constant volume. Normally called heat capacity at constant volume.

**Temperature coefficient of enthalpy** The derivative of the enthalpy with respect to temperature at constant pressure. Normally called heat capacity at constant pressure.

**Thermostatics** Theories of thermostatics try to derive the conditions pertaining only to static thermal situations. Usually, these conditions are derived by maximizing or minimizing functions such as the entropy or the energy of a system.

**Uniform processes** Spatially uniform processes, i.e. processes in which variables of a system have the same value at every point at a given moment.

**Using energy** Same as binding of energy.
APPENDIX 4

ANSWERS TO QUESTIONS

CHAPTER 4

Note: If the term heat is used, it is used in the sense of entropy.

1. Different size bodies.
2. $T$ measures how warm an object is.
3. Thermal capacitance of the body of water $f$ must be higher than that of the piece of copper.
4. Temperature difference is driving force for flow, flow is in direction of decreasing $T$.
5. No, heat can also melt a body. No, we can compress air.
6. $T$ changes independently of changes of heat.
7. Heat can be produced or taken from the environment. For the body, it does not matter where heat comes from.
8. Energy for pumping heat (like pumping water). More energy is needed to pump additional heat.
9. Looks analogous to electricity ($P = UIQ = U^2/R$). We assume that the heat flow is proportional to $\Delta T$.
11. All processes except for the production of heat can be reversed.
12. No heat flow. Heat inside air has been compressed into smaller space.
13. Could change by more because of production of entropy.
14. The rate at which energy is needed to pumped the entropy (not equal to the rate at which energy is made available).
15. Thermal power is the same.
16. Thermal power: 1.0 W. Used inside the battery.
17. For an element of the bar, the thermal power is $\Delta T$ multiplied by the local entropy current.
18. 24 kg.
19. Ohm’s law and capacitive relation.
20. Hot water in the environment has a cooling curve analogous to the one found in discharging of a capacitor.
21. It freezes and boils. Its density has a maximum at 4°C.
22. Pressure of the ideal gas. Pressure is absolute, electric, gravitational potentials, and speed are not. (See also Question 9.)
23. In a voluntary process, energy is released. There is no other process than dissipation.
24. No.
25. Yes (example: expansion of air).
26. Upward to the right.
27. The gas has to be heated to keep its temperature.
28. Horizontal to the left. Entropy of system decreases. Entropy is communicated to environment.
29. Thermal energy currents are added.
30. Engine gets more efficient.
31. See Question 9.
33. 5000 W/K.
34. 0.5. 0.3/0.5 = 0.6.
35. Difference of thermal energy currents equals thermal power.
36. Since $P_{diss} = T\Pi_S$, the relevant temperature difference is $T - 0$.
37. 1.0 W/K. 1.0 W/K and 400 W.
38. 20 W/K.
39. They are equal.
40. It is defined as the useful (= thermal)
power divided by the energy current from the heater (rather than the useful power divided by the thermal power).

41. 10.

42. Loss of power is always positive, and it is proportional to the entropy production rate.

43. Otherwise, entropy production rates would be undetermined.

44. Entropy added to a material can also lead to changes of volume. Temperature can also change as a result of expansion or compression.

45. Linear measure $TS$ relation. Yes.

46. 7.7 J/(K·kg).

47. Zero.

48. 1400 J/K, 420 kJ.

49. Since $k = c/T$ with $c =$ const. Or it leads to Equ.(4.40) with $c =$ const.

50. Increases. Decreases.

51. It varies as the inverse of temperature. Take the derivative of Equ.(4.42) with respect to temperature.

52. Heating and cooling of simple bodies in an environment of constant temperature ($T$ behaves like $U$ of a capacitor).

53. Energy is released in the fall of entropy from high to low $T$; if there is no other obvious process, the energy is dissipated.

54. It increases by 100%.

55. A junction is not considered a storage element for entropy, so the steady-state balance applies.

56. The actual temperatures matter.

57. Because of entropy production.

58. Entropy would not flow (could neither enter nor leave the engine).

59. The fall of entropy through a part of the total temperature difference is assumed to be reversible. The model can be quite useful for real engines.

60. Entropy is absorbed and emitted at constant temperatures.

61. The transport of entropy with charge is assumed to be non-dissipative.

62. Entropy flows conductively from hot to cold, reducing the effect of pumping.

**CHAPTER 5**

1. Entropy of steam and water together decreases, entropy of environment increases.

2. Wax melts, absorbing entropy from the water without changing its temperature.

3. Only if the substance is not flowing into or out of the control volume.

4. Yes, phase change by itself is reversible.

5. The energy added is part of the change of the energy of the system; another part is related to the change of volume.

6. Roughly 550 J/(K·kg).

7. More entropy can be stored in a given volume. Phase change temperature should be in the range of temperatures required for hot water.

8. Because $T$ is constant (see Equ.(5.4)).

9. Both temperature and volume can change.

10. The entropy that leads to a volume change at constant $T$, per unit volume.

11. The entropy that leads to a change of temperature at constant $V$, per unit temperature.

12. Constant pressure heating.

13. It takes less entropy to change the temperature of air at constant volume.

14. Constant $p$ curve is less steep.

15. The entropy in the gas is compressed into a smaller volume. For a formal answer, see Equ.(5.39).


17. Isothermal compression give larger change of $V$ (entropy is emitted by the air).

18. The compression is close to adiabatic which makes the air hot. This in turn makes the pump hot: non-adiabatic phase of cooling of air.

19. When $dW/dt = 0$, we have $dT/dt = 0$. With $I_2 \neq 0$, the condition no longer holds.

20. Latent entropy with respect to volume is positive ($T > 4^\circ C$) or negative ($0^\circ C < T < 4^\circ C$). Adiabats have a minimum (Fig. 5.13).

21. The difference of the entropy capaci-
APPENDIX 4. ANSWERS TO QUESTIONS

22. Take values for O$_2$ and N$_2$: $c_V = 2.5R$, $c_P = 3.5R$. Adiabatic exponent: 1.4.
24. Entropy is exchanged between the dry part and the water vapor component.
25. Processes undergone by the materials modeled here are reversible.
26. $0 = TdS/dt – PdV/dt$.
27. $c_P/c_V = (T_κP)/(T_κV)$.
28. $ΔE = C_V(T_2 – T_1)$, $A_V = P/T$, and Equ.(5.66). Alternatively: $C_V$ is the temperature coefficient of energy, and the energy of the ideal gas only depends upon temperature.
29. Part of it is emitted to the environment as a consequence of expansion. Energy stored = energy absorbed – $PΔV$.
30. – 10 kJ.
31. Entropy is absorbed at temperatures lower than the highest one, and emitted at temperatures higher than the lowest one.

CHAPTER 6

1. Smaller amount of substance means smaller pressure.
2. More than twice as much H$_2$ than O$_2$, H$_2$ will be left over.
3. See Fig. 6.1 and interpretation given there.
4. Compare to two communicating containers containing fluids of different densities.
5. Energy is released by chemical reactions, used to pump electric charge. Batteries do not get fresh fuel.
6. First reaction emits entropy, second reaction takes entropy from its environment.
7. Chemical potentials of water and (saturated) vapor are equal.
8. Temperature of boiling point rises.
9. 18 g.
10. 0.091
11. 500 moles of H$_2$, 250 moles of O$_2$ gas, 500 moles of water.
12. 0.0060 mole/min, 0.46 g/min, – 0.184 g/min, 0.28 g/min.
13. 1.0·10$^{-6}$ mole/s.
14. Higher chemical potential in air (it will flow into water, since there is 4 times more toluene in water in equilibrium).
15. Changes of all chemical potentials have to be considered to find the chemical potential difference at higher $T$.
16. Driving force is negative potential difference. Compare to voltage in electricity.
17. The chemical potential difference of a transformation has to be equal to zero in equilibrium.
18. Boiling point is lowered. Chemical potential of air decreases.
19. Energy is released; energy is used. Charging a battery.
20. Chemical power in reactions would not be definite if potential were not absolute.
21. Substances A and B are destroyed and make energy available (according to their amounts); this energy is used by C (according to its amount).
22. Power equals difference of all energy currents going in and all energy currents going out.
23. Voltage across terminals drops. OC voltage is not affected (no reactions).
24. Entropy is emitted, entropy is absorbed.
25. Yes, entropy of products must be smaller than entropy of reactants.
26. Entropy of products must be smaller than entropy of reactants.
27. Substance and charge must be directly coupled.
28. Gravitochemical potential is constant.
29. Logarithmic dependence.
30. Chemical potential of CO$_2$ is smaller in water (having no CO$_2$). Use chemical equilibrium.
31. Depends upon its molar fraction.
32. Diffusion.
33. Pressure and chemical potential of the liquid are lowered.
34. Salt dissociates into two ions.
35. The chemical potential of the liquid is lowered; at the original boiling point,
APPENDIX 4. ANSWERS TO QUESTIONS

vapor condenses. Effect of change of $\mu$ is larger for salt.
36. For given driving force ($\Delta \mu$), the current depends upon how much substance there is to be transported.
37. Smaller than 1?
38. The net flux becomes zero.
39. $\mu$ of water is proportional to its pressure.
40. There is always solute in the cells. The difference of water pressure (osmotic pressure) does not go to zero.
41. Both phenomena are caused by the respective chemical potential difference which takes the same form. Equ.(6.75) and Equ.(6.88).
42. Third order (quadratic in the concentration of hydrogen, linear in the concentration of oxygen).
43. Exponential decaying to zero.
44. Concentration of B remains (almost) constant.
45. The chemical driving force is logarithmic but the concentrations are exponentials as functions of time.
46. Product concentration is small. Product concentration is large. Concentrations of products and reactants are comparable. Transfer of a substance between identical environment.
47. – 1415 J/mole.

CHAPTER 7

1. Temperature difference. Pressure difference.
2. No. Specific entropy of water remaining in tank stays constant.
3. Current of entropy: distributed over a surface; entropy source rate: distributed over a volume.
4. In the former case, entropy is not produced, it is only transported.
5. Yes, and yes.
6. 25 W/K.
7. Because of entropy production.
8. For the second material: slower reaction to changes.
9. No.
10. Convective mixing.
11. Different temperatures, different (thickness of) boundary layer.
12. It increases in thickness. Temperature decreasing toward the plate.
13. With 10 cm thickness, neglecting convection would lead to an error of about 20%.
14. Transfer resistances from water to metal and through metal are very small.
15. The expression for conduction contains the thickness of the layer, the expression for convection does not.
16. Radiation flows in different directions at a point in space. Emission and absorption are volumetric processes.
17. Radiation is more like convection (depends upon storage density of entropy). Yes.
18. The current of entropy away from the body is larger than the source (sink) rate in the body (by a factor 4/3).
19. 20
20. 19 of 20 units of what flows away are produced.
21. Yes, the temperature is still the same (see Equ.(7.33) and Equ.(7.34)).
22. In parallel.
23. Not for a gray surface. Yes, for a selective surface.
24. Yes (Table 7.3).

CHAPTER 8

1. Specific entropy does not change. Specific entropy is reduced.
2. Its speed.
3. Pressure (and possibly speed and gravitational potential) also factors in.
5. They are equal if the volume of the substance cannot change.
6. First, $T_1$ will decrease, $T_2$ will stay constant. Later, $T_1$ will stay constant and $T_2$ will increase.
7. Different phenomena (pushing fluid versus compressing it).
8. The effect mentioned here does not
necessarily lead to motion of the center of mass.
9. Specific quantities refer to a part of the fluid—we move with the fluid.
10. Pressure does not change.
11. They can be changed if the temperature changes with pressure.
12. Use the temperature coefficient of the chemical potential at standard conditions, and add the entropy related to the temperature change.
13. Entropy transfer is reversible too (the fluid receives entropy at the proper temperature everywhere). In our model, dissipation is due to the fact that we treat the fluid as uniform.
14. Equ.(8.70): fluid flowing in is at the same pressure as fluid already present.
15. Relaxation of pressure: energy is released and dissipated. Second term in Equ.(8.74).
16. Liquid flows in through a throttle.
17. The fluid in the tank gets hotter every day: collector losses increase.
18. With stratified water, cooler water returns to collector, making the collector more efficient. Mixing leads to higher losses in the collector.

**Chapter 9**

1. Entropy that is produced has to be emitted to the environment and takes energy with it.
2. Only if there is a single constant temperature of the environment that receives the rejected entropy.
3. In fuel cells, the reactions run without entropy production (theoretically).
4. Yes. They use entropy that is already available in the environment.
5. Higher losses means more entropy production.
6. The cyclic operation of the fluid in the engine works reversibly. The fluid undergoes heating and cooling at constant temperatures.
7. Entropy needs temperature differences to flow into and out of the engine.
8. \( \eta_{CA} = 29\% \).
9. Flow speed increases which makes the heat transfer from absorber to fluid more efficient.
10. Yes.

**Chapter 13**

1. (a) Entropy density; (b) entropy current density; (c) entropy production density.
2. Introduce a negative sign in the surface integral (Equ.(13.5)).
3. Because of entropy production.
4. Sources: entropy flows from somewhere else.
5. Three. For (a) entropy density, (b) entropy current density, (c) entropy production rate density.
6. Entropy flows in the direction of decreasing temperature.
7. Yes; introduce Fourier’s law.
8. \( k_E \) has to be constant.
9. Equilibrium relations: no flows as independent variables (only \( T, P \) ...).
10. Example: energy released in a flow of entropy through a temperature difference is used to drive a flow (dissipation) and to change the flow (inertia).
11. So that the entropy production rate will certainly be positive or zero.
12. Use Peltier element between two bodies of water at equal temperatures. Measure rates of change of \( T \) in terms of \( I_Q \).
13. Charged particles flow through different materials.
14. A combination of electro-chemical potential with temperature (Equ.(13.70)).
15. Non-dissipative transport of charge and entropy; dissipative conduction.
16. Transport of entropy with charge in one direction; conduction in the other direction. Coupled transport has to be stronger than conduction.
17. Two sources of irreversibility: conduction of entropy and of charge.
18. \( j_Q dT/dx \) can be positive or negative, so these terms must represent non-dissipative processes. Dissipation means entropy production.
CHAPTER 14

1. Divide Eq.(14.1) by $T_s$.
2. Equations for developed flow.
3. Two pressure terms (including longitudinal friction), two shear friction terms.
4. For given geometry, flow behavior depends on the dimensionless groups only.
5. Difference between incoming and outgoing radiative fluxes. See Answer to Question 17., Chapter 7.
6. Steady-state and no loss from fluid to environment.
7. Yes.
8. The collector’s capacitance is much smaller than that of the storage element.
9. Eq.(14.26) includes $T_{f,in}$ which is the temperature of the water in the tank. In Eq.(14.26), the spatial temperature variation is treated properly.
10. Entropy transfer through $\Delta T$. Ideal: no entropy loss to the environment.
11. Increase NTU.
12. Average $\Delta T$ is smaller.
13. Two counteracting effects are needed.

CHAPTER 15

1. All of entropy, not all of the energy.
2. They are equal.
3. Along horizontal (constant $T$) lines in the liquid-vapor area.
4. Eq.(15.15).
5. Smaller ($\mu$ because of $\phi < 1$, equal $h$).
6. Molar mass of moist air is lower ($M_0$ of water is low). Moist air rises.
7. Equal temperatures, ideal gas model.
8. The stream of air has to remain in the adiabatic saturator long enough.
9. Evaporation as diffusive (conductive) transport of vapor through air: see conduction of charge or entropy.
11. Transform the argument of the logarithm in Eq.(15.43).
14. No dissipation between plant and environment. This is violated noticeably in the condenser.
15. From the values pertaining to saturated liquid and saturated vapor.
16. It separates mixtures if liquid and vapor from liquid or vapor.
17. It remains constant.
18. Specific entropy $s$ is constant, so $\mu$ increases with pressure, see Eq.(15.53).
19. The volume is independent of temperature (Equations (15.55) and (15.56)).
20. Saturated vapor will partly condense.
21. Entropy is produced in the valve.

CHAPTER 16

1. Radiant power: solar constant multiplied by surface of sphere surrounding Sun having radius equal to Sun-Earth distance. Temperature from black-body radiation law.
2. Surface temperature from Fig. 16.1, use black-body radiation law.
3. Above the Earth’s atmosphere.
4. Distance of air crossed by Sun’s rays if the Sun is vertically above us.
5. Constant attenuation coefficient.
6. Treat radiation as a thermal system and use basic thermodynamic relations (Part III).
7. Temperature gives us the incoming entropy and energy, allows calculation of dissipation.
9. Temperature will be higher than that of the environment.
10. This effect does not have anything to do with reflectance and emittance. Losses and dissipation are temperature dependent.
11. $T$ of imperfect emitter is higher, entropy production rate is lower.
CHAPTER 1

1. \( \frac{dV}{dt} = -0.010 \text{ m}^3/\text{s} \). (a) \( V_3 = 0.0125 \text{ m}^3/\text{s} - 10^{-4} \text{ m}^3/\text{s}^2 \cdot t \). (b) 0.10 m3.
2. 
3. 
4. \( CV = A/(2 \cdot \rho \cdot g) \)
5. (a) \( IV = 4.81 \cdot 10^{-6} \text{ m}^3/\text{s} \). (b) \( PA = 1.0 \) bar, \( PB = 1.0078 \) bar, \( PC = 1.027 \) bar, \( PD = 1.0 \) bar. (c) Exponential functions approaching \( h = 0.20 \) m with a time constant of 208 s.
6. 
7. (a) Two tanks connected by pipe, additional pipe for outflow, valves for each pipe. (c) \( dV_1(t)/dt = -IV_1 \), INIT \( V_1 = \frac{C_1 \cdot p_{1, init}}{C_1 + C_2} \), \( dV_2(t)/dt = IV_1 - IV_2 \), INIT \( V_2 = \frac{C_2 \cdot p_{2, init}}{C_1 + C_2} \), \( IV_1 = \frac{\Delta p_R_1}{R_1} \), \( IV_2 = IF \) (TIME > 50) THEN \( \Delta p_{R, 1}/R_1, \Delta p_{R, 2} = IF \) (TIME > 50) ELSE 0. (d) \( UC_2 \) mirrors the \( UC_1 \), time constant of 6.0 s. (e) 1.5 \cdot 10^{-4} \text{ F} . (f) 100 \text{ k}\Omega . (g) \( IV_1 = 0 \text{ A}, IV_2 = 2.0 \cdot 10^{-5} \text{ A}, dUC_1/dt = 0 \text{ V/s}, dUC_2/dt = -0.133 \text{ V/s}. \)
8. 
9. (b) \( dM/dt = P - V, dP/dt = \text{Diff}/L \), Diff = E – M; First equation: Law of balance. Second equation: analogous to law of induction. Diff: analogous to pressure difference. Unit (dimension) of L: time squared. (e) Undamped Oscillation, Period = \( 2\pi \sqrt{L} \).
10. (a) \( IL \) starts at 0, \( IC \) becomes negative.

CHAPTER 2

1. \( P_{\text{Pump}} = 3.02 \text{ kW} \).
2. (b) \( Vf^2/(2CV) \). Energy is stored in the system.
3. 
4. 
5. (a) \( UF = U_1 i/(C_1 i + C_2) \), \( Q1f = U_1 i/C_1^2/(C_1 i + C_2) \), \( Q2f = U_1 i/(C_1 i + C_2) \). (b) No. (c) Two communicating tanks, energy loss because of friction when water flows.
6. (a) \( IQ(t) = -[U_B/R \cdot \exp(-t/\tau)] \). (b) \( PB = -0.86 \) W, \( PR = 0.44 \) W, \( PC = 0.42 \) W. (d) \( I_{E_{BC}} = 0.86 \) W, \( I_{E_{CR}} = 0.44 \) W. (e) 0.42 W. (f) Depends upon emission of heat.
7. 
8. (a) 1.25 \cdot 10^{14} \text{ J} . (b) 8.75 \cdot 10^{14} \text{ J} . (c) 40 MW, 30 MW. (d) 8.75 \cdot 10^{14} \text{ J} . (e) 4 \cdot 10^{15} \text{ J} \) (in Switzerland).
9. 
10. (a) 62.5 \cdot 10^{9} \text{ J} . (b) 0.20 m/s.
11. (a) 1.25 \cdot 10^{14} \text{ J} . (b) 0.13 \text{ J} . (c) 0.13 \text{ J} . (d) \( E_{\text{diss}} = 0.050 \text{ J} \). (e) 1.34 s \leq t \leq 1.45 s, 0.065 J.
12. 

CHAPTER 3

1. 
2. 
4. \( djp/dx = \rho \cdot g \cdot jp(x) = \rho \cdot g \cdot (-L + x) \).
5. 
6. (a) Larger change of speed belongs to smaller glider. (b) 3.1 \cdot 10^{-3} \text{ } . (c) 0.419 \text{ N} . (d) Radiative (source rate).
7. 

APPENDIX 5. SOME SOLUTIONS OF END OF CHAPTER PROBLEMS
8. (a) $10^6$ N/m. (b) 0.314 s. (c) Shortening of spring damping force points in the direction of force of spring. Stretching of spring: damping force points opposite to force of spring. This explains the jump of the acceleration of the car at about 1.04 s. $10^5$ N.

9. (a) 0.944 N, – 3.78 N. (b) 77.7 N, – 17.66 N.

10. – 4.21 N.

11. (a) $\frac{\Delta r \cdot \tau}{2 \pi r^3 l \omega}$. 

12. $L_p = \frac{1}{D}$ (D: spring constant). Omega $= \sqrt{C_p L_p} = \sqrt{\frac{D}{m}}$.

13. (a) Mass is changing. (b) 18 9 m/s$^2$, 54.2 m/s$^2$. (c) 1280 m/s.

14. $\frac{1}{2} D \cdot \text{stretching}^2$.

15. (a) Absorbed: 2250 J/K, emitted: 3000 J/K. (b) – 750 J/K. (c) – 750 J/K.

16. (a) – 70 W/K + 5.0 W/(K s). (b) – 1000 W/K. (c) – 400 J/K.

17. (b) Entropy is produced, so more entropy and energy are emitted to the environment.

18. (a) 2.04 W/K. (b) 2.27 W/K.

19. (a) $\frac{dS}{dt} = IS_{in}$. (b) $\frac{dS}{dt} = \Pi_{S}$.

20. 0.055 W/K.

21. 1.4·10$^{-8}$ W/K.

22. (b) 3.33·10$^{-6}$ W/K. (c) 5.56·10$^{-6}$ W/K. (d) 2.22·10$^{-6}$ W/K. (e) 7.78·10$^{-6}$ W/K.

23. (b) 444 W/K. (c) 267 kW. (d) 444 W/K, 133 kW. (e) 300 kW. (f) 556 W/K.

24. (a) 1.02 W/K. (b) 281 W. (c) 0.38.

25. (a) 0.625 W/K. (b) 147 W. (c) Entropy is produced because of entropy transfer in the insulation of the freezer, and in the heat exchangers of the heat pump. (d) 0.171 W/K.

26. 0.055 W/K.

27. B is better by a factor of 4.

28. (a) 0.135 W/K. (b) 103 J/K.

29. 940 J/K and 345 kJ.

30. 1/2·K·(Tf$^2$ – Ti$^2$).

31. 60.7 MJ.

32. 1190 J/(K·kg), 0.175 W/(K·m). Entropy related values: 4.0 J/(K$^2$·kg), 5.8·10$^{-4}$ W/(K$^2$·m).

33. (a) 36 kJ/K$^2$ and 10.8 MJ/K. (b) 10.1 W/K. (c) 101 W. (d) 371 W.

34. (a) 1200 W/(K·m$^2$). (b) – 100 kJ and 100 kJ. (c) 1.0·10$^{-3}$ W/K$^2$.

35. 5.8·10$^{-4}$ W/(K$^2$·m).

36. (a) 371 W. (b) Yes, because of entropy transfer. (c) 2.0 W/K. (d) $dT_1/dt = -0.0286 K/s$, $dT_2/dt = 0.0429 K/s$, $dT_3/dt = -0.0143 K/s$. (f) Final temperature: 50 °C, time constants of the order of 1000 s.

37. (b) roc$_P$ = T_diff/tA. (d) $dP/dt + (TH-TC)/tA$.

38. (a) 1200 W/(K·m$^2$). (b) 1.0·10$^{-3}$ W/K$^2$.

39. (a) $10^6$ N/m. (b) 0.314 s. (c) Shortening of spring damping force points in the direction of force of spring. Stretching of spring: damping force points opposite to force of spring. This explains the jump of the acceleration of the car at about 1.04 s. $10^5$ N.

40. (a) $\frac{dS}{dt} = IS_{in}$. (b) $\frac{dS}{dt} = \Pi_{S}$.

41. (a) $\frac{dS}{dt} = IS_{in}$. (b) $\frac{dS}{dt} = IS_{out}$. (c) $\frac{dS}{dt} = IS_{prod} - SE_{out}$.

42. $\frac{dS}{dt} = \Pi_{S}$. (f) $\frac{dS}{dt} = -IS_{1}$. (g) $\frac{dS}{dt} = IS_{cont}/dt = +IS_{2} - IS_{3}$, $IS_{2} > IS_{1}$. (h) $\frac{dS}{dt} = IS_{out}$.

43. $IS_{net} = 100 W/K$. $\frac{dS}{dt} = 100 W/K$. 

44. (b) $r_0 = T_{diff}/tA$. (d) $dP/dt + (TH-TC)/tA$. (e) 1.25 s. (f) Like charging of a capacitor, final
APPENDIX 5. SOME SOLUTIONS OF END OF CHAPTER PROBLEMS

APPENDIX

**CHAPTER 5**

1. (a) \( \frac{IE_{th}}{dn/dt} / T \) (b) 1230 J/(K·kg).
2.
3. (a) 7.0 g/s. (b) 3 g/s.
4. (a) 0.822 W/K. (b) – 1.15 · 10^-4 kg/s.
   (c) – 0.108 W/K. (d) 6210 J/(K·kg).
5. 946 m^3.
6. 0.0405 m.
7. (a) – 1.73 kJ. (b) \( S_e = -5.77 J/K \).
8. \( f = 2 \pi \cdot \text{SQRT} \left( \gamma \cdot \text{P} \cdot \text{A}^2 / (m \cdot \text{V}) \right) \).
9. (a, b) 0.90 – CV/T. Entropy is injected into the gaseous component when the temperature decreases.
10. \( \rho = b \cdot T^n (n = 1/(\gamma - 1)); P = B \cdot \rho^n (1+1/n) \).
11. \( E_{comp} = CV \cdot (T_f - T_i) \).
12.
13. (b) \( \gamma = (P_i - P_0) / (P_f - P_0) \). (c) Energy of the gas is the same if the temperature is the same.
14. (a) Change of volume; – 50 kJ. (b) Heating; + 50 kJ. (c) Only energy exchanged in heating can be shown.
15. \( \Delta E = \text{T} \cdot \Delta S - P \cdot (V_{gas} - V_{liquid}); 2.09 \) kJ. (See also Table 15.1.)
16. 2°C: \( dE/dt < 0 \). 20°C: \( IE_{mech} < 0 \); \( IE_{th} > 0 \); cannot be decided on the basis of what we know at this point.
17. (a) 4.92 MJ. (b) 10^6 Pa. (c) \( IE_{mech} = -nRT / (V_1 + nV/dV/dt) \cdot dV/dt, dV/dt = -1.93 m^3/s, V_1 = 21.4 m^3 \).
18. 154.3 J/(K·mole).
19. 20.
20. 8°C.
21. 22.
22. No heating, no friction. \( dS/dt = 0 \). \( dE/dt = IE_{comp} = -P \cdot dV/dt. \) Energy decreases.
23.
24.
25.
26. Function shifts to the left.
27. All the entropy stays in the body; \( \Delta E / E_{th} = 1/\gamma \).
28.
29. (a) 39.7 mole; 1.15 kg. (b) 3.47 · 10^-4 W/K. (c) 2.87 J/K^2; 4.01 J/K^2. (d) 8.65 · 10^-5 K/s.
30. (a) – 2.14 kJ. (b) 5.36 J.
31. (a) 2.9 mm. (b) 37.5 mJ.
32.
33. P = 5 · 10^14 Pa, T = 2 · 10^7 K, \( \rho = 4 \cdot 10^13 \) Pa = 0.08 P.
34. (a) Entropy of universe turns out to be constant. (b) \( l = 10^4 \). (c) \( (P(t)/R_0) = \rho_{rad,0}/\rho_{matter,0} \cdot \rho_{matter}/\rho_{rad} \). \( \rho_{rad,0}/\rho_{matter,0} \) could be comparable at a size \( 10^4 \) times smaller than today.
35. (a) \( V \cdot T^3 = V_0 \cdot T_0^3, \gamma = 4/3 \). (b) \( E_{th, isothermal} = 4/3 \cdot a \cdot T^4 \cdot \Delta V, \) \( E_{mech, isothermal} = -1/3 \cdot a \cdot T^4 \cdot \Delta V; \) \( \Delta E = a \cdot T^4 \cdot \Delta V \).
36. (b) P = 2/3 · \rho_E. (c) CV = 3/2 · n · R.
37. Statics: computation of equilibrium states. Dynamics: requires “equations of motion,” i.e., combinations of the balance of entropy in dynamical form and constitutive relations.

**CHAPTER 6**

1. – 1.3 mole/min (consumption).
2.
3. – 394.4 kG.
4.
6.
7. (a) 1.7. (b) – 1320 G.
8. (a) CH4 + 2O2 \( \rightarrow \) Co2 + 2H2O. (b) \( 2744.5 J/(K·mole) \). (c) – 242.64 J/(K·mole). (d) – 2987 J/(K·mole) (emit-
APPENDIX 5

THE DYNAMICS OF HEAT

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CHAPTER 7

1. (a) 1.0 W/K. (b) dS/dt ≥ 1.0 W/K. (c) – 1.0 W/K; no (conductive) fluxes.
2. (a) – 400 K/m. (b) jS = 800 W/(K·m^2); jE = 3.2·10^5 W/m^2, kE = 800 W/(K·m). (c) – 0.80 W/K.
3. 203 W. The energy current decreases when a mineral deposit builds up.
4.
5. (a) 18.1 kW. (b) 9.6 m.
6. (a) 463 K. (b) 334 K.
7.
8. T_Sirius = 9100 K.
9. (a) 4.1·10^4 W/K. (b) 2.8·10^4 W/K. (c) 3.8·10^4 W/K. (d) 5.17·10^4 W/K.
10. (a) 120 W. (b) C_dT/dt = alpha·G_Sun – A·h(T – Ta) – A·σ(T^4 – Ta^4) – ef-
ficiency·G_Sun. (c) 0.56 K/s. (d) 331.4 K. (e) P_el_final = 78 W.
11.
12. h(300 K) = 5 W/(K·m^2), h(500 K) = 11 W/(K·m^2), h(800 K) = 32 W/(K·m^2).
13. 105 min.
14. 1.3 days.
15. (a) 4.85·10^4 s. (b) 2.09 W/K. (c) 0.78·10^5 W/K. (d) 22.7 MJ.
16. (a) 250 W/K. (b) 9.7·10^7 J/K. (c) 30 kW.
17.

CHAPTER 8

1. (a) 121 kW. (b) 73.5 kW. (c) 23.4 kNm.
2.
3. 2800 K.
4.
5. (a) Viscosity changes with tempera-
ture, and there is a current of substance due to evaporation. (b) dm/dt = – Im,pipe – Im,evaporation.
6.
7.
8. (a) 300 K, 6425 W/K. (b) 344.4 K, 6760 W/K. (c) 300 K, 9310 W/K.
10.

**CHAPTER 9**

1. Minimum entropy production rate at a radius of 0.040 m.
2. Loss of energy from the pipe and pumping power do not add up to the loss of available power.
3. (a) $2.0 \times 10^4$ W/K. (b) 815 MW. (c) $1.776 \times 10^6$ W/K. 5.33 $\times 10^8$ W; yes.
4. Add the additional heat exchanger surface at the cold end.
5. (a) $\pi = IE/TH – hA \cdot (2 – TL/TH – TH/TL)$. (b) 482 K. (c) 514 K; two sinks for entropy at different temperatures.
6. Balance of losses due to friction and to heat loss. (b) $Dt_{opt}^2 = 1/T \cdot RV \cdot V/\rho \cdot \beta / (T – Ta)^2$.
7. (a) $\gamma = 1 + aV^2 \cdot c^2 / \kappa P$; (b) $\beta = 1/p \cdot \alpha V^2 / \kappa P + 1/c^2$; (c) $\Lambda V = \rho \cdot \alpha V c^2 / (\kappa P + \alpha V^2 c^2)$; where $\alpha V = – 1/p \cdot \partial p / \partial T$ is the temperature coefficient of expansion.
8. (a) $7.68 \times 10^4$ W/m$^2$. (b) 603 W. (c) 110 W/(K m$^3$) and 206 W/(K m$^3$). (d) 0.59 W/K.
9.
10.

**CHAPTER 10**

1. (a) $2.0 \times 10^4$ W/(m$^2$-sr). (b) 5770 K; temperature of sunlight at the distance of the Earth is equal to the surface temperature of the Sun. (c) $i_{Eb} = 3/4 \cdot T \cdot i_{Sb}$; $i_{Sb} = 4.6 \times 10^3$ W/(K m$^2$-sr); 0.32 W/(K m$^2$).
2. (b) Sun: $6.3 \times 10^7$ W/m$^2$; oven: $6.4 \times 10^3$ W/m$^2$.
3. $F_{21} = A_1/A_2 \cdot F_{12}$.
4. $IE = \sigma / R_{total} \cdot (T_1^4 – T_2^4)$; $R_{total} = 958$ 1/m$^2$.
5. (a) $\kappa E = – 1/\Delta x \cdot \Delta iE / iE$. (b) $\Delta iE/dx = – \mu E$, where $\mu = \kappa E + \beta E$. (c) 3.5 $\times 10^4$ /m.
6. $l_{mean} = 0.06$ m; $\kappa \rho = 0.01$ m$^2$/kg.
7. (a) $y = 1/x^5 \cdot 1/(\exp(1/x) – 1)$. (b) 501 nm.
8. (a) 2330 K. (b) The new entropy of radiation is 2.7 times the old entropy.
9.
10.

**CHAPTER 11**

1. Both processes lead to source rate densities. In the case of production, the quantity appearing in a system is not coming from a different system.
2. (a) $\partial p / \partial t – k \cdot \partial^2 p / \partial x^2 = 0$. (b) $\partial^2 p / \partial x^2 = 0$, $\rho(x) = a + b \cdot x$, two boundary conditions are needed.
3. (a) $\partial p f / \partial t = pf f(t, x)$, $pf = net production – destruction rate, \rho f = density of food$.
4. No; convection is implicitly in the form using the material derivative.
5. Coordinate independent form for a scalar function $f$: $Df/Dt = df/dx + v \cdot grad(f)$; $v$ and grad(f) are vectors, the product is the scalar product.
6. (a) $\gamma = 1 + \alpha V^2 \cdot c^2 / \kappa P$; (b) $\beta = 1/\rho \cdot \alpha V^2 / \kappa P + 1/c^2$; (c) $\Lambda V = \rho \cdot \alpha V c^2 / (\kappa P + \alpha V^2 c^2)$; where $\alpha V = – 1/\rho \cdot \partial \rho / \partial T$ is the temperature coefficient of expansion.
7. (a) $\gamma = 1/x^5 \cdot 1/(\exp(1/x) – 1)$. (b) 501 nm.
8. (a) 2330 K. (b) The new entropy of radiation is 2.7 times the old entropy.
9.
10.

**CHAPTER 12**

1. (a) $2.0 \times 10^3$ W/(m$^2$-sr). (b) 6377 K; temperature of sunlight at the distance of the Earth is equal to the surface temperature of the Sun. (c) $i_{Eb} = 3/4 \cdot T \cdot i_{Sb}$; $i_{Sb} = 4.6 \times 10^3$ W/(K m$^2$-sr); 0.32 W/(K m$^2$).
2. (b) Sun: $6.3 \times 10^7$ W/m$^2$; oven: $6.4 \times 10^3$ W/m$^2$.
3. $F_{21} = A_1/A_2 \cdot F_{12}$.
4. $IE = \sigma / R_{total} \cdot (T_1^4 – T_2^4)$; $R_{total} = 958$ 1/m$^2$.
5. (a) $\kappa E = – 1/\Delta x \cdot \Delta iE / iE$. (b) $\Delta iE/dx = – \mu E$, where $\mu = \kappa E + \beta E$. (c) 3.5 $\times 10^4$ /m.
6. $l_{mean} = 0.06$ m; $\kappa \rho = 0.01$ m$^2$/kg.
7. (a) $y = 1/x^5 \cdot 1/(\exp(1/x) – 1)$. (b) 501 nm.
8. (a) 2330 K. (b) The new entropy of radiation is 2.7 times the old entropy.
9.
10.

**CHAPTER 13**

1. (a) $7.68 \times 10^4$ W/m$^2$. (b) 603 W. (c) 110 W/(K m$^3$) and 206 W/(K m$^3$). (d) 0.59 W/K.
APPENDIX 5. SOME SOLUTIONS OF END OF CHAPTER PROBLEMS

2. (a) Steeper at the colder end.
3. (a) 0.19 W/m^3. (b) 6.2·10^–4 W/(K·m^3).
4. (b) \( \frac{dT}{dx} \) = \(- \frac{sE}{kE} \cdot L \) – \( \frac{1}{kE} \) · \( jE(0) \). (c) – 0.025 K/m.
5. (b) \( \frac{dT}{dx} \) (L) = \(- \frac{sE}{kE} \cdot L \) – \( \frac{1}{kE} \) · \( jE(0) \). (c) – 0.025 K/m.
6. According to Equ.(13.54), the term in parentheses in Equ.(13.61) equals \( jS/kS \).
7. (b) First two terms arise in thermal conduction alone; third term is due to dissipation in electric process.
8. \( \frac{dT}{dx} \) (cold) = 0; \( T(\text{hot}) = \text{const.} \)
9. (a) \( GE = \text{const.} \) (c) \( \text{Power} = a \cdot IQ \cdot (Th – Tc) – R \cdot IQ^2; \) efficiency = \( \text{Power / IE,th,h.} \)

CHAPTER 14

1. 2. 3.
4. Uniform model: includes entropy production due to mixing of incoming fluid stream with fluid present in the collector. This term does not occur in continuous models.
5. 6. 7. 8. 9.
10. Counter-flow: 0.833; parallel flow: 0.500.
11. Strongly unbalanced: \( e_{\text{unbalanced}} > e_{\text{balanced}} \); nearly balanced: \( e_{\text{unbalanced}} \approx e_{\text{balanced}} \).
12. 13. 14. 15. Power = 4.4·10^12 W, efficiency \approx 0.3.
16. Excess of gradient: 6.4·10^–8 K/m, compared to actual gradient of 1.1·10^–2 K/m.

CHAPTER 15

1. Moist air has smaller molar mass than dry air.
2. 3.
5. \( j_{\text{net}} = – \frac{D}{R} \cdot (P – P_v) \cdot \frac{dP_v}{dz}. \) (Remember: \( x = P_v/P \).)
6. See Fig. 15.21 for a dynamical model that represents a similar situation.
7. (a) 1470 J/(K·kg) vs. 1550 J/(K·kg). (b) 2.24 MJ/kg; 1.8·10^9 W.
8. 9. \( 1 – \frac{T_{\text{out}}}{T_{\text{in av}}}. \)
10. Efficiency increases if (1) boiler pressure is increased, (2) if condenser pressure is decreased. A condenser allows the pressure at the cold end to be decreased below atmospheric pressure.
11. \( 1 – 313/573 = 0.45 > 0.37 \) for the Rankine efficiency. Ideal Rankine cycle does not produce entropy, so the difference is not due to dissipation.
12. 13. (a) 0.15. (b) 19 m^2.
14. 15. (a) 6500 J/(K·kg), 3000 kJ/kg. (b) 190°C, 10 bar. (c) 1.0 bar, 0.9.
16. (a) – 53.26 kJ/K. (b) – 25.0 MJ. (c) 3.05 MJ.

CHAPTER 16

1. 1.79·10^9 W/(m^2·m).
2. 5800 K, 0.32 W/(K·m^2).
3.
4. See Problem 12 in Chapter 7, add a convective term \( A_1 \cdot h_{12} \cdot (T_1 – T_2) \) to the expression for \( IE \) from absorber to glass cover.
5. 6. 7. \( \Pi_{\text{S_loss}} = 0.20 \) W/K, \( \Pi_{\text{S_abs}} = 2.3 \) W/K for 1.0 m^2 of collector area.
APPENDIX 6.

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