## PROPERTIES OF LIQUIDS

 solids, or the triple point for sublimating substances $\left(\mathrm{C}_{2} \mathrm{H}_{2}, \mathrm{CO}_{2}, \mathrm{SF}_{8}\right.$ and $\left.\mathrm{UF}_{8}\right)$.

| Substance | Formula | Melting temp. $T_{f}$ K | Boiling temp. <br> $T_{b}$ <br> K | Melting enthalpy $h_{s l}$ $\mathrm{kJ} / \mathrm{kg}$ | Boiling enthalpy $h_{l v}$ kJ/kg | Density (mass) <br> $\rho$ $\mathrm{kg} / \mathrm{m}^{3}$ | $\begin{array}{\|c\|} \hline \begin{array}{c} \text { Thermal } \\ \text { expansion } \end{array} \\ \frac{\alpha \cdot 10^{6}}{\underline{\mathrm{~K}^{-1}}} \end{array}$ | Compres -sibility ${ }^{\text {a }}$ к. $10^{9}$ $\mathrm{Pa}^{-1}$ | Surface tension ${ }^{\text {b }}$ <br> $\sigma$ <br> $\mathrm{N} / \mathrm{m}$ | Thermal capacity <br> $c_{p}$ $\mathrm{J} /(\mathrm{kg} \cdot \mathrm{K})$ | $\begin{array}{\|c} \text { Thermal } \\ \text { conductivity } \\ k \\ \mathrm{~W} /(\mathrm{m} \cdot \mathrm{~K}) \end{array}$ | Dynamic viscosity $\mu \cdot 10^{6}$ $\mathrm{Pa} \cdot \mathrm{~s}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Acetylene | $\mathrm{C}_{2} \mathrm{H}_{2}$ | $193{ }^{\text {c }}$ | $193{ }^{\text {c }}$ | $115^{\text {c }}$ | $700^{\text {c }}$ | $615^{\text {c }}$ | 2500 |  | 0.001 | 3000 | 0.50 | 160 |
| Acetone | $\mathrm{C}_{3} \mathrm{H}_{6} \mathrm{O}$ | 178 | 329 | 98 | 532 | 749 | 1400 | 1.2 | 0.024 | 2150 | 0.18 | 330 |
| Ammonia | $\mathrm{NH}_{3}$ | 195 | 240 | 332 | 1357 | 697 | 1800 | 0.7 | 0.022 | 4600 | 0.50 | 266 |
| Aniline | $\mathrm{C}_{6} \mathrm{H}_{7} \mathrm{~N}$ | 276 | 457 | 114 | 434 | 1021 | 840 | 0.36 | 0.042 | 2140 | 0.17 | 4467 |
| Argon | Ar | 84 | 87 | 30 | 163 | 1395 | 4500 | 2.1 | 0.014 | 625 | 0.13 | 240 |
| 1,3-Butadiene | $\mathrm{C}_{4} \mathrm{H}_{6}$ | 164 | 269 | 148 |  | 621 | 1800 | 1.9 | 0.013 | 2260 | 0.13 |  |
| Benzene | $\mathrm{C}_{6} \mathrm{H}_{6}$ | 279 | 353 | 126 | 394 | 884 | 1400 | 1.6 | 0.029 | 1720 | 0.15 | 653 |
| n-Butane | $\mathrm{C}_{4} \mathrm{H}_{10}$ | 135 | 273 | 80 | 365 | $602{ }^{\text {d }}$ | 1800 | 2.2 | 0.012 | 2400 | 0.12 | 282 |
| iso-Butane | $\mathrm{C}_{4} \mathrm{H}_{10}$ | 114 | 261 | 78 | 366 | $594{ }^{\text {e }}$ | 1900 | 2.3 | 0.012 | 2300 | 0.12 | 150 |
| Carbon dioxide | $\mathrm{CO}_{2}$ | $217{ }^{\text {f }}$ | $217{ }^{\text {f }}$ | $185{ }^{\text {f }}$ | $350^{\text {f }}$ | $1180^{\text {f }}$ | $3200{ }^{\text {f }}$ | $1.9{ }^{\text {f }}$ | $0.017^{\text {f }}$ | $1950{ }^{\text {f }}$ | $0.18{ }^{\text {f }}$ | $260{ }^{\text {f }}$ |
| Carbon tetrachloride | $\mathrm{CCl}_{4}$ | 250 | 350 | 30 | 195 | 1590 | 1240 | 1.0 | 0.027 | 840 | 0.11 | 967 |
| Cyclohexane | $\mathrm{C}_{6} \mathrm{H}_{12}$ | 280 | 354 | 31 | 360 | 778 | 1400 | 1.9 | 0.025 | 1860 | 0.13 | 411 |
| Chloroform | $\mathrm{CHCl}_{3}$ | 210 | 335 | 74 | 247 | 1489 | 1200 | 0.69 | 0.027 | 980 | 0.13 | 562 |
| n_Decane | $\mathrm{C}_{10} \mathrm{H}_{22}$ | 243 | 447 | 202 | 276 | 730 | 1010 | 0.84 | 0.024 | 2000 | 0.15 | 920 |
| Diesel | $\left(\mathrm{C}_{12} \mathrm{H}_{26}\right)$ | $235{ }^{\text {g }}$ | $470{ }^{\text {g }}$ |  | 250 | 840 | 830 |  | 0.028 | 1900 | 0.15 | 2400 |
| 1-Dodecene | $\mathrm{C}_{12} \mathrm{H}_{24}$ | 238 | 586 | 122 | 373 | 761 | 980 |  |  | 2150 | 0.14 | 1360 |
| n-Dodecane | $\mathrm{C}_{12} \mathrm{H}_{26}$ | 263 | 489 | 216 | 257 | 780 | 920 | 0.77 | 0.025 | 2220 | 0.14 | 1340 |
| DME (dimethyl ether) | $\mathrm{C}_{2} \mathrm{H}_{6} \mathrm{O}$ | 132 | 250 | 107 | 460 | 736 | 1900 | 1.6 | 0.011 | 2540 | 0.14 | 100 |


| ETBE (ethyl tert-butyl ether) | $\mathrm{C}_{6} \mathrm{H}_{14} \mathrm{O}$ | 179 | 340 |  |  | 770 |  |  |  |  |  | 400 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Ethane | $\mathrm{C}_{2} \mathrm{H}_{6}$ | 90 | 185 | 95 | 520 | $544^{\text {h }}$ | $2300^{\text {h }}$ | $1.8^{\text {h }}$ | $0.016^{\text {b }}$ | $2440^{\text {h }}$ | $0.17{ }^{\text {h }}$ | $169{ }^{\text {h }}$ |
| Ethanol | $\mathrm{C}_{2} \mathrm{H}_{6} \mathrm{O}$ | 156 | 351 | 108 | 860 | 790 | 1100 | 1.1 | 0.023 | 2440 | 0.18 | 1194 |
| Ether (diethyl ether) | $\mathrm{C}_{4} \mathrm{H}_{10} \mathrm{O}$ | 157 | 308 | 99 | 351 | 715 | 1630 |  | 0.016 | 2260 | 0.14 | 230 |
| Ethylene glycol | $\mathrm{C}_{2} \mathrm{H}_{6} \mathrm{O}_{2}$ | 262 | 471 | 181 | 800 | 1110 | 650 | 0.33 | 0.048 | 2400 | 0.26 | $16 \cdot 10^{3}$ |
| Ethylene | $\mathrm{C}_{2} \mathrm{H}_{4}$ | 104 | 169 | 120 | 483 | $568{ }^{\text {i }}$ | 2500 | 1.8 | 0.016 | 2420 | 0.19 | 176 |
| Gasoline | $\left(\mathrm{C}_{8} \mathrm{H}_{18}\right)$ | $217{ }^{\text {g }}$ | $360^{\text {g }}$ |  | 340 | 750 | 900 |  | 0.025 | 2100 | 0.15 | 380 |
| Glycerol (glycerine) | $\mathrm{C}_{3} \mathrm{H}_{8} \mathrm{O}_{3}$ | 291 | 560 | 199 | 663 | 1260 | 500 | 0.21 | 0.064 | 2430 | 0.30 | $1400 \cdot 10^{3}$ |
| Helium ( ${ }^{4} \mathrm{He}$ ) | He | 0.95 | 4.2 | 3.5 | 20.7 | 125 | 205000 | 520 | 0.0001 | 5000 | 0.02 | 3.2 |
| Helium-3 ( ${ }^{3} \mathrm{He}$ ) | He | NA | 3.2 | NA | 8.7 | 59 | 50000 | 300 |  | 1500 |  |  |
| n-Heptane | $\mathrm{C}_{7} \mathrm{H}_{16}$ | 182 | 372 | 140 | 321 | 684 | 1600 | 2.9 | 0.020 | 2220 | 0.13 | 409 |
| n -Hexane | $\mathrm{C}_{6} \mathrm{H}_{14}$ | 178 | 342 | 150 | 337 | 658 | 1600 | 2.7 | 0.019 | 2260 | 0.12 | 320 |
| n-Hexadecane (cetane) | $\mathrm{C}_{16} \mathrm{H}_{34}$ | 291 | 550 | 230 | 358 | 773 |  |  | 0.028 | 2210 | 0.15 | 3030 |
| Hydrazine | $\mathrm{N}_{2} \mathrm{H}_{4}$ | 275 | 387 | 395 | 1400 | 1010 | 2090 | 0.22 | 0.067 | 3080 | 0.57 | 900 |
| Hydrogen ${ }^{1}$ | $\mathrm{H}_{2}$ | 14 | 20 | 59 | 448 | 71 | 16600 | 19 | 0.002 | 8700 | 0.12 | 10 |
| (Hydrogen) Deuterium | $\mathrm{D}_{2}$ | 19 | 23 | 49 | 304 | 163 | 16700 | 13 |  | 8000 | 0.14 |  |
| Hydrogen peroxide | $\mathrm{H}_{2} \mathrm{O}_{2}$ | 273 | 423 | 368 | 1519 | 1450 | 790 | 0.21 | 0.080 | 2620 | 0.55 | 1200 |
| Kerosene, Jet A-1, RP1 | $\left(\mathrm{C}_{12} \mathrm{H}_{24}\right)$ | $230^{\text {g }}$ | $450{ }^{\text {g }}$ |  | 250 | 820 | 830 | 0.70 | 0.028 | 2000 | 0.13 | 2400 |
| Mercury | Hg | 234 | 630 | 12 | 301 | 13546 | 180 | 0.038 | 0.490 | 139 | 9.3 | 1550 |
| Methane | $\mathrm{CH}_{4}$ | 91 | 112 | 58 | 511 | 423 | 3500 | 2.2 | 0.012 | 3420 | 0.18 | 110 |
| Methanol | $\mathrm{CH}_{4} \mathrm{O}$ | 175 | 338 | 99 | 1100 | 791 | 1490 | 1.05 | 0.023 | 2510 | 0.21 | 593 |
| MMH (monomethyl hydrazine) | $\mathrm{CH}_{6} \mathrm{~N}_{2}$ | 221 | 364 |  |  | 875 |  |  |  | 2950 | 0.25 |  |
| MTBE (methyl tert-butyl ether) | $\mathrm{C}_{5} \mathrm{H}_{12} \mathrm{O}$ | 164 | 328 | 88 |  | 740 |  |  |  | 2090 | 0.12 | 350 |
| Nitric acid | $\mathrm{HNO}_{3}$ | 231 | 394 | 167 | 615 | 1510 |  | 0.32 | 0.042 | 2000 | 0.29 | 800 |
| Nitrogen | $\mathrm{N}_{2}$ | 63 | 77 | 26 | 199 | 807 | 5700 | 3.2 | 0.012 | 2040 | 0.145 | 161 |
| di-Nitrogen oxide | $\mathrm{N}_{2} \mathrm{O}$ | 182 | 185 | 149 | 376 | 1230 | 2400 | 1.1 | 0.024 | 1720 | 0.20 | 325 |
| di-Nitrogen tetroxide ${ }^{\text {k }}$ | $\mathrm{N}_{2} \mathrm{O}_{4}$ | 262 | 294 | 160 | 330 | 1440 |  |  |  | 1550 | 0.29 |  |


| n-Octane | $\mathrm{C}_{8} \mathrm{H}_{18}$ | 217 | 399 | 181 | 306 | 703 | 2000 | 4 | 0.022 | 2100 | 0.15 | 562 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| iso-Octane | $\mathrm{C}_{8} \mathrm{H}_{18}$ | 166 | 372 | 180 | 308 | 692 |  |  | 0.018 | 2100 | 0.10 | 350 |
| Oil (mineral, vegetable...) ${ }^{1}$ | $\mathrm{C}_{18} \mathrm{H}_{36} \mathrm{O}_{2}$ |  |  |  |  | 900 | 900 | 0.5 |  | 2000 | 0.15 | $10^{3} . .10^{7}$ |
| Oxygen | $\mathrm{O}_{2}$ | 54 | 90 | 14 | 213 | 1142 | 4400 | 2.0 | 0.020 | 1700 | 0.15 |  |
| n-Pentane | $\mathrm{C}_{5} \mathrm{H}_{12}$ | 143 | 309 | 116 | 356 | 626 | 1700 | 2.4 | 0.016 | 2180 | 0.14 | 229 |
| Propane ${ }^{\text {m }}$ | $\mathrm{C}_{3} \mathrm{H}_{8}$ | 85 | 231 | 95 | 430 | 581 | 2000 | 2.0 | 0.016 | 2140 | 0.13 | $198{ }^{\text {j }}$ |
| Propylene (propene) | $\mathrm{C}_{3} \mathrm{H}_{6}$ | 88 | 225 | 71 | 437 | 612 | 2000 | 2.0 | 0.008 | 2200 | 0.11 | 190 |
| Propylene glycol | $\mathrm{C}_{3} \mathrm{H}_{8} \mathrm{O}_{2}$ | 214 | 461 | 99 | 800 | 1036 | 730 |  | 0.040 | 2790 | 0.20 | $42 \cdot 10^{3}$ |
| R12 ${ }^{\text {n }}$ | $\mathrm{CCl}_{2} \mathrm{~F}_{2}$ | 115 | 243 |  | 165 | 1488 | 2000 | 2.0 | 0.016 | 966 | 0.07 | 200 |
| R134a (tetrafluoroethane) ${ }^{\circ}$ | $\mathrm{CF}_{3} \mathrm{CH}_{2} \mathrm{~F}$ | 170 | 247 | 1300 | 215 | 1380 | 2200 | 2.0 | 0.015 | 1280 | 0.10 | 380 |
| R410A ${ }^{\text {p }}$ | n.a. | 120 | 222 |  | 190 | 1350 | 2300 | 1.7 | 0.018 | 1368 | 0.17 |  |
| Silicone oil DMS-10 | -[Si( $\left.\left.\mathrm{CH}_{3}\right)_{2} \mathrm{O}\right]-$ |  |  | 1050 |  | 950 | 900 | 0.6 | 0.021 | 1800 | 0.11 | 9500 |
| Sodium ${ }^{\text {q }}$ | Na | 371 | 1160 | 115 | 1020 | $780{ }^{\text {a }}$ | 70 | 0.2 | 0.200 | 1250 | 60 | 200 |
| Sulfur dioxide | $\mathrm{SO}_{2}$ | 198 | 263 | 135 | 389 | 1455 | 1700 | 1.0 |  |  | 0.20 | 550 |
| Sulfur hexafluoride ${ }^{\text {r }}$ | $\mathrm{SF}_{6}$ | 223 | 223 | 40 | 162 | 1845 | 2800 | 3.2 | 0.011 | 837 |  |  |
| Sulfuric acid | $\mathrm{H}_{2} \mathrm{SO}_{4}$ | 283 | 561 |  | 745 | 1840 |  | 0.3 |  | 1400 |  | 23000 |
| Tetradecafluorohexane ${ }^{\text {s }}$ (FC-72) | $\mathrm{C}_{6} \mathrm{~F}_{14}$ | 183 | 329 |  | 88 | 1680 | 1560 |  | 0.010 | 1100 | 0.057 | 640 |
| UDMH (unsym.dim.hydrazine) | $\mathrm{C}_{2} \mathrm{H}_{8} \mathrm{~N}_{2}$ | 216 | 337 |  |  | 790 |  |  |  | 2650 | 0.16 |  |
| Uranium hexafluoride ${ }^{t}$ | $\mathrm{UF}_{6}$ | 337 | 337 | 54 | 82 | 3670 | 6000 |  | 0.018 | 620 | 1.9 | 900 |
| Water ${ }^{\text {u }}$ | $\mathrm{H}_{2} \mathrm{O}$ | 273 | 373 | 334 | 2257 | 999 | 150 | 0.45 | $0.073{ }^{\text {t }}$ | 4180 | 0.60 | $1000^{t}$ |
| Water, Heavy ${ }^{\text {v }}$ | $\mathrm{D}_{2} \mathrm{O}$ | 277 | 374 | 319 | 2090 | 1105 | 100 | 0.47 | 0.073 | 4210 | 0.60 |  |
| Xenon | Xe | 161 | 165 | 17 | 96 | 2990 | 2300 | 1.7 | 0.018 | 350 | 0.07 | 450 |

a) The compressibility coefficient, $\kappa$, is related to the speed of sound, $c$, and the density by $c=(\rho \kappa)^{-1 / 2}$ (e.g. for pure water $c=(\rho \kappa)^{-1 / 2}=\left(998 \cdot 0.46 \cdot 10^{-9}\right)^{-1 / 2}=1480$ $\mathrm{m} / \mathrm{s}$; and roughly the same for sea water). For liquid-vapour equilibrium, $\kappa$ and $\alpha$ increase a lot with $T$ and $p$ diverging at the critical point.
b) Surface tension for liquid in air. For liquid in water (if immiscible, of course), values may differ (e.g. for benzene in air $\sigma=0.029 \mathrm{~N} / \mathrm{m}$ but $\sigma=0.035 \mathrm{~N} / \mathrm{m}$ for benzene in water).
c) Acetylene has no normal points for melting and boiling because at the normal pressure of 100 kPa the only phase change is the solid-gas transition at 189 K (normal sublimation point). Data in this table refers to the triple point: $p_{t r}=128 \mathrm{kPa}, T_{t r}=193 \mathrm{~K}=-80^{\circ} \mathrm{C}$; i.e., $\rho_{l, t r}=615 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=h_{s l}+h_{l v}=115+700=815 \mathrm{~kJ} / \mathrm{kg}$. Sublimation point data: $T=189 \mathrm{~K}=-84^{\circ} \mathrm{C}, \rho_{s}=729 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=820 \mathrm{~kJ} / \mathrm{kg}$. See additional comments in f).
d) n-Butane liquid density at 288 K and its equilibrium pressure ( 175 kPa ): $\rho_{l}=584 \mathrm{~kg} / \mathrm{m}^{3}$.
e) iso-Butane liquid density at 288 K and its equilibrium pressure ( 258 kPa ): $\rho_{l}=563 \mathrm{~kg} / \mathrm{m}^{3}$.
f) Carbon dioxide has no normal points for melting and boiling because at the normal pressure of 100 kPa the only phase change is the solid-gas transition at 195 K (normal sublimation point). Data in this table refers to the triple point: $p_{t r}=518 \mathrm{kPa}, T_{t r}=217 \mathrm{~K}=-56.3^{\circ} \mathrm{C}$; i.e., $\rho_{l, t}=615 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=h_{s l}+h_{l v}=185+350=535 \mathrm{~kJ} / \mathrm{kg}$. Sublimation point data: $T=195 \mathrm{~K}=-78.5^{\circ} \mathrm{C}, \rho_{s}=1560 \mathrm{~kg} / \mathrm{m}^{3}$ (if well compacted), $h_{s v}=575 \mathrm{~kJ} / \mathrm{kg}$. Notice that most liquid properties vary a lot near the critical point, which is the case at room temperature for $\mathrm{CO}_{2}, \mathrm{C}_{2} \mathrm{H}_{2}, \mathrm{C}_{2} \mathrm{H}_{4}, \mathrm{C}_{2} \mathrm{H}_{6}, \mathrm{~N}_{2} \mathrm{O}, \mathrm{SF}_{6}$, and $\mathrm{UF}_{6}$. For liquid $\mathrm{CO}_{2}$ at 288 K and its equilibrium pressure ( 5.1 MPa ): $\rho=823 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=3200 \cdot 10^{-6} \mathrm{~K}^{-1}, \kappa=7.8 \cdot 10^{-9} \mathrm{~Pa}^{-1}, \sigma=0.002 \mathrm{~N} / \mathrm{m}, k=0.09 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K})$, and $\mu=70 \cdot 10^{-6} \mathrm{~Pa} \cdot \mathrm{~s}$, and $c_{p}=3420 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K})$, growing from $c_{p}=1950 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K})$ at the triple point, to infinity at the critical point (the difference between $c_{p}$ and $c_{v}$ of the saturated liquid is important in this case: the thermal capacity at constant volume at 288 K and 5.1 MPa is $c_{v}=990 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K})$ ).
g) Diesel, gasoline and kerosene are mixtures of various compositions and have not precise boiling or melting points (e.g. at $300 \mathrm{~K} 10 \% \mathrm{wt}$ of gasoline is in the vapour state, and at $440 \mathrm{~K} 90 \%$ ). Surface tension may vary in the range $\sigma=0.022 .0 .035 \mathrm{~N} / \mathrm{m}$. Jet A-1 is a kerosene fuel with additives to freeze at $-50^{\circ} \mathrm{C}$ and $\left.\rho=800 . .820 \mathrm{~kg} / \mathrm{m}^{3}, c=2000 . .2100 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), k=0.10 . .0 .14 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K})\right)$. Rocket propellant RP1 is similar to Jet A-1. Surrogate pure components are often used for theoretical studies, but only a few properties can be properly matched: octane (normal or iso) is used as surrogate of gasoline, and dodecane or dodecene for diesel, kerosene, Jet A-1 and RP1.
h) Liquid ethane at 288 K and its equilibrium pressure ( 3.36 MPa ) has $\rho_{l}=358 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=0.013 \mathrm{~K}^{-1}, c=430 \mathrm{~m} / \mathrm{s}, c_{p}=4750 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), . \mathrm{k}=0.079 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K})$, and $\mu=45 \cdot 10^{-}$ ${ }^{6} \mathrm{~Pa} \cdot \mathrm{~s}$.
i) There are two spin-isomers of $\mathrm{H}_{2}$ : ortho and para. Gas at room temperature is mostly orthohydrogen, but, when liquefied, it is important to convert it to almost pure parahydrogen because otherwise there is a slow natural conversion of ortho to para with a release of $516 \mathrm{~kJ} / \mathrm{kg}$ that contributes to boil-off.
j) Data for $\mathrm{H}_{2} \mathrm{O}_{2}$ pure. $\mathrm{H}_{2} \mathrm{O}_{2}$ is most used in aqueous solutions, with $>80 \%$ mass fraction in propulsion (named $\underline{\mathrm{HTP}}$, high test peroxide), with around $30 \%$ as a chemical in industry for bleaching (its main application), and with around $3 \%$ in medicine as antiseptic. The peroxide bond (a single bond HO-OH) is unstable and slowly decomposes, so that storage tanks should be vented, and kept cool and in the dark. It decomposes violently at high temperature (its boiling point is extrapolated, but solutions may be safely distilled under reduced pressure), or at room temperature in contact with catalysts like silver. Density of solid at melting point is $1700 \mathrm{~kg} / \mathrm{m}^{3}$, and that of pure liquid at $100^{\circ} \mathrm{C}$ is $1350 \mathrm{~kg} / \mathrm{m}^{3} . \mathrm{H}_{2} \mathrm{O}_{2} / \mathrm{H}_{2} \mathrm{O}$ solutions are eutectic, i.e. although both pure substances melt at around $0^{\circ} \mathrm{C}$, a $50 \% \mathrm{wt}$ mix melts at $-52^{\circ} \mathrm{C}$.
k) At equilibrium, there is always a mixture of dinitrogen tetroxide $\left(\mathrm{N}_{2} \mathrm{O}_{4}\right)$ and nitrogen dioxide $\left(\mathrm{NO}_{2}\right)$. The $\mathrm{NO}_{2} / \mathrm{N}_{2} \mathrm{O}_{4}$ equilibrium depends on temperature, $\mathrm{NO}_{2}$ being favoured in the gas phase at high temperatures, whereas $\mathrm{N}_{2} \mathrm{O}_{4}$ is preponderant in the gas phase at low temperature, and in condensed phases. When condensing, at $21.3^{\circ} \mathrm{C}$ at 100 kPa , most of the liquid is $\mathrm{N}_{2} \mathrm{O}_{4}$ which is colourless or pale brownish; when solidified ( $\mathrm{at}-11.2^{\circ} \mathrm{C}$ ) a white solid appears. $\mathrm{N}_{2} \mathrm{O}_{4}$ is a hypergolic propellant that spontaneously reacts upon contact with various forms of hydrazine, all of them liquid at normal pressure; this fact, and the ease of liquefying the $\mathrm{N}_{2} \mathrm{O}_{4}$ (liquid at 100 kPa for $T<21^{\circ} \mathrm{C}$ ), makes them popular bipropellants for spacecraft rockets.

1) Formula of oleic acid $\left(\mathrm{CH}_{3}-\left(\mathrm{CH}_{2}\right)_{7}-\mathrm{CH}=\mathrm{CH}-\left(\mathrm{CH}_{2}\right)_{7}-\mathrm{COOH}, T_{\mathrm{m}}=268 \mathrm{~K}, h_{s l}=75 \mathrm{~kJ} / \mathrm{kg}\right.$,), the major component in olive oil. Oils are thick liquids (non-volatile and viscous) made directly (natural oils) or indirectly (synthetic oils) from fossil matter, living matter, or minerals. Mineral oils are high hydrocarbons obtained from petroleum distillation and used either as fuels (diesel oil and heavy fuel oil) or as lubricants (lube oils). Fat oils are triglycerides-esters from plants or animals (olive, soybean, peanut sunflower, coconut, corn linseed, palm, essential oils, whale, castor). They are organic (carbon) or inorganic (silicon) polymers with a range of molar mass values, and do not show sharp phase transitions. Density: they are usually less dense than water (but sulphuric oleum nearly reaches a density double than water): e.g. olive and vegetable oils have some $\rho=915 . .925 \mathrm{~kg} / \mathrm{m}^{3}$, whereas lubricant, combustible and hydraulic oils may have $\rho=800 . .1000$ $\mathrm{kg} / \mathrm{m}^{3}$. Thermal capacity: values are near $c_{p}=2000 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ ) in most cases; lube oils have about $1800 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ ) at 250 K , linearly increasing to about $3000 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ ) at 600 K ; oils use for heat transfer may have values some $200 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ ) lower. Thermal conductivity: all of them are poor conductors, with $k=0.10 . .0 .15 \mathrm{~W} / \mathrm{m} \cdot \mathrm{K}$ ), slightly decreasing with temperature, even for thermal oils, which are just more resistant to high temperatures (up to 600 K ). Viscosity: oil viscosity may vary orders of magnitude from one oil to the other, and decreases exponentially with temperature; e.g. at $15^{\circ} \mathrm{C}, \mu=3 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ for light silicone oils, gas oil and diesel oil, $\mu=80 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ for olive oil and light mineral oils, $\mu>1000 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ for fuel oil and thick silicone oils).
m) Liquid propane at 288 K and its equilibrium pressure ( 729 kPa ) has $\rho_{l}=508 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=2990 \cdot 10^{-6} \mathrm{~K}^{-1}, c=780 \mathrm{~m} / \mathrm{s}, c_{p}=2620 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), k=0.099 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K})$, and $\mu=108 \cdot 10^{-6} \mathrm{~Pa} \cdot \mathrm{~s}$.
n) R12, dichlorodifluoromethane (also named freon), was the most used refrigerant in the $20^{\text {th }} \mathrm{c}$. since its first synthesis in 1929 to its production banning in 1995 . Liquid R12 at 288 K and its equilibrium pressure ( 488 kPa ) has $\rho_{l}=1350 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=2600 \cdot 10^{-6} \mathrm{~K}^{-1}, c=553 \mathrm{~m} / \mathrm{s}, \sigma=0.010 \mathrm{~N} / \mathrm{m}, c_{p}=964 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), k=0.087 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K})$, and $\mu=343 \cdot 10^{-6} \mathrm{~Pa} \cdot \mathrm{~s}$.
o) Liquid R134a at 288 K and its equilibrium pressure ( 486 kPa ) has $\rho_{l}=1244 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=2920 \cdot 10^{-6} \mathrm{~K}^{-1}, c=553 \mathrm{~m} / \mathrm{s}, \sigma=0.010 \mathrm{~N} / \mathrm{m}, c_{p}=1390 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), . \mathrm{k}=0.085$ $\mathrm{W} /(\mathrm{m} \cdot \mathrm{K})$, and $\mu=221 \cdot 10^{-6} \mathrm{~Pa} \cdot \mathrm{~s}$.
p) R410A is a near-azeotropic mixture of R32 (difluoromethane, $\mathrm{CH}_{2} \mathrm{~F}_{2}$ ) and R 125 (pentafluoroethane, $\mathrm{CHF}_{2} \mathrm{CF}_{3}$ ), $50 / 50$ by weight ( $70 / 30$ molar), which can be approximated as a pure substance. Liquid R410A at 288 K and its equilibrium pressure ( 1253 kPa ) has $\rho_{l}=1107 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=4220 \cdot 10^{-6} \mathrm{~K}^{-1}, c=485 \mathrm{~m} / \mathrm{s}, \sigma=0.007$ $\mathrm{N} / \mathrm{m}, c_{p}=1610 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K})$.
q) Sodium, $M=0.023 \mathrm{~kg} / \mathrm{mol}, \rho_{\mathrm{L}}=780 \mathrm{~kg} / \mathrm{m}^{3}, \rho_{\mathrm{s}}=970 \mathrm{~kg} / \mathrm{m}^{3}$. The $\mathrm{Na}-\mathrm{K}$ eutectic alloy, with $22 \% \mathrm{Na}$ by mass, is a room-temperature liquid, $T_{\mathrm{m}}=-12.6^{\circ} \mathrm{C}, T_{\mathrm{b}}=785$ ${ }^{\circ} \mathrm{C}$, used in high-temperature high-heat-transfer applications; at $100^{\circ} \mathrm{C}, \rho=855 \mathrm{~kg} / \mathrm{m}^{3}, \alpha=340 \cdot 10^{-6} 1 / \mathrm{K}, c=936 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K}), k=23 \mathrm{~W} /(\mathrm{m} \cdot \mathrm{K}), \mu=505 \cdot 10^{-6} \mathrm{~Pa} \cdot \mathrm{~s}$, $\sigma=115 \cdot 10^{-3} \mathrm{~N} / \mathrm{m}$ and $\sigma_{\text {elec }}=2.5 \cdot 10^{8} \mathrm{~S} / \mathrm{m}$, i.e. $4 \%$ that of Cu .
r) Sulfur hexafluoride has no normal points for melting and boiling because at the normal pressure of 100 kPa the only phase change is the solid-gas transition at 209 K (normal sublimation point). Data in this table refers to the triple point: $p_{t r}=226 \mathrm{kPa}, T_{t r}=224 \mathrm{~K}=-49.4^{\circ} \mathrm{C}$; i.e., $\rho_{l, t r}=1845 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=h_{s l}+h_{l v}=40+162=202$ $\mathrm{kJ} / \mathrm{kg}$. Sublimation point data: $T=209 \mathrm{~K}=-63.9^{\circ} \mathrm{C}, \rho_{\mathrm{s}}=2770 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=202 \mathrm{~kJ} / \mathrm{kg}$. Liquid at 288 K and its equilibrium pressure ( 1.85 MPa ) has $\rho_{l}=1440 \mathrm{~kg} / \mathrm{m}^{3}$, $\alpha=7070 \cdot 10^{-6} \mathrm{~K}^{-1}, c=252 \mathrm{~m} / \mathrm{s}, \sigma=0.003 \mathrm{~N} / \mathrm{m}$, and $c_{p}=1165 \mathrm{~J} /(\mathrm{kg} \cdot \mathrm{K})$. See further data under Gas properties. See additional comments in f).
s) Tetradecafluorohexane or perfluorohexane (traded as Fluorinert FC-72, or as Flutec PP1), is a liquid coolant commonly used in electronics cooling because of its electrical insulation properties and stability (thermal, chemical, and biological). Its vapour pressure at $25^{\circ} \mathrm{C}$ is 30 kPa . Its refractive index is $n=1.251$. It has zero ozone depletion potential ( $\mathrm{ODP}=0$ ), but a high global warming potential (GWP>5000).
t) Uranium hexafluoride has no normal points for melting and boiling because at the normal pressure of 100 kPa the only phase change is the solid-gas transition at 329 K (normal sublimation point). Data in this table refers to the triple point: $p_{t r}=152 \mathrm{kPa}, T_{t r}=337 \mathrm{~K}=-64{ }^{\circ} \mathrm{C}$; i.e., $\rho_{l, t}=3700 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=h_{s l}+h_{l v}=54+82=136$ $\mathrm{kJ} / \mathrm{kg}$. Sublimation point data: $T=329 \mathrm{~K}=56.4^{\circ} \mathrm{C}, \rho_{s}=4850 \mathrm{~kg} / \mathrm{m}^{3}, h_{s v}=136 \mathrm{~kJ} / \mathrm{kg}$. See further data under Gas properties. See additional comments in f).
u) Water properties may be used as a first approximation for many natural aqueous solutions (milk, wine, beer, vinegar, seawater, urine, fruit juices, etc.). Their densities are typically $\rho=1020 . .1030 \mathrm{~kg} / \mathrm{m}^{3}$, their melting points $1 . .2 \mathrm{~K}$ below that of water, their boiling points $0.5 . .1 .5 \mathrm{~K}$ above that of water, their thermal capacities some $80 \%$ of water. Pure water has anomalous dilatation in the $0 . .4^{\circ} \mathrm{C}$ range, with maximum density $\rho=1000 \mathrm{~kg} / \mathrm{m}^{3}$ at $T_{4}=3.98^{\circ} \mathrm{C}=277.13 \mathrm{~K}$ decreasing with temperature to $958 \mathrm{~kg} / \mathrm{m}^{3}$ at $100^{\circ} \mathrm{C}$ (with a minimum of $322 \mathrm{~kg} / \mathrm{m}^{3}$ at the critical point); a good approximation in the $0 . .200{ }^{\circ} \mathrm{C}$ range may be $\rho=1000-0.1 \cdot\left(T-T_{4}\right)-0.0033 \cdot\left(T-T_{4}\right)^{2} \mathrm{~kg} / \mathrm{m}^{3}$, with $T_{4}$ as above. Interface tension of water/air or water/vapour is $0.073 \mathrm{~N} / \mathrm{m}$, but for water $/ \mathrm{mercury} 0.390 \mathrm{~N} / \mathrm{m}$, water/octane $0.052 \mathrm{~N} / \mathrm{m}$, water/benzene $0.035 \mathrm{~N} / \mathrm{m}$. Contact angle water/glass in air $0^{\circ}$ if pure, some $30^{\circ}$ typical; mercury/glass in air $140^{\circ}$ if pure, some $120^{\circ}$ typical. Liquid viscosity varies a lot with temperature; e.g. for water, $\mu=1.8 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ at $0^{\circ} \mathrm{C}, 0.5 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ at $50^{\circ} \mathrm{C}$ and $0.35 \cdot 10^{-3} \mathrm{~Pa} \cdot \mathrm{~s}$ at $100{ }^{\circ} \mathrm{C}$. The boiling point of water at 100 kPa is $T_{b}=372.75 \pm 0.02 \mathrm{~K}\left(99.60 \pm 0.02^{\circ} \mathrm{C}\right)$, whereas at $101.325 \mathrm{kPa}(1 \mathrm{~atm})$ it is $373.12 \pm 0.02 \mathrm{~K}\left(99.97 \pm 0.02^{\circ} \mathrm{C}\right)$.
v) Heavy water usually means water that has been enriched in the deuterium isotope, D , which is not radioactive (without changing oxygen isotope composition), in the form HDO or $\mathrm{D}_{2} \mathrm{O}$; data here only apply to $\mathrm{D}_{2} \mathrm{O}$. Heavy water, contrary to normal (or light) water, does not quench thirst; seeds do not germinate. Additional data: for $\mathrm{H}_{2} \mathrm{O}$ (i.e. hydrogen oxide), $\rho_{\max }=1000 \mathrm{~kg} / \mathrm{m}^{3}$ at $3.98{ }^{\circ} \mathrm{C}\left(\rho_{\text {sol }}=917 \mathrm{~kg} / \mathrm{m}^{3}\right.$ at $T_{\mathrm{f}}=0{ }^{\circ} \mathrm{C}$ ); for $\mathrm{D}_{2} \mathrm{O}$ (i.e. deuterium oxide): $\rho_{\max }=1106 \mathrm{~kg} / \mathrm{m}^{3}$ at $11.2^{\circ} \mathrm{C}$, $\rho_{\text {sol }}=1018 \mathrm{~kg} / \mathrm{m}^{3}$ at $T_{\mathrm{f}}=3.82^{\circ} \mathrm{C}$ (thus, a heavy-water ice-cube sinks in normal water); for $\mathrm{T}_{2} \mathrm{O}$ (i.e. tritium oxide): $\rho_{\text {max }}=1215 \mathrm{~kg} / \mathrm{m}^{3}$ at $13.4^{\circ} \mathrm{C}$, $\rho_{\text {sol }}=$ ?? $\mathrm{kg} / \mathrm{m}^{3}$ at $T_{\mathrm{f}}=4.49^{\circ} \mathrm{C}$.
