

$$\therefore \dot{m}(s_4 - s_1) = \frac{-\dot{Q}}{T_{surr}} + \dot{S}_{gen}$$

$$\therefore s_{gen} = \frac{\dot{S}_{gen}}{\dot{m}} = (s_4 - s_1) - \frac{-q}{T_{surr}}$$

Since

$$\begin{aligned} s_4 - s_1 &= C_p \ln \frac{T_4}{T_1} - R \ln \frac{P_4}{P_1} \\ &= 1.005 \ln \frac{454.7}{(273.15 + 10)} - 0.287 \ln \frac{900}{101} \\ &= -0.1517 \text{ kJ/kgK} \end{aligned}$$

Therefore, the total specific entropy generation is

$$\begin{aligned} s_{gen} &= (s_4 - s_1) - \frac{-q}{T_{surr}} \\ &= -0.1517 + \frac{120.6}{(273.15 + 30)} = 0.246 \text{ kJ/kgK} > 0 \end{aligned}$$

Comment:

Compare the results from part (2) and part (3),  $s_{gen} > s_{gen,1} + s_{gen,2}$ , because the heat transfer process in the heat exchanger is irreversible and generates additional entropy.

(4) If the air is directly compressed from  $P_1 = 101 \text{ kPa}$  to  $P_4 = 900 \text{ kPa}$  in a polytropic process with  $n = 1.58486$ , then its final temperature at the exit of stage 2 will be

$$\therefore \frac{P_4}{P_1} = \left( \frac{T_4'}{T_1} \right)^{\frac{n}{n-1}}$$

$$\begin{aligned}
 \therefore T_{4'} &= T_1 \left( \frac{P_4}{P_1} \right)^{\frac{n-1}{n}} \\
 &= (273.15 + 10) \left( \frac{900}{101} \right)^{\frac{0.58486}{1.58486}} \\
 &= 634.7 \text{ K} = 361.5^\circ \text{C}
 \end{aligned}$$

The specific work of the compressor will be

$$w_{tot'} = C_p(T_{4'} - T_1) = 1.005 \times (361.5 - 10) = 353.3 \text{ kJ/kg}$$

Comment:

Intercoolers are commonly used in multiple-stage compressors. Without intercoolers, the air temperature in the compressor may increase significantly, which may reduce the efficiency of the compressor. In addition, by comparing the specific work in part 1 and part 4,  $w_{tot'} > w_{tot}$ , it is apparent that without intercoolers, the compressor will need to consume much more power in order to achieve the same final pressure.

Practice Problems



An interactive H5P element has been excluded from this version of the text. You can view it online here:

<https://pressbooks.bccampus.ca/thermo1/?p=1876#h5p-49>

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## 6.11 Chapter review

In this chapter, we have introduced two statements of the second law of thermodynamics including the Kelvin-Planck statement and the Clausius statement, and the ideal model of Carnot cycles. These concepts establish a theoretical foundation for evaluating the best possible performance, in terms of the thermal efficiency or COP, of heat engines, refrigerators, or heat pumps operating between two heat reservoirs.

The second law of thermodynamics can be expressed in terms of entropy generation. Due to the existence of irreversibilities, a real process or cycle always proceeds in the direction that obeys  $S_{gen} > 0$ . For an ideal, reversible process or cycle, such as the Carnot cycles,  $S_{gen} = 0$ . Any real or ideal process or cycle must satisfy both the first and the second laws of thermodynamics.

The first and second laws of thermodynamics are often used together with the thermodynamic tables or ideal gas equations in thermal analysis. When applying the second law of thermodynamics for closed or open systems, it is important to write an appropriate entropy balance equation. Entropy, entropy transfer, and entropy generation are three important concepts in the entropy balance equation. They have different physical meanings.

- Entropy is a measure of the degree of the “randomness” or “disorder” of a system. It is a thermodynamic property of the system and a state function. The change of entropy,  $\Delta S$ , in a process only depends on the initial and final states of the process.
- Entropy generation,  $S_{gen}$ , is a measure of the irreversibilities in a process. It is not a property of the system. It depends on the path of a process; the more irreversible a process is, the larger

$S_{gen}$  is.

- Entropy transfer always accompanies mass transfer and heat transfer in a process or a cycle. Entropy transfer is a boundary phenomenon. It relates to the mass flow rate or heat transfer across the system boundary, as well as the temperature of the boundary.

## 6.12 Key equations

### Heat engine

|  |  |
|--|--|
| Net work output                          | $\dot{W}_{net, out} = \dot{Q}_H - \dot{Q}_L$   |
| Thermal efficiency of any heat engine    | $\eta_{th} = \frac{\text{desired output}}{\text{required input}} = \frac{\dot{W}_{net, out}}{\dot{Q}_H} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H}$ |
| Thermal efficiency of Carnot heat engine | $\eta_{th, rev} = 1 - \frac{T_L}{T_H}$   |

### Refrigerator and heat pump

|                            |  |
|----------------------------|--|
| Net work input             | $\dot{W}_{net, in} = \dot{Q}_H - \dot{Q}_L$  |
| COP of any refrigerator    | $COP_R = \frac{\text{desired output}}{\text{required input}} = \frac{\dot{Q}_L}{\dot{W}_{net, in}} = \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L} = \frac{1}{\dot{Q}_H/\dot{Q}_L - 1}$    |
| COP of Carnot refrigerator | $COP_{R, rev} = \frac{T_L}{T_H - T_L} = \frac{1}{T_H/T_L - 1}$   |
| COP of any heat pump       | $COP_{HP} = \frac{\text{desired output}}{\text{required input}} = \frac{\dot{Q}_H}{\dot{W}_{net, in}} = \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_L} = \frac{1}{1 - \dot{Q}_L/\dot{Q}_H}$ |
| COP of Carnot heat pump    | $COP_{HP, rev} = \frac{T_H}{T_H - T_L} = \frac{1}{1 - T_L/T_H}$  |

## Entropy and entropy generation

|                                  |   |
|----------------------------------|---|
| The inequality of Clausius       | $\oint \frac{\delta Q}{T} \leq 0$ (= for reversible cycles; < for irreversible)   |
| Definition of entropy            | <p>Infinitesimal form : <math>dS = \left( \frac{\delta Q}{T} \right)_{rev}</math></p> <p>Integral form : <math>\Delta S = S_2 - S_1 = \int_1^2 \left( \frac{\delta Q}{T} \right)</math></p> |
| Definition of entropy generation | <p>Infinitesimal form : <math>dS = \frac{\delta Q}{T}</math></p> <p>where <math>\delta S_{gen} \geq 0</math></p> <p>(= for reversible processes; &gt; for irreversible)</p>                 |

## The second law of thermodynamics

|   |  |
|---|--|
| <p>For closed systems (control mass)</p>                                  | $S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen}$ $\cong \sum \frac{Q_k}{T_k} + S_{gen} \quad (S_{gen} \geq 0)$ <p>where <math>T_k</math> is the absolute temperature of the system boundary, in Kelvin.</p>     |
| <p>For steady-state, steady flow in a control volume (open systems)</p>   | $\sum \dot{m}_e s_e - \sum \dot{m}_i s_i = \sum \frac{\dot{Q}_{c.v.}}{T} + \dot{S}_{gen} \quad (\dot{S}_{gen} \geq 0)$   |
| <p>For steady and isentropic flow</p>                                     | $\sum \dot{m}_e s_e = \sum \dot{m}_i s_i$  |
| <p>Change of specific entropy between two states of a solid or liquid</p> | $s_2 - s_1 = C_p \ln \frac{T_2}{T_1}$  |
| <p>Change of specific entropy between two states of an ideal gas</p>      | <p>Assume constant <math>C_p</math> and <math>C_v</math> in the temperature range,</p> $s_2 - s_1 = C_p \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$ $s_2 - s_1 = C_v \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$ |
| <p>Isentropic relations for ideal gases</p>                               | $Pv^k = \text{constant}$ $\frac{P_2}{P_1} = \left( \frac{v_1}{v_2} \right)^k = \left( \frac{T_2}{T_1} \right)^{k/(k-1)}$ <p>where <math>k = \frac{C_p}{C_v}</math> and <math>T</math> is in Kelvin</p>             |



# Appendix A: Thermodynamic Properties of Water

## Table A1: Saturated Water

| T (°C) | P (MPa) | Specific Volume<br>m <sup>3</sup> /kg |                      | Specific Internal Energy<br>kJ/kg |                      | Specific Enthalpy<br>kJ/kg |                      | Specific Entropy<br>kJ/kgK |                      |
|--------|---------|---------------------------------------|----------------------|-----------------------------------|----------------------|----------------------------|----------------------|----------------------------|----------------------|
|        |         | <i>v<sub>f</sub></i>                  | <i>v<sub>g</sub></i> | <i>u<sub>f</sub></i>              | <i>u<sub>g</sub></i> | <i>h<sub>f</sub></i>       | <i>h<sub>g</sub></i> | <i>s<sub>f</sub></i>       | <i>s<sub>g</sub></i> |
| 0.01   | 0.00061 | 0.001000                              | 205.991              | 0.00                              | 2374.90              | 0.00                       | 2500.92              | 0.0000                     | 9.1555               |
| 5      | 0.00087 | 0.001000                              | 147.011              | 21.02                             | 2381.78              | 21.02                      | 2510.06              | 0.0763                     | 9.0248               |
| 10     | 0.00123 | 0.001000                              | 106.303              | 42.02                             | 2388.65              | 42.02                      | 2519.21              | 0.1511                     | 8.8998               |
| 15     | 0.00171 | 0.001001                              | 77.8755              | 62.98                             | 2395.49              | 62.98                      | 2528.33              | 0.2245                     | 8.7803               |
| 20     | 0.00234 | 0.001002                              | 57.7567              | 83.91                             | 2402.32              | 83.91                      | 2537.43              | 0.2965                     | 8.6660               |
| 25     | 0.00317 | 0.001003                              | 43.3373              | 104.83                            | 2409.13              | 104.83                     | 2546.51              | 0.3672                     | 8.5567               |
| 30     | 0.00425 | 0.001004                              | 32.8783              | 125.73                            | 2415.91              | 125.73                     | 2555.55              | 0.4368                     | 8.4520               |
| 35     | 0.00563 | 0.001006                              | 25.2053              | 146.63                            | 2422.67              | 146.63                     | 2564.55              | 0.5051                     | 8.3517               |
| 40     | 0.00738 | 0.001008                              | 19.5151              | 167.53                            | 2429.39              | 167.53                     | 2573.51              | 0.5724                     | 8.2556               |
| 45     | 0.00960 | 0.001010                              | 15.2521              | 188.43                            | 2436.08              | 188.44                     | 2582.43              | 0.6386                     | 8.1633               |
| 50     | 0.01235 | 0.001012                              | 12.0269              | 209.33                            | 2442.73              | 209.34                     | 2591.29              | 0.7038                     | 8.0748               |
| 55     | 0.01576 | 0.001015                              | 9.56428              | 230.24                            | 2449.34              | 230.26                     | 2600.09              | 0.7680                     | 7.9898               |
| 60     | 0.01995 | 0.001017                              | 7.66723              | 251.16                            | 2455.90              | 251.18                     | 2608.83              | 0.8313                     | 7.9082               |
| 65     | 0.02504 | 0.001020                              | 6.19354              | 272.09                            | 2462.41              | 272.12                     | 2617.50              | 0.8937                     | 7.8296               |
| 70     | 0.03120 | 0.001023                              | 5.03954              | 293.03                            | 2468.86              | 293.07                     | 2626.10              | 0.9551                     | 7.7540               |
| 75     | 0.03860 | 0.001026                              | 4.12894              | 313.99                            | 2475.24              | 314.03                     | 2634.60              | 1.0158                     | 7.6812               |
| 80     | 0.04741 | 0.001029                              | 3.40516              | 334.96                            | 2481.56              | 335.01                     | 2643.02              | 1.0756                     | 7.6111               |
| 85     | 0.05787 | 0.001032                              | 2.82584              | 355.96                            | 2487.81              | 356.02                     | 2651.33              | 1.1346                     | 7.5434               |
| 90     | 0.07018 | 0.001036                              | 2.35906              | 376.97                            | 2493.97              | 377.04                     | 2659.53              | 1.1929                     | 7.4781               |
| 95     | 0.08461 | 0.001040                              | 1.98056              | 398.00                            | 2500.04              | 398.09                     | 2667.61              | 1.2504                     | 7.4151               |
| 100    | 0.10142 | 0.001043                              | 1.67177              | 419.06                            | 2506.02              | 419.17                     | 2675.57              | 1.3072                     | 7.3541               |
| 105    | 0.12090 | 0.001047                              | 1.41838              | 440.15                            | 2511.90              | 440.27                     | 2683.39              | 1.3634                     | 7.2952               |
| 110    | 0.14338 | 0.001052                              | 1.20929              | 461.26                            | 2517.67              | 461.42                     | 2691.06              | 1.4188                     | 7.2381               |

|     |         |          |          |         |         |         |         |        |        |
|-----|---------|----------|----------|---------|---------|---------|---------|--------|--------|
| 115 | 0.16918 | 0.001056 | 1.03584  | 482.42  | 2523.33 | 482.59  | 2698.58 | 1.4737 | 7.1828 |
| 120 | 0.19867 | 0.001060 | 0.891212 | 503.60  | 2528.86 | 503.81  | 2705.93 | 1.5279 | 7.1291 |
| 125 | 0.23224 | 0.001065 | 0.770026 | 524.83  | 2534.27 | 525.07  | 2713.10 | 1.5816 | 7.0770 |
| 130 | 0.27028 | 0.001070 | 0.668004 | 546.10  | 2539.53 | 546.38  | 2720.08 | 1.6347 | 7.0264 |
| 135 | 0.31323 | 0.001075 | 0.581729 | 567.41  | 2544.65 | 567.75  | 2726.87 | 1.6872 | 6.9772 |
| 140 | 0.36154 | 0.001080 | 0.508454 | 588.77  | 2549.62 | 589.16  | 2733.44 | 1.7392 | 6.9293 |
| 145 | 0.41569 | 0.001085 | 0.445962 | 610.19  | 2554.42 | 610.64  | 2739.80 | 1.7908 | 6.8826 |
| 150 | 0.47617 | 0.001091 | 0.392453 | 631.66  | 2559.05 | 632.18  | 2745.93 | 1.8418 | 6.8371 |
| 155 | 0.54350 | 0.001096 | 0.346460 | 653.19  | 2563.51 | 653.79  | 2751.81 | 1.8924 | 6.7926 |
| 160 | 0.61824 | 0.001102 | 0.306782 | 674.79  | 2567.78 | 675.47  | 2757.44 | 1.9426 | 6.7491 |
| 165 | 0.70093 | 0.001108 | 0.272431 | 696.46  | 2571.85 | 697.24  | 2762.81 | 1.9923 | 6.7066 |
| 170 | 0.79219 | 0.001114 | 0.242589 | 718.20  | 2575.73 | 719.08  | 2767.90 | 2.0417 | 6.6650 |
| 175 | 0.89260 | 0.001121 | 0.216581 | 740.02  | 2579.39 | 741.02  | 2772.71 | 2.0906 | 6.6241 |
| 180 | 1.00281 | 0.001127 | 0.193842 | 761.92  | 2582.83 | 763.05  | 2777.21 | 2.1393 | 6.5841 |
| 185 | 1.12346 | 0.001134 | 0.173901 | 783.91  | 2586.04 | 785.19  | 2781.41 | 2.1875 | 6.5447 |
| 190 | 1.25524 | 0.001141 | 0.156362 | 806.00  | 2589.01 | 807.43  | 2785.28 | 2.2355 | 6.5059 |
| 195 | 1.39882 | 0.001149 | 0.140892 | 828.18  | 2591.74 | 829.79  | 2788.82 | 2.2832 | 6.4678 |
| 200 | 1.55493 | 0.001157 | 0.127210 | 850.47  | 2594.20 | 852.27  | 2792.01 | 2.3305 | 6.4302 |
| 205 | 1.72430 | 0.001164 | 0.115078 | 872.87  | 2596.40 | 874.88  | 2794.83 | 2.3777 | 6.3930 |
| 210 | 1.90767 | 0.001173 | 0.104292 | 895.39  | 2598.31 | 897.63  | 2797.27 | 2.4245 | 6.3563 |
| 215 | 2.10584 | 0.001181 | 0.094680 | 918.04  | 2599.94 | 920.53  | 2799.32 | 2.4712 | 6.3200 |
| 220 | 2.31959 | 0.001190 | 0.086092 | 940.82  | 2601.25 | 943.58  | 2800.95 | 2.5177 | 6.2840 |
| 225 | 2.54972 | 0.001199 | 0.078404 | 963.74  | 2602.24 | 966.80  | 2802.15 | 2.5640 | 6.2483 |
| 230 | 2.79709 | 0.001209 | 0.071504 | 986.81  | 2602.90 | 990.19  | 2802.90 | 2.6101 | 6.2128 |
| 235 | 3.06253 | 0.001219 | 0.065298 | 1010.04 | 2603.20 | 1013.77 | 2803.17 | 2.6561 | 6.1775 |
| 240 | 3.34693 | 0.001229 | 0.059705 | 1033.44 | 2603.13 | 1037.55 | 2802.96 | 2.7020 | 6.1423 |

|     |          |          |          |         |         |         |         |        |        |
|-----|----------|----------|----------|---------|---------|---------|---------|--------|--------|
| 245 | 3.65117  | 0.001240 | 0.054654 | 1057.02 | 2602.67 | 1061.55 | 2802.22 | 2.7478 | 6.1072 |
| 250 | 3.97617  | 0.001252 | 0.050083 | 1080.79 | 2601.79 | 1085.77 | 2800.93 | 2.7935 | 6.0721 |
| 255 | 4.32289  | 0.001264 | 0.045939 | 1104.77 | 2600.49 | 1110.23 | 2799.07 | 2.8392 | 6.0369 |
| 260 | 4.69226  | 0.001276 | 0.042173 | 1128.97 | 2598.72 | 1134.96 | 2796.60 | 2.8850 | 6.0016 |
| 265 | 5.08529  | 0.001289 | 0.038746 | 1153.41 | 2596.45 | 1159.96 | 2793.49 | 2.9307 | 5.9661 |
| 270 | 5.50299  | 0.001303 | 0.035621 | 1178.10 | 2593.67 | 1185.27 | 2789.69 | 2.9765 | 5.9304 |
| 275 | 5.94639  | 0.001318 | 0.032766 | 1203.07 | 2590.33 | 1210.90 | 2785.17 | 3.0224 | 5.8944 |
| 280 | 6.41658  | 0.001333 | 0.030153 | 1228.33 | 2586.39 | 1236.88 | 2779.87 | 3.0685 | 5.8579 |
| 285 | 6.91466  | 0.001349 | 0.027756 | 1253.92 | 2581.81 | 1263.25 | 2773.73 | 3.1147 | 5.8209 |
| 290 | 7.44178  | 0.001366 | 0.025555 | 1279.86 | 2576.53 | 1290.03 | 2766.70 | 3.1612 | 5.7834 |
| 295 | 7.99911  | 0.001385 | 0.023529 | 1306.19 | 2570.49 | 1317.27 | 2758.70 | 3.2080 | 5.7451 |
| 300 | 8.58790  | 0.001404 | 0.021660 | 1332.95 | 2563.62 | 1345.01 | 2749.64 | 3.2552 | 5.7059 |
| 305 | 9.20943  | 0.001425 | 0.019934 | 1360.18 | 2555.85 | 1373.30 | 2739.43 | 3.3028 | 5.6657 |
| 310 | 9.86505  | 0.001448 | 0.018335 | 1387.93 | 2547.07 | 1402.22 | 2727.95 | 3.3510 | 5.6244 |
| 315 | 10.55620 | 0.001472 | 0.016851 | 1416.28 | 2537.17 | 1431.83 | 2715.05 | 3.3998 | 5.5816 |
| 320 | 11.28430 | 0.001499 | 0.015471 | 1445.31 | 2526.01 | 1462.22 | 2700.59 | 3.4494 | 5.5372 |
| 325 | 12.05100 | 0.001528 | 0.014183 | 1475.11 | 2513.41 | 1493.52 | 2684.33 | 3.5000 | 5.4909 |
| 330 | 12.85810 | 0.001561 | 0.012979 | 1505.80 | 2499.15 | 1525.87 | 2666.03 | 3.5518 | 5.4422 |
| 335 | 13.70730 | 0.001597 | 0.011847 | 1537.56 | 2482.96 | 1559.45 | 2645.35 | 3.6050 | 5.3906 |
| 340 | 14.60070 | 0.001638 | 0.010781 | 1570.62 | 2464.44 | 1594.53 | 2621.85 | 3.6601 | 5.3356 |
| 345 | 15.54060 | 0.001685 | 0.009769 | 1605.30 | 2443.09 | 1631.48 | 2594.90 | 3.7176 | 5.2762 |
| 350 | 16.52940 | 0.001740 | 0.008802 | 1642.13 | 2418.14 | 1670.89 | 2563.64 | 3.7784 | 5.2110 |
| 355 | 17.57010 | 0.001808 | 0.007868 | 1681.96 | 2388.40 | 1713.72 | 2526.65 | 3.8439 | 5.1380 |
| 360 | 18.66600 | 0.001895 | 0.006949 | 1726.28 | 2351.78 | 1761.66 | 2481.49 | 3.9167 | 5.0536 |
| 365 | 19.82140 | 0.002017 | 0.006012 | 1777.79 | 2303.79 | 1817.77 | 2422.95 | 4.0014 | 4.9497 |
| 370 | 21.04360 | 0.002215 | 0.004954 | 1844.07 | 2230.26 | 1890.69 | 2334.52 | 4.1112 | 4.8012 |

|        |          |          |          |         |         |         |         |        |        |
|--------|----------|----------|----------|---------|---------|---------|---------|--------|--------|
| 373.95 | 22.06400 | 0.003106 | 0.003106 | 2015.73 | 2015.73 | 2084.26 | 2084.26 | 4.4070 | 4.4070 |
|--------|----------|----------|----------|---------|---------|---------|---------|--------|--------|

---

## Table A2: Superheated Vapor, Water

| T (°C) | $v$<br>m <sup>3</sup> /kg            | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--------------------------------------|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 10 kPa (Sat. T = 45.80°C)</b> |              |              |               | <b>P = 50 kPa (Sat.</b>   |              |
| Sat    | 14.6701                              | 2437.16      | 2583.86      | 8.1488        | 3.24003                   | 2483.21      |
| 50     | 14.8670                              | 2443.30      | 2591.97      | 8.1741        | -                         | -            |
| 100    | 17.1964                              | 2515.49      | 2687.46      | 8.4489        | 3.41867                   | 2511.49      |
| 150    | 19.5132                              | 2587.91      | 2783.04      | 8.6892        | 3.88973                   | 2585.73      |
| 200    | 21.8256                              | 2661.34      | 2879.60      | 8.9049        | 4.35616                   | 2659.96      |
| 250    | 24.1361                              | 2736.09      | 2977.45      | 9.1015        | 4.82061                   | 2735.12      |
| 300    | 26.4456                              | 2812.28      | 3076.74      | 9.2827        | 5.28405                   | 2811.56      |
| 350    | 28.7545                              | 2890.00      | 3177.55      | 9.4513        | 5.74690                   | 2889.44      |
| 400    | 31.0631                              | 2969.32      | 3279.95      | 9.6094        | 6.20940                   | 2968.86      |
| 450    | 33.3714                              | 3050.27      | 3383.98      | 9.7584        | 6.67166                   | 3049.89      |
| 500    | 35.6796                              | 3132.89      | 3489.69      | 9.8998        | 7.13376                   | 3132.58      |
| 550    | 37.9876                              | 3217.24      | 3597.11      | 10.0344       | 7.59574                   | 3216.96      |
| 600    | 40.2956                              | 3303.32      | 3706.27      | 10.1631       | 8.05763                   | 3303.08      |
| 650    | 42.6035                              | 3391.17      | 3817.20      | 10.2866       | 8.51946                   | 3390.96      |
| 700    | 44.9113                              | 3480.79      | 3929.90      | 10.4055       | 8.98123                   | 3480.60      |
| 750    | 47.2191                              | 3572.18      | 4044.37      | 10.5202       | 9.44296                   | 3572.02      |
| 800    | 49.5269                              | 3665.35      | 4160.62      | 10.6311       | 9.90467                   | 3665.20      |
| 850    | 51.8347                              | 3760.27      | 4278.61      | 10.7386       | 10.3663                   | 3760.13      |
| 900    | 54.1424                              | 3856.91      | 4398.33      | 10.8429       | 10.8280                   | 3856.79      |
| 950    | 56.4501                              | 3955.25      | 4519.75      | 10.9442       | 11.2896                   | 3955.14      |
| 1000   | 58.7578                              | 4055.24      | 4642.82      | 11.0428       | 11.7513                   | 4055.14      |
|        |                                      |              |              |               |                           |              |
| T (°C) | $v$<br>m <sup>3</sup> /kg            | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |

|        | P = 100 kPa (Sat. T = 99.60°C)  |              |              |               | P = 200 kPa (Sat. T = 119.63°C) |              |  |
|--------|---------------------------------|--------------|--------------|---------------|---------------------------------|--------------|--|
| Sat    | 1.69393                         | 2505.55      | 2674.95      | 7.3589        | 0.885682                        | 2529.09      |  |
| 150    | 1.93665                         | 2582.94      | 2776.60      | 7.6148        | 0.959855                        | 2577.13      |  |
| 200    | 2.17243                         | 2658.21      | 2875.45      | 7.8356        | 1.080480                        | 2654.63      |  |
| 250    | 2.40615                         | 2733.90      | 2974.51      | 8.0346        | 1.198890                        | 2731.43      |  |
| 300    | 2.63885                         | 2810.65      | 3074.53      | 8.2172        | 1.316230                        | 2808.82      |  |
| 350    | 2.87095                         | 2888.73      | 3175.83      | 8.3866        | 1.432970                        | 2887.31      |  |
| 400    | 3.10269                         | 2968.29      | 3278.56      | 8.5452        | 1.549330                        | 2967.15      |  |
| 450    | 3.33420                         | 3049.42      | 3382.84      | 8.6946        | 1.665460                        | 3048.48      |  |
| 500    | 3.56553                         | 3132.18      | 3488.73      | 8.8362        | 1.781420                        | 3131.39      |  |
| 550    | 3.79675                         | 3216.62      | 3596.30      | 8.9710        | 1.897260                        | 3215.95      |  |
| 600    | 4.02788                         | 3302.79      | 3705.58      | 9.0998        | 2.013010                        | 3302.20      |  |
| 650    | 4.25895                         | 3390.70      | 3816.60      | 9.2235        | 2.128700                        | 3390.18      |  |
| 700    | 4.48997                         | 3480.37      | 3929.37      | 9.3424        | 2.244330                        | 3479.92      |  |
| 750    | 4.72094                         | 3571.82      | 4043.91      | 9.4572        | 2.359930                        | 3571.41      |  |
| 800    | 4.95189                         | 3665.02      | 4160.21      | 9.5682        | 2.475500                        | 3664.65      |  |
| 850    | 5.18280                         | 3759.97      | 4278.25      | 9.6757        | 2.591030                        | 3759.64      |  |
| 900    | 5.41370                         | 3856.64      | 4398.01      | 9.7800        | 2.706550                        | 3856.34      |  |
| 950    | 5.64458                         | 3955.00      | 4519.46      | 9.8813        | 2.822050                        | 3954.72      |  |
| 1000   | 5.87545                         | 4055.01      | 4642.56      | 9.9800        | 2.937540                        | 4054.76      |  |
|        |                                 |              |              |               |                                 |              |  |
|        |                                 |              |              |               |                                 |              |  |
| T (°C) | $v$<br>m <sup>3</sup> /kg       | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg       | $u$<br>kJ/kg |  |
|        | P = 300 kPa (Sat. T = 133.52°C) |              |              |               | P = 400 kPa (Sat. T = 143.63°C) |              |  |
| Sat    | 0.60576                         | 2543.15      | 2724.88      | 6.9916        | 0.462383                        | 2553.10      |  |
| 150    | 0.63401                         | 2570.98      | 2761.19      | 7.0791        | 0.470883                        | 2564.43      |  |

|               |  |                                 |                                 |                                  |  |                                 |  |
|---------------|--|---------------------------------|---------------------------------|----------------------------------|--|---------------------------------|--|
| 200           | 0.71642                                    | 2650.96                         | 2865.89                         | 7.3131                           | 0.534334                                   | 2647.19                         |  |
| 250           | 0.79644                                    | 2728.93                         | 2967.87                         | 7.5180                           | 0.595196                                   | 2726.39                         |  |
| 300           | 0.87534                                    | 2806.98                         | 3069.58                         | 7.7037                           | 0.654892                                   | 2805.12                         |  |
| 350           | 0.95363                                    | 2885.88                         | 3171.97                         | 7.8750                           | 0.713958                                   | 2884.45                         |  |
| 400           | 1.03154                                    | 2966.00                         | 3275.47                         | 8.0347                           | 0.772645                                   | 2964.85                         |  |
| 450           | 1.10921                                    | 3047.53                         | 3380.29                         | 8.1849                           | 0.831085                                   | 3046.58                         |  |
| 500           | 1.18671                                    | 3130.59                         | 3486.60                         | 8.3271                           | 0.889357                                   | 3129.79                         |  |
| 550           | 1.26409                                    | 3215.26                         | 3594.49                         | 8.4623                           | 0.947510                                   | 3214.58                         |  |
| 600           | 1.34139                                    | 3301.61                         | 3704.03                         | 8.5914                           | 1.005570                                   | 3301.02                         |  |
| 650           | 1.41861                                    | 3389.67                         | 3815.25                         | 8.7153                           | 1.063570                                   | 3389.15                         |  |
| 700           | 1.49579                                    | 3479.46                         | 3928.20                         | 8.8344                           | 1.121520                                   | 3479.00                         |  |
| 750           | 1.57293                                    | 3571.00                         | 4042.88                         | 8.9494                           | 1.179430                                   | 3570.59                         |  |
| 800           | 1.65003                                    | 3664.28                         | 4159.29                         | 9.0604                           | 1.237300                                   | 3663.92                         |  |
| 850           | 1.72711                                    | 3759.30                         | 4277.44                         | 9.1680                           | 1.295150                                   | 3758.97                         |  |
| 900           | 1.80417                                    | 3856.03                         | 4397.28                         | 9.2724                           | 1.352980                                   | 3855.73                         |  |
| 950           | 1.88121                                    | 3954.45                         | 4518.81                         | 9.3739                           | 1.410790                                   | 3954.17                         |  |
| 1000          | 1.95823                                    | 4054.51                         | 4641.98                         | 9.4726                           | 1.468580                                   | 4054.25                         |  |
|               |  |                                 |                                 |                                  |  |                                 |  |
| <b>T (°C)</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> | <b><math>h</math><br/>kJ/kg</b> | <b><math>s</math><br/>kJ/kgK</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> |  |
|               | <b>P = 500 kPa (Sat. T = 151.83°C)</b>     |                                 |                                 |                                  | <b>P = 600 kPa (Sat.</b>                   |                                 |  |
| Sat           | 0.37481                                    | 2560.71                         | 2748.11                         | 6.8207                           | 0.315583                                   | 2566.79                         |  |
| 200           | 0.42503                                    | 2643.32                         | 2855.84                         | 7.0610                           | 0.352121                                   | 2639.34                         |  |
| 250           | 0.47443                                    | 2723.82                         | 2961.04                         | 7.2724                           | 0.393901                                   | 2721.21                         |  |
| 300           | 0.52261                                    | 2803.25                         | 3064.55                         | 7.4614                           | 0.434418                                   | 2801.36                         |  |
| 350           | 0.57015                                    | 2883.01                         | 3168.08                         | 7.6346                           | 0.474275                                   | 2881.56                         |  |

|               |  |                                 |                                 |                                  |  |                                 |  |
|---------------|--|---------------------------------|---------------------------------|----------------------------------|--|---------------------------------|--|
| 400           | 0.61730                                    | 2963.70                         | 3272.35                         | 7.7955                           | 0.513741                                   | 2962.54                         |  |
| 450           | 0.66421                                    | 3045.63                         | 3377.74                         | 7.9465                           | 0.552957                                   | 3044.68                         |  |
| 500           | 0.71094                                    | 3129.00                         | 3484.47                         | 8.0892                           | 0.592002                                   | 3128.20                         |  |
| 550           | 0.75756                                    | 3213.90                         | 3592.68                         | 8.2249                           | 0.630925                                   | 3213.22                         |  |
| 600           | 0.80409                                    | 3300.43                         | 3702.47                         | 8.3543                           | 0.669761                                   | 3299.84                         |  |
| 650           | 0.85055                                    | 3388.63                         | 3813.90                         | 8.4784                           | 0.708529                                   | 3388.11                         |  |
| 700           | 0.89696                                    | 3478.54                         | 3927.02                         | 8.5977                           | 0.747246                                   | 3478.08                         |  |
| 750           | 0.94332                                    | 3570.18                         | 4041.84                         | 8.7128                           | 0.785923                                   | 3569.77                         |  |
| 800           | 0.98966                                    | 3663.55                         | 4158.38                         | 8.8240                           | 0.824568                                   | 3663.18                         |  |
| 850           | 1.03597                                    | 3758.64                         | 4276.63                         | 8.9317                           | 0.863187                                   | 3758.31                         |  |
| 900           | 1.08226                                    | 3855.43                         | 4396.56                         | 9.0362                           | 0.901785                                   | 3855.13                         |  |
| 950           | 1.12853                                    | 3953.90                         | 4518.16                         | 9.1377                           | 0.940365                                   | 3953.62                         |  |
| 1000          | 1.17479                                    | 4054.00                         | 4641.40                         | 9.2364                           | 0.978931                                   | 4053.75                         |  |
|               |  |                                 |                                 |                                  |  |                                 |  |
| <b>T (°C)</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> | <b><math>h</math><br/>kJ/kg</b> | <b><math>s</math><br/>kJ/kgK</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> |  |
|               | <b>P = 800 kPa (Sat. T = 170.40°C)</b>     |                                 |                                 |                                  | <b>P = 1000 kPa (Sat. T = 179.91°C)</b>    |                                 |  |
| Sat           | 0.24034                                    | 2576.03                         | 2768.30                         | 6.6616                           | 0.194362                                   | 2582.75                         |  |
| 200           | 0.26088                                    | 2631.04                         | 2839.75                         | 6.8176                           | 0.206022                                   | 2622.24                         |  |
| 250           | 0.29321                                    | 2715.87                         | 2950.44                         | 7.0401                           | 0.232747                                   | 2710.38                         |  |
| 300           | 0.32416                                    | 2797.53                         | 3056.86                         | 7.2345                           | 0.257988                                   | 2793.64                         |  |
| 350           | 0.35442                                    | 2878.63                         | 3162.17                         | 7.4106                           | 0.282504                                   | 2875.68                         |  |
| 400           | 0.38428                                    | 2960.21                         | 3267.64                         | 7.5734                           | 0.306606                                   | 2957.87                         |  |
| 450           | 0.41389                                    | 3042.77                         | 3373.88                         | 7.7257                           | 0.330447                                   | 3040.85                         |  |
| 500           | 0.44332                                    | 3126.60                         | 3481.25                         | 7.8692                           | 0.354113                                   | 3124.99                         |  |
| 550           | 0.47263                                    | 3211.85                         | 3589.96                         | 8.0055                           | 0.377655                                   | 3210.48                         |  |

|               |  |                                 |                                 |                                  |  |                                 |  |
|---------------|--|---------------------------------|---------------------------------|----------------------------------|--|---------------------------------|--|
| 600           | 0.50185                                    | 3298.65                         | 3700.14                         | 8.1354                           | 0.401108                                   | 3297.47                         |  |
| 650           | 0.53101                                    | 3387.08                         | 3811.88                         | 8.2598                           | 0.424494                                   | 3386.04                         |  |
| 700           | 0.56011                                    | 3477.17                         | 3925.26                         | 8.3794                           | 0.447828                                   | 3476.25                         |  |
| 750           | 0.58917                                    | 3568.95                         | 4040.29                         | 8.4947                           | 0.471121                                   | 3568.14                         |  |
| 800           | 0.61820                                    | 3662.45                         | 4157.01                         | 8.6061                           | 0.494382                                   | 3661.71                         |  |
| 850           | 0.64721                                    | 3757.64                         | 4275.41                         | 8.7139                           | 0.517618                                   | 3756.98                         |  |
| 900           | 0.67619                                    | 3854.52                         | 4395.48                         | 8.8185                           | 0.540832                                   | 3853.92                         |  |
| 950           | 0.70516                                    | 3953.07                         | 4517.19                         | 8.9201                           | 0.564028                                   | 3952.52                         |  |
| 1000          | 0.73411                                    | 4053.24                         | 4640.53                         | 9.0189                           | 0.587210                                   | 4052.74                         |  |
|               |  |                                 |                                 |                                  |  |                                 |  |
| <b>T (°C)</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> | <b><math>h</math><br/>kJ/kg</b> | <b><math>s</math><br/>kJ/kgK</b> | <b><math>v</math><br/>m<sup>3</sup>/kg</b> | <b><math>u</math><br/>kJ/kg</b> |  |
|               | <b>P = 1200 kPa (Sat. T = 187.95°C)</b>    |                                 |                                 |                                  | <b>P = 1400 kPa (Sat.</b>                  |                                 |  |
| Sat           | 0.16326                                    | 2587.83                         | 2783.74                         | 6.5217                           | 0.140778                                   | 2591.76                         |  |
| 200           | 0.16934                                    | 2612.85                         | 2816.06                         | 6.5909                           | 0.143025                                   | 2602.72                         |  |
| 250           | 0.19241                                    | 2704.71                         | 2935.60                         | 6.8313                           | 0.163561                                   | 2698.88                         |  |
| 300           | 0.21386                                    | 2789.69                         | 3046.32                         | 7.0335                           | 0.182324                                   | 2785.67                         |  |
| 350           | 0.23455                                    | 2872.70                         | 3154.16                         | 7.2139                           | 0.200292                                   | 2869.68                         |  |
| 400           | 0.25482                                    | 2955.51                         | 3261.29                         | 7.3793                           | 0.217820                                   | 2953.14                         |  |
| 450           | 0.27482                                    | 3038.93                         | 3368.71                         | 7.5332                           | 0.235078                                   | 3036.99                         |  |
| 500           | 0.29464                                    | 3123.38                         | 3476.94                         | 7.6779                           | 0.252156                                   | 3121.76                         |  |
| 550           | 0.31434                                    | 3209.11                         | 3586.31                         | 7.8150                           | 0.269109                                   | 3207.73                         |  |
| 600           | 0.33395                                    | 3296.28                         | 3697.01                         | 7.9455                           | 0.285970                                   | 3295.09                         |  |
| 650           | 0.35349                                    | 3385.00                         | 3809.18                         | 8.0704                           | 0.302764                                   | 3383.96                         |  |
| 700           | 0.37297                                    | 3475.33                         | 3922.90                         | 8.1904                           | 0.319505                                   | 3474.41                         |  |
| 750           | 0.39242                                    | 3567.32                         | 4038.22                         | 8.3060                           | 0.336206                                   | 3566.50                         |  |

|               |   |  |  |   |   |  |  |
|---------------|---|--|--|---|---|--|--|
| 800           | 0.41184                                       | 3660.98                                      | 4155.18                                      | 8.4176  | 0.352874                                      | 3660.24                                      |  |
| 850           | 0.43123                                       | 3756.31                                      | 4273.78                                      | 8.5256  | 0.369516                                      | 3755.65                                      |  |
| 900           | 0.45059                                       | 3853.32                                      | 4394.03                                      | 8.6303  | 0.386137                                      | 3852.71                                      |  |
| 950           | 0.46994                                       | 3951.96                                      | 4515.90                                      | 8.7320  | 0.402741                                      | 3951.41                                      |  |
| 1000          | 0.48928                                       | 4052.23                                      | 4639.37                                      | 8.8310  | 0.419330                                      | 4051.72                                      |  |
|               |   |  |  |   |   |  |  |
| <b>T (°C)</b> | <b><math>v</math><br/><math>m^3/kg</math></b> | <b><math>u</math><br/><math>kJ/kg</math></b> | <b><math>h</math><br/><math>kJ/kg</math></b> | <b><math>s</math><br/><math>kJ/kgK</math></b> | <b><math>v</math><br/><math>m^3/kg</math></b> | <b><math>u</math><br/><math>kJ/kg</math></b> |  |
|               | <b>P = 1600 kPa (Sat. T = 201.37°C)</b>       |  |  |   | <b>P = 1800 kPa (Sat. T = 196.37°C)</b>       |  |  |
| Sat           | 0.12374                                       | 2594.83                                      | 2792.82                                      | 6.4199  | 0.110368                                      | 2597.24                                      |  |
| 250           | 0.19241                                       | 2704.71                                      | 2935.60                                      | 6.8313  | 0.163561                                      | 2698.88                                      |  |
| 300           | 0.21386                                       | 2789.69                                      | 3046.32                                      | 7.0335  | 0.182324                                      | 2785.67                                      |  |
| 350           | 0.23455                                       | 2872.70                                      | 3154.16                                      | 7.2139  | 0.200292                                      | 2869.68                                      |  |
| 400           | 0.25482                                       | 2955.51                                      | 3261.29                                      | 7.3793  | 0.217820                                      | 2953.14                                      |  |
| 450           | 0.27482                                       | 3038.93                                      | 3368.71                                      | 7.5332  | 0.235078                                      | 3036.99                                      |  |
| 500           | 0.29464                                       | 3123.38                                      | 3476.94                                      | 7.6779  | 0.252156                                      | 3121.76                                      |  |
| 550           | 0.31434                                       | 3209.11                                      | 3586.31                                      | 7.8150  | 0.269109                                      | 3207.73                                      |  |
| 600           | 0.33395                                       | 3296.28                                      | 3697.01                                      | 7.9455  | 0.285970                                      | 3295.09                                      |  |
| 650           | 0.35349                                       | 3385.00                                      | 3809.18                                      | 8.0704  | 0.302764                                      | 3383.96                                      |  |
| 700           | 0.37297                                       | 3475.33                                      | 3922.90                                      | 8.1904  | 0.319505                                      | 3474.41                                      |  |
| 750           | 0.39242                                       | 3567.32                                      | 4038.22                                      | 8.3060  | 0.336206                                      | 3566.50                                      |  |
| 800           | 0.41184                                       | 3660.98                                      | 4155.18                                      | 8.4176  | 0.352874                                      | 3660.24                                      |  |
| 850           | 0.43123                                       | 3756.31                                      | 4273.78                                      | 8.5256  | 0.369516                                      | 3755.65                                      |  |
| 900           | 0.45059                                       | 3853.32                                      | 4394.03                                      | 8.6303  | 0.386137                                      | 3852.71                                      |  |
| 950           | 0.46994                                       | 3951.96                                      | 4515.90                                      | 8.7320  | 0.402741                                      | 3951.41                                      |  |
| 1000          | 0.48928                                       | 4052.23                                      | 4639.37                                      | 8.8310  | 0.419330                                      | 4051.72                                      |  |

| T (°C)                                   | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK                            | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--|---------------------------|--------------|--------------|--|---------------------------|--------------|
| <b>P = 2000 kPa (Sat. T = 212.37° C)</b> |                           |              |              | <b>P = 2500 kPa (Sat. T = 212.37° C)</b> |                           |              |
| Sat                                      | 0.09959                   | 2599.12      | 2798.29      | 6.3390                                   | 0.079949                  | 2602.06      |
| 250                                      | 0.11150                   | 2680.25      | 2903.24      | 6.5475                                   | 0.087053                  | 2663.26      |
| 300                                      | 0.12551                   | 2773.17      | 3024.18      | 6.7684                                   | 0.098937                  | 2762.24      |
| 350                                      | 0.13860                   | 2860.45      | 3137.65      | 6.9583                                   | 0.109786                  | 2852.53      |
| 400                                      | 0.15122                   | 2945.91      | 3248.34      | 7.1292                                   | 0.120119                  | 2939.78      |
| 450                                      | 0.16354                   | 3031.13      | 3358.22      | 7.2866                                   | 0.130152                  | 3026.19      |
| 500                                      | 0.17568                   | 3116.87      | 3468.24      | 7.4337                                   | 0.139992                  | 3112.77      |
| 550                                      | 0.18770                   | 3203.58      | 3578.97      | 7.5725                                   | 0.149700                  | 3200.10      |
| 600                                      | 0.19962                   | 3291.51      | 3690.74      | 7.7043                                   | 0.159314                  | 3288.51      |
| 650                                      | 0.21147                   | 3380.83      | 3803.75      | 7.8302                                   | 0.168858                  | 3378.21      |
| 700                                      | 0.22326                   | 3471.64      | 3918.17      | 7.9509                                   | 0.178349                  | 3469.33      |
| 750                                      | 0.23502                   | 3564.03      | 4034.07      | 8.0670                                   | 0.187798                  | 3561.98      |
| 800                                      | 0.24674                   | 3658.03      | 4151.51      | 8.1791                                   | 0.197215                  | 3656.18      |
| 850                                      | 0.25844                   | 3753.65      | 4270.53      | 8.2874                                   | 0.206605                  | 3751.98      |
| 900                                      | 0.27012                   | 3850.90      | 4391.13      | 8.3925                                   | 0.215974                  | 3849.38      |
| 950                                      | 0.28178                   | 3949.76      | 4513.31      | 8.4945                                   | 0.225325                  | 3948.37      |
| 1000                                     | 0.29342                   | 4050.20      | 4637.04      | 8.5936                                   | 0.234661                  | 4048.94      |
| <b>P = 3000 kPa (Sat. T = 233.85° C)</b> |                           |              |              | <b>P = 4000 kPa (Sat. T = 233.85° C)</b> |                           |              |
| Sat                                      | 0.06666                   | 2603.16      | 2803.15      | 6.1856                                   | 0.049776                  | 2601.72      |
| 250                                      | 0.07063                   | 2644.65      | 2856.53      | 6.2893                                   | -                         | -            |

|      |         |         |         |        |          |         |
|------|---------|---------|---------|--------|----------|---------|
| 300  | 0.08118 | 2750.80 | 2994.33 | 6.5412 | 0.058870 | 2726.21 |
| 350  | 0.09056 | 2844.39 | 3116.06 | 6.7449 | 0.066473 | 2827.43 |
| 400  | 0.09938 | 2933.55 | 3231.69 | 6.9235 | 0.073431 | 2920.75 |
| 450  | 0.10789 | 3021.18 | 3344.84 | 7.0856 | 0.080043 | 3011.00 |
| 500  | 0.11620 | 3108.63 | 3457.22 | 7.2359 | 0.086442 | 3100.25 |
| 550  | 0.12437 | 3196.60 | 3569.70 | 7.3769 | 0.092700 | 3189.54 |
| 600  | 0.13245 | 3285.50 | 3682.83 | 7.5103 | 0.098859 | 3279.43 |
| 650  | 0.14045 | 3375.58 | 3796.94 | 7.6373 | 0.104945 | 3370.30 |
| 700  | 0.14841 | 3467.02 | 3912.24 | 7.7590 | 0.110976 | 3462.37 |
| 750  | 0.15632 | 3559.91 | 4028.87 | 7.8758 | 0.116966 | 3555.78 |
| 800  | 0.16420 | 3654.33 | 4146.92 | 7.9885 | 0.122922 | 3650.63 |
| 850  | 0.17205 | 3750.31 | 4266.46 | 8.0973 | 0.128852 | 3746.97 |
| 900  | 0.17988 | 3847.87 | 4387.50 | 8.2028 | 0.134759 | 3844.83 |
| 950  | 0.18769 | 3946.99 | 4510.06 | 8.3051 | 0.140649 | 3944.22 |
| 1000 | 0.19549 | 4047.67 | 4634.14 | 8.4045 | 0.146525 | 4045.13 |

## Table A3: Compressed Liquid Water

| T (°C) | $v$<br>m <sup>3</sup> /kg               | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg  | $u$<br>kJ/kg |
|--------|---|--------------|--------------|---------------|----------------------------|--------------|
|        | <b>P = 500 kPa (Sat. T = 151.83°C)</b>  |              |              |               | <b>P = 2000 kPa (Sat.</b>  |              |
| Sat    | 0.001093                                | 639.54       | 640.09       | 1.8604        | 0.001177                   | 906.15       |
| 0.01   | 0.001000                                | 0.01         | 0.51         | 0.0000        | 0.000999                   | 0.04         |
| 20     | 0.001002                                | 83.88        | 84.38        | 0.2964        | 0.001001                   | 83.79        |
| 40     | 0.001008                                | 167.47       | 167.97       | 0.5722        | 0.001007                   | 167.28       |
| 60     | 0.001017                                | 251.08       | 251.58       | 0.8310        | 0.001016                   | 250.81       |
| 80     | 0.001029                                | 334.86       | 335.37       | 1.0753        | 0.001028                   | 334.51       |
| 100    | 0.001043                                | 418.94       | 419.47       | 1.3069        | 0.001042                   | 418.51       |
| 120    | 0.001060                                | 503.49       | 504.02       | 1.5276        | 0.001059                   | 502.96       |
| 140    | 0.001080                                | 588.71       | 589.25       | 1.7391        | 0.001079                   | 588.07       |
| 160    | -                                       | -            | -            | -             | 0.001101                   | 674.08       |
| 180    | -                                       | -            | -            | -             | 0.001127                   | 761.30       |
| 200    | -                                       | -            | -            | -             | 0.001156                   | 850.14       |
|        |   |              |              |               |                            |              |
| T (°C) | $v$<br>m <sup>3</sup> /kg               | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg  | $u$<br>kJ/kg |
|        | <b>P = 5000 kPa (Sat. T = 263.94°C)</b> |              |              |               | <b>P = 10000 kPa (Sat.</b> |              |
| Sat    | 0.001286                                | 1148.21      | 1154.64      | 2.9210        | 0.001453                   | 1393.54      |
| 0.01   | 0.000998                                | 0.09         | 5.07         | 0.0003        | 0.000995                   | 0.16         |
| 20     | 0.001000                                | 83.61        | 88.61        | 0.2954        | 0.000997                   | 83.31        |
| 40     | 0.001006                                | 166.92       | 171.95       | 0.5705        | 0.001004                   | 166.33       |
| 60     | 0.001015                                | 250.29       | 255.36       | 0.8287        | 0.001013                   | 249.43       |
| 80     | 0.001027                                | 333.82       | 338.96       | 1.0723        | 0.001024                   | 332.69       |
| 100    | 0.001041                                | 417.65       | 422.85       | 1.3034        | 0.001038                   | 416.23       |
| 120    | 0.001058                                | 501.91       | 507.19       | 1.5236        | 0.001055                   | 500.18       |

|     |          |         |         |        |          |         |   |
|-----|----------|---------|---------|--------|----------|---------|---|
| 140 | 0.001077 | 586.79  | 592.18  | 1.7344 | 0.001074 | 584.71  |   |
| 160 | 0.001099 | 672.55  | 678.04  | 1.9374 | 0.001095 | 670.06  |   |
| 180 | 0.001124 | 759.46  | 765.08  | 2.1338 | 0.001120 | 756.48  |   |
| 200 | 0.001153 | 847.91  | 853.68  | 2.3251 | 0.001148 | 844.31  |   |
| 220 | 0.001187 | 938.39  | 944.32  | 2.5127 | 0.001181 | 934.00  |   |
| 240 | 0.001227 | 1031.58 | 1037.71 | 2.6983 | 0.001219 | 1026.14 | 1 |
| 260 | 0.001275 | 1128.53 | 1134.91 | 2.8841 | 0.001265 | 1121.61 |   |
| 280 | -        | -       | -       | -      | 0.001323 | 1221.80 | 1 |
| 300 | -        | -       | -       | -      | 0.001398 | 1329.35 | 1 |

| T (°C) | $v$<br>m <sup>3</sup> /kg                | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg                | $u$<br>kJ/kg |  |
|--------|--|--------------|--------------|---------------|--|--------------|--|
|        | <b>P = 15000 kPa (Sat. T = 342.16°C)</b> |              |              |               | <b>P = 20000 kPa (Sat. T = 342.16°C)</b> |              |  |
| Sat    | 0.001657                                 | 1585.35      | 1610.20      | 3.6846        | 0.002040                                 | 1786.41      |  |
| 0.01   | 0.000993                                 | 0.22         | 15.11        | 0.0006        | 0.000990                                 | 0.27         |  |
| 20     | 0.000995                                 | 83.01        | 97.93        | 0.2932        | 0.000993                                 | 82.71        |  |
| 40     | 0.001001                                 | 165.75       | 180.77       | 0.5666        | 0.000999                                 | 165.17       |  |
| 60     | 0.001011                                 | 248.58       | 263.74       | 0.8234        | 0.001008                                 | 247.75       |  |
| 80     | 0.001022                                 | 331.59       | 346.92       | 1.0659        | 0.001020                                 | 330.50       |  |
| 100    | 0.001036                                 | 414.85       | 430.39       | 1.2958        | 0.001034                                 | 413.50       |  |
| 120    | 0.001052                                 | 498.49       | 514.28       | 1.5148        | 0.001050                                 | 496.85       |  |
| 140    | 0.001071                                 | 582.69       | 598.75       | 1.7243        | 0.001068                                 | 580.71       |  |
| 160    | 0.001092                                 | 667.63       | 684.01       | 1.9259        | 0.001089                                 | 665.28       |  |
| 180    | 0.001116                                 | 753.58       | 770.32       | 2.1206        | 0.001112                                 | 750.77       |  |
| 200    | 0.001144                                 | 840.84       | 857.99       | 2.3100        | 0.001139                                 | 837.49       |  |
| 220    | 0.001175                                 | 929.80       | 947.43       | 2.4951        | 0.001170                                 | 925.77       |  |

|               |   |  |  |   |   |  |   |
|---------------|---|--|--|---|---|--|---|
| 240           | 0.001212                                      | 1020.98                                      | 1039.16                                      | 2.6774  | 0.001205                                      | 1016.07                                      | 1 |
| 260           | 0.001256                                      | 1115.12                                      | 1133.96                                      | 2.8586  | 0.001247                                      | 1109.02                                      | 1 |
| 280           | 0.001310                                      | 1213.36                                      | 1233.00                                      | 3.0409  | 0.001298                                      | 1205.55                                      | 1 |
| 300           | 0.001378                                      | 1317.63                                      | 1338.30                                      | 3.2279  | 0.001361                                      | 1307.15                                      | 1 |
| 320           | 0.001473                                      | 1431.93                                      | 1454.02                                      | 3.4263  | 0.001445                                      | 1416.59                                      | 1 |
| 340           | 0.001631                                      | 1567.89                                      | 1592.36                                      | 3.6555  | 0.001569                                      | 1540.20                                      | 1 |
| 360           | -   | -  | -  | -   | 0.001825                                      | 1703.60                                      | 1 |
|               |   |  |  |   |   |  |   |
| <b>T (°C)</b> | <b><math>v</math><br/><math>m^3/kg</math></b> | <b><math>u</math><br/><math>kJ/kg</math></b> | <b><math>h</math><br/><math>kJ/kg</math></b> | <b><math>s</math><br/><math>kJ/kgK</math></b> | <b><math>v</math><br/><math>m^3/kg</math></b> | <b><math>u</math><br/><math>kJ/kg</math></b> |   |
|               | <b>P = 30000 kPa</b>                          |  |  |   | <b>P = 50000 kPa</b>                          |  |   |
| 0.01          | 0.000986                                      | 0.33   | 29.90  | 0.0004  | 0.000977                                      | 0.33   |   |
| 20            | 0.000989                                      | 82.11  | 111.77                                       | 0.2897  | 0.000980                                      | 80.93  |   |
| 40            | 0.000995                                      | 164.05                                       | 193.90                                       | 0.5607  | 0.000987                                      | 161.90                                       |   |
| 60            | 0.001004                                      | 246.14                                       | 276.26                                       | 0.8156  | 0.000996                                      | 243.08                                       |   |
| 80            | 0.001016                                      | 328.40                                       | 358.86                                       | 1.0564  | 0.001007                                      | 324.42                                       |   |
| 100           | 0.001029                                      | 410.87                                       | 441.74                                       | 1.2847  | 0.001020                                      | 405.94                                       |   |
| 120           | 0.001045                                      | 493.66                                       | 525.00                                       | 1.5020  | 0.001035                                      | 487.69                                       |   |
| 140           | 0.001062                                      | 576.90                                       | 608.76                                       | 1.7098  | 0.001052                                      | 569.77                                       |   |
| 160           | 0.001082                                      | 660.74                                       | 693.21                                       | 1.9094  | 0.001070                                      | 652.32                                       |   |
| 180           | 0.001105                                      | 745.40                                       | 778.55                                       | 2.1020  | 0.001091                                      | 735.49                                       |   |
| 200           | 0.001130                                      | 831.10                                       | 865.02                                       | 2.2888  | 0.001115                                      | 819.45                                       |   |
| 220           | 0.001159                                      | 918.14                                       | 952.93                                       | 2.4707  | 0.001141                                      | 904.39                                       |   |
| 240           | 0.001193                                      | 1006.87                                      | 1042.66                                      | 2.6491  | 0.001171                                      | 990.55                                       | 1 |
| 260           | 0.001231                                      | 1097.77                                      | 1134.71                                      | 2.8250  | 0.001204                                      | 1078.22                                      | 1 |
| 280           | 0.001277                                      | 1191.47                                      | 1229.77                                      | 3.0001  | 0.001243                                      | 1167.74                                      | 1 |

|     |          |         |         |        |          |         |   |
|-----|----------|---------|---------|--------|----------|---------|---|
| 300 | 0.001332 | 1288.92 | 1328.89 | 3.1760 | 0.001288 | 1259.57 | 1 |
| 320 | 0.001401 | 1391.65 | 1433.69 | 3.3557 | 0.001341 | 1354.33 |   |
| 340 | 0.001493 | 1502.34 | 1547.14 | 3.5438 | 0.001405 | 1452.87 |   |
| 360 | 0.001628 | 1626.74 | 1675.57 | 3.7498 | 0.001485 | 1556.46 | 1 |
| 380 | 0.001873 | 1782.04 | 1838.22 | 4.0025 | 0.001588 | 1667.07 | 1 |

### Reference States, default for fluid

- **Enthalpy**  $H = 2551.013479$  kJ/kg at 26.9 C and 0.0010 MPa.
- **Entropy**  $S = 9.103679$  J/g\*K at 26.9 C and 0.0010 MPa.

Source: Eric W. Lemmon, Mark O. McLinden and Daniel G. Friend, "Thermophysical Properties of Fluid Systems" in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <https://doi.org/10.18434/T4D303>, (retrieved May 2021).

# Appendix B: Thermodynamic Properties of Ammonia

## Table B1: Saturated Ammonia

| T (°C) | P (MPa) | Specific Volume<br>m <sup>3</sup> /kg |                | Specific Internal Energy<br>kJ/kg |                |
|--------|---------|---------------------------------------|----------------|-----------------------------------|----------------|
|        |         | v <sub>f</sub>                        | v <sub>g</sub> | u <sub>f</sub>                    | u <sub>g</sub> |
| -50    | 0.04084 | 0.001424                              | 2.627750       | 118.37                            | 1418.5         |
| -45    | 0.05449 | 0.001436                              | 2.007080       | 140.23                            | 1418.5         |
| -40    | 0.07169 | 0.001449                              | 1.553280       | 162.22                            | 1418.5         |
| -35    | 0.09310 | 0.001462                              | 1.216780       | 184.34                            | 1418.5         |
| -30    | 0.11943 | 0.001475                              | 0.963963       | 206.58                            | 1418.5         |
| -25    | 0.15147 | 0.001489                              | 0.771672       | 228.94                            | 1418.5         |
| -20    | 0.19008 | 0.001503                              | 0.623730       | 251.42                            | 1418.5         |
| -15    | 0.23617 | 0.001518                              | 0.508679       | 274.01                            | 1418.5         |
| -10    | 0.29071 | 0.001534                              | 0.418303       | 296.72                            | 1418.5         |
| -5     | 0.35476 | 0.001550                              | 0.346635       | 319.54                            | 1418.5         |
| 0      | 0.42939 | 0.001566                              | 0.289297       | 342.48                            | 1418.5         |
| 5      | 0.51575 | 0.001583                              | 0.243039       | 365.55                            | 1418.5         |
| 10     | 0.61505 | 0.001601                              | 0.205426       | 388.74                            | 1418.5         |
| 15     | 0.72853 | 0.001619                              | 0.174614       | 412.06                            | 1418.5         |
| 20     | 0.85748 | 0.001639                              | 0.149198       | 435.53                            | 1418.5         |
| 25     | 1.00324 | 0.001659                              | 0.128092       | 459.16                            | 1418.5         |
| 30     | 1.16720 | 0.001680                              | 0.110457       | 482.95                            | 1518.5         |
| 35     | 1.35077 | 0.001702                              | 0.095633       | 506.93                            | 1518.5         |
| 40     | 1.55542 | 0.001726                              | 0.083101       | 531.11                            | 1518.5         |
| 45     | 1.78266 | 0.001750                              | 0.072450       | 555.51                            | 1518.5         |
| 50     | 2.03403 | 0.001777                              | 0.063350       | 580.16                            | 1518.5         |
| 55     | 2.31113 | 0.001804                              | 0.055538       | 605.09                            | 1518.5         |
| 60     | 2.61560 | 0.001834                              | 0.048797       | 630.33                            | 1518.5         |
| 65     | 2.94913 | 0.001866                              | 0.042955       | 655.91                            | 1518.5         |

|        |          |          |          |         |    |
|--------|----------|----------|----------|---------|----|
| 70     | 3.31347  | 0.001900 | 0.037868 | 681.90  | 15 |
| 75     | 3.71045  | 0.001937 | 0.033419 | 708.34  | 14 |
| 80     | 4.14197  | 0.001978 | 0.029509 | 735.31  | 14 |
| 85     | 4.61002  | 0.002022 | 0.026058 | 762.88  | 14 |
| 90     | 5.11672  | 0.002071 | 0.022997 | 791.16  | 14 |
| 95     | 5.66432  | 0.002127 | 0.020268 | 820.29  | 14 |
| 100    | 6.25527  | 0.002190 | 0.017820 | 850.46  | 14 |
| 105    | 6.89227  | 0.002263 | 0.015610 | 881.91  | 14 |
| 110    | 7.57834  | 0.002350 | 0.013596 | 915.03  | 14 |
| 115    | 8.31700  | 0.002456 | 0.011740 | 950.47  | 14 |
| 120    | 9.11249  | 0.002594 | 0.009993 | 989.44  | 14 |
| 125    | 9.97022  | 0.002795 | 0.008283 | 1034.97 | 13 |
| 130    | 10.89770 | 0.003202 | 0.006379 | 1100.28 | 13 |
| 132.25 | 11.33930 | 0.004444 | 0.004444 | 1211.98 | 12 |

## Table B2: Superheated Ammonia

| T (°C) | $v$<br>m <sup>3</sup> /kg             | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---------------------------------------|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 50 kPa (Sat. T = -46.51°C)</b> |              |              |               | <b>P = 100 kPa</b>        |              |
| Sat    | 2.17495                               | 1431.47      | 1540.22      | 6.8401        | 1.13809                   | 1447.        |
| -30    | 2.34496                               | 1458.80      | 1576.05      | 6.9927        | 1.15730                   | 1453.        |
| -20    | 2.44645                               | 1475.09      | 1597.42      | 7.0788        | 1.21016                   | 1470.        |
| -10    | 2.54720                               | 1491.30      | 1618.66      | 7.1611        | 1.26220                   | 1487.        |
| 0      | 2.64739                               | 1507.47      | 1639.84      | 7.2402        | 1.31365                   | 1504.        |
| 10     | 2.74715                               | 1523.67      | 1661.02      | 7.3163        | 1.36463                   | 1520.        |
| 20     | 2.84657                               | 1539.91      | 1682.24      | 7.3899        | 1.41527                   | 1537.        |
| 30     | 2.94572                               | 1556.23      | 1703.51      | 7.4613        | 1.46562                   | 1554.        |
| 40     | 3.04466                               | 1572.64      | 1724.88      | 7.5306        | 1.51576                   | 1570.        |
| 50     | 3.14343                               | 1589.17      | 1746.34      | 7.5981        | 1.56571                   | 1587.        |
| 60     | 3.24205                               | 1605.83      | 1767.93      | 7.6639        | 1.61552                   | 1604.        |
| 70     | 3.34056                               | 1622.63      | 1789.65      | 7.7281        | 1.66521                   | 1621.        |
| 80     | 3.43896                               | 1639.57      | 1811.52      | 7.7910        | 1.71480                   | 1638.        |
| 90     | 3.53729                               | 1656.68      | 1833.54      | 7.8525        | 1.76431                   | 1655.        |
| 100    | 3.63554                               | 1673.95      | 1855.73      | 7.9127        | 1.81374                   | 1672.        |
| 110    | 3.73373                               | 1691.40      | 1878.08      | 7.9718        | 1.86311                   | 1690.        |
| 120    | 3.83187                               | 1709.02      | 1900.62      | 8.0299        | 1.91243                   | 1708.        |
| 130    | 3.92996                               | 1726.83      | 1923.33      | 8.0869        | 1.96170                   | 1725.        |
| 140    | 4.02801                               | 1744.83      | 1946.23      | 8.1431        | 2.01094                   | 1744.        |

|     |         |         |         |        |         |       |
|-----|---------|---------|---------|--------|---------|-------|
| 150 | 4.12603 | 1763.03 | 1969.33 | 8.1983 | 2.06013 | 1762. |
| 160 | 4.22402 | 1781.42 | 1992.62 | 8.2527 | 2.10930 | 1780. |
| 170 | 4.32198 | 1800.01 | 2016.11 | 8.3063 | 2.15844 | 1799. |
| 180 | 4.41991 | 1818.81 | 2039.80 | 8.3592 | 2.20755 | 1818. |
| 190 | 4.51783 | 1837.81 | 2063.70 | 8.4113 | 2.25664 | 1837. |
| 200 | 4.61572 | 1857.03 | 2087.81 | 8.4628 | 2.30572 | 1856. |

| T (°C) | $v$<br>m <sup>3</sup> /kg               | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 150 kPa (Sat. T = -25.20 °C)</b> |              |              |               | <b>P = 200 kPa</b>        |              |
| Sat    | 0.778759                                | 1456.69      | 1573.50      | 6.4577        | 0.594648                  | 1463.        |
| -20    | 0.797792                                | 1466.08      | 1585.75      | 6.5066        | -                         | -            |
| -10    | 0.833689                                | 1483.73      | 1608.78      | 6.5958        | 0.619287                  | 1479.        |
| 0      | 0.868939                                | 1501.03      | 1631.37      | 6.6801        | 0.646486                  | 1497.        |
| 10     | 0.903705                                | 1518.10      | 1653.66      | 6.7602        | 0.673171                  | 1515.        |
| 20     | 0.938100                                | 1535.05      | 1675.77      | 6.8370        | 0.699467                  | 1532.        |
| 30     | 0.972207                                | 1551.95      | 1697.78      | 6.9108        | 0.725463                  | 1549.        |
| 40     | 1.006090                                | 1568.84      | 1719.75      | 6.9821        | 0.751222                  | 1566.        |
| 50     | 1.039780                                | 1585.76      | 1741.73      | 7.0512        | 0.776793                  | 1584.        |
| 60     | 1.073330                                | 1602.75      | 1763.75      | 7.1183        | 0.802212                  | 1601.        |
| 70     | 1.106750                                | 1619.83      | 1785.85      | 7.1836        | 0.827505                  | 1618.        |
| 80     | 1.140070                                | 1637.02      | 1808.03      | 7.2474        | 0.852693                  | 1635.        |

|     |          |         |         |        |          |        |
|-----|----------|---------|---------|--------|----------|--------|
| 90  | 1.173310 | 1654.34 | 1830.34 | 7.3096 | 0.877795 | 1653.  |
| 100 | 1.206470 | 1671.79 | 1852.76 | 7.3706 | 0.902823 | 1670.  |
| 110 | 1.239570 | 1689.40 | 1875.34 | 7.4303 | 0.927789 | 1688.  |
| 120 | 1.272610 | 1707.17 | 1898.06 | 7.4888 | 0.952700 | 1706.  |
| 130 | 1.305610 | 1725.10 | 1920.94 | 7.5463 | 0.977565 | 1724.  |
| 140 | 1.338570 | 1743.21 | 1944.00 | 7.6028 | 1.002390 | 1742.  |
| 150 | 1.371500 | 1761.51 | 1967.23 | 7.6583 | 1.027180 | 1760.  |
| 160 | 1.404390 | 1779.99 | 1990.65 | 7.7130 | 1.051930 | 1779.  |
| 170 | 1.437260 | 1798.66 | 2014.25 | 7.7669 | 1.076660 | 1797.5 |
| 180 | 1.470100 | 1817.53 | 2038.05 | 7.8200 | 1.101370 | 1816.5 |
| 190 | 1.502920 | 1836.60 | 2062.04 | 7.8724 | 1.126050 | 1836.  |
| 200 | 1.535710 | 1855.88 | 2086.24 | 7.9241 | 1.150710 | 1855.  |
| 210 | 1.568500 | 1875.36 | 2110.64 | 7.9751 | 1.175360 | 1874.  |
| 220 | 1.601260 | 1895.06 | 2135.25 | 8.0255 | 1.199990 | 1894.  |

| T (°C) | $v$<br>m <sup>3</sup> /kg               | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 300 kPa (Sat. T = -9.224 °C)</b> |              |              |               | <b>P = 400 kPa</b>        |              |
| Sat    | 0.406085                                | 1472.98      | 1594.81      | 6.2175        | 0.309410                  | 1479.5       |
| 0      | 0.423819                                | 1490.74      | 1617.89      | 6.3035        | 0.312249                  | 1483.5       |
| 10     | 0.442489                                | 1509.34      | 1642.08      | 6.3905        | 0.326987                  | 1503.5       |
| 20     | 0.460728                                | 1527.48      | 1665.70      | 6.4725        | 0.341246                  | 1522.5       |

|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 30  | 0.478641 | 1545.32 | 1688.91 | 6.5503 | 0.355149 | 1540. |
| 40  | 0.496302 | 1562.98 | 1711.87 | 6.6249 | 0.368782 | 1558. |
| 50  | 0.513762 | 1580.54 | 1734.67 | 6.6965 | 0.382202 | 1576. |
| 60  | 0.531063 | 1598.05 | 1757.37 | 6.7657 | 0.395454 | 1594. |
| 70  | 0.548233 | 1615.58 | 1780.05 | 6.8328 | 0.408571 | 1612. |
| 80  | 0.565296 | 1633.15 | 1802.74 | 6.8979 | 0.421576 | 1630. |
| 90  | 0.582269 | 1650.79 | 1825.47 | 6.9614 | 0.434489 | 1648. |
| 100 | 0.599166 | 1668.53 | 1848.28 | 7.0234 | 0.447324 | 1666. |
| 110 | 0.616000 | 1686.38 | 1871.18 | 7.0839 | 0.460094 | 1684. |
| 120 | 0.632778 | 1704.36 | 1894.19 | 7.1432 | 0.472807 | 1702. |
| 130 | 0.649508 | 1722.49 | 1917.34 | 7.2014 | 0.485473 | 1720. |
| 140 | 0.666198 | 1740.77 | 1940.63 | 7.2584 | 0.498096 | 1739. |
| 150 | 0.682851 | 1759.22 | 1964.07 | 7.3145 | 0.510683 | 1757. |
| 160 | 0.699473 | 1777.83 | 1987.68 | 7.3696 | 0.523238 | 1776. |
| 170 | 0.716066 | 1796.63 | 2011.45 | 7.4239 | 0.535764 | 1795. |
| 180 | 0.732635 | 1815.61 | 2035.40 | 7.4774 | 0.548266 | 1814. |
| 190 | 0.749181 | 1834.79 | 2059.54 | 7.5300 | 0.560745 | 1833. |
| 200 | 0.765708 | 1854.16 | 2083.87 | 7.5820 | 0.573204 | 1853. |
| 210 | 0.782217 | 1873.73 | 2108.39 | 7.6333 | 0.585645 | 1872. |
| 220 | 0.798710 | 1893.50 | 2133.11 | 7.6839 | 0.598070 | 1892. |
| 230 | 0.815188 | 1913.48 | 2158.04 | 7.7340 | 0.610480 | 1912. |

|               |                                       |                          |                          |                           |                                      |                        |
|---------------|---------------------------------------|--------------------------|--------------------------|---------------------------|--------------------------------------|------------------------|
| 240           | 0.831653                              | 1933.67                  | 2183.17                  | 7.7834                    | 0.622877                             | 1932.                  |
| 250           | 0.848105                              | 1954.08                  | 2208.51                  | 7.8323                    | 0.635261                             | 1953.                  |
| 260           | 0.864547                              | 1974.69                  | 2234.06                  | 7.8807                    | 0.647635                             | 1973.                  |
|               |                                       |                          |                          |                           |                                      |                        |
|               |                                       |                          |                          |                           |                                      |                        |
| <b>T (°C)</b> | <b><math>v</math><sup>3</sup>/kg</b>  | <b>u</b><br><b>kJ/kg</b> | <b>h</b><br><b>kJ/kg</b> | <b>s</b><br><b>kJ/kgK</b> | <b><math>v</math><sup>3</sup>/kg</b> | <b>u</b><br><b>kJ/</b> |
|               | <b>P = 500 kPa (Sat. T = 4.13 °C)</b> |                          |                          |                           | <b>P = 600 kPa</b>                   |                        |
| Sat           | 0.250324                              | 1484.53                  | 1609.69                  | 6.0393                    | 0.210353                             | 1488.                  |
| 10            | 0.257544                              | 1496.73                  | 1625.50                  | 6.0957                    | 0.211117                             | 1489.                  |
| 20            | 0.269459                              | 1516.75                  | 1651.48                  | 6.1859                    | 0.221513                             | 1511.0                 |
| 30            | 0.280985                              | 1536.04                  | 1676.54                  | 6.2699                    | 0.231480                             | 1531.2                 |
| 40            | 0.292219                              | 1554.85                  | 1700.96                  | 6.3492                    | 0.241132                             | 1550.                  |
| 50            | 0.303228                              | 1573.34                  | 1724.95                  | 6.4246                    | 0.250546                             | 1569.                  |
| 60            | 0.314060                              | 1591.62                  | 1748.65                  | 6.4968                    | 0.259773                             | 1588.                  |
| 70            | 0.324751                              | 1609.77                  | 1772.15                  | 6.5663                    | 0.268852                             | 1606.                  |
| 80            | 0.335327                              | 1627.88                  | 1795.54                  | 6.6335                    | 0.277812                             | 1625.                  |
| 90            | 0.345807                              | 1645.98                  | 1818.88                  | 6.6987                    | 0.286674                             | 1643.                  |
| 100           | 0.356208                              | 1664.10                  | 1842.21                  | 6.7621                    | 0.295454                             | 1661.                  |
| 110           | 0.366541                              | 1682.30                  | 1865.57                  | 6.8239                    | 0.304166                             | 1680.                  |
| 120           | 0.376818                              | 1700.58                  | 1888.99                  | 6.8842                    | 0.312819                             | 1698.                  |
| 130           | 0.387045                              | 1718.97                  | 1912.49                  | 6.9432                    | 0.321422                             | 1717.                  |
| 140           | 0.397230                              | 1737.48                  | 1936.10                  | 7.0011                    | 0.329982                             | 1735.                  |

|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 150 | 0.407378 | 1756.14 | 1959.83 | 7.0578 | 0.338505 | 1754. |
| 160 | 0.417494 | 1774.94 | 1983.69 | 7.1136 | 0.346995 | 1773. |
| 170 | 0.427580 | 1793.91 | 2007.70 | 7.1683 | 0.355455 | 1792. |
| 180 | 0.437642 | 1813.04 | 2031.86 | 7.2223 | 0.363891 | 1811. |
| 190 | 0.447681 | 1832.35 | 2056.19 | 7.2754 | 0.372303 | 1831. |
| 200 | 0.457700 | 1851.85 | 2080.70 | 7.3277 | 0.380695 | 1850. |
| 210 | 0.467700 | 1871.54 | 2105.39 | 7.3794 | 0.389069 | 1870. |
| 220 | 0.477684 | 1891.41 | 2130.26 | 7.4303 | 0.397427 | 1890. |
| 230 | 0.487654 | 1911.49 | 2155.32 | 7.4806 | 0.405769 | 1910. |
| 240 | 0.497610 | 1931.77 | 2180.58 | 7.5303 | 0.414099 | 1930. |
| 250 | 0.507554 | 1952.26 | 2206.04 | 7.5795 | 0.422416 | 1951. |
| 260 | 0.517487 | 1972.96 | 2231.70 | 7.6281 | 0.430721 | 1972. |

| T (°C) | $v$<br>m <sup>3</sup> /kg             | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---------------------------------------|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 800 kPa (Sat. T = 17.84°C)</b> |              |              |               | <b>P = 1000 kPa</b>       |              |
| Sat    | 0.159551                              | 1494.11      | 1621.75      | 5.8725        | 0.128497                  | 1498.        |
| 20     | 0.161354                              | 1499.04      | 1628.12      | 5.8943        | -                         | -            |
| 30     | 0.169445                              | 1521.03      | 1656.59      | 5.9898        | 0.132037                  | 1510.        |
| 40     | 0.177166                              | 1541.90      | 1683.63      | 6.0776        | 0.138657                  | 1532.        |
| 50     | 0.184614                              | 1561.99      | 1709.68      | 6.1595        | 0.144962                  | 1554.        |
| 60     | 0.191854                              | 1581.56      | 1735.04      | 6.2367        | 0.151035                  | 1574.        |

|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 70  | 0.198934 | 1600.77 | 1759.91 | 6.3103 | 0.156931 | 1594. |
| 80  | 0.205884 | 1619.74 | 1784.45 | 6.3808 | 0.162688 | 1614. |
| 90  | 0.212730 | 1638.57 | 1808.76 | 6.4487 | 0.168333 | 1633. |
| 100 | 0.219490 | 1657.33 | 1832.92 | 6.5143 | 0.173887 | 1652. |
| 110 | 0.226178 | 1676.06 | 1857.01 | 6.5780 | 0.179366 | 1671. |
| 120 | 0.232805 | 1694.81 | 1881.06 | 6.6400 | 0.184782 | 1690. |
| 130 | 0.239381 | 1713.61 | 1905.12 | 6.7004 | 0.190144 | 1709. |
| 140 | 0.245912 | 1732.49 | 1929.22 | 6.7595 | 0.195460 | 1729. |
| 150 | 0.252405 | 1751.47 | 1953.39 | 6.8173 | 0.200737 | 1748. |
| 160 | 0.258864 | 1770.56 | 1977.65 | 6.8739 | 0.205979 | 1767. |
| 170 | 0.265294 | 1789.78 | 2002.02 | 6.9295 | 0.211191 | 1787. |
| 180 | 0.271697 | 1809.15 | 2026.51 | 6.9842 | 0.216376 | 1806. |
| 190 | 0.278077 | 1828.68 | 2051.14 | 7.0380 | 0.221538 | 1826. |
| 200 | 0.284437 | 1848.36 | 2075.91 | 7.0909 | 0.226678 | 1846. |
| 210 | 0.290778 | 1868.23 | 2100.85 | 7.1430 | 0.231800 | 1866. |
| 220 | 0.297102 | 1888.27 | 2125.95 | 7.1945 | 0.236905 | 1886. |
| 230 | 0.303412 | 1908.49 | 2151.22 | 7.2452 | 0.241995 | 1906. |
| 240 | 0.309708 | 1928.91 | 2176.68 | 7.2953 | 0.247071 | 1926. |
| 250 | 0.315991 | 1949.53 | 2202.32 | 7.3448 | 0.252135 | 1947. |
| 260 | 0.322263 | 1970.34 | 2228.15 | 7.3937 | 0.257187 | 1968. |
| 270 | 0.328525 | 1991.36 | 2254.18 | 7.4420 | 0.262229 | 1989. |



|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 180 | 0.179491 | 1803.90 | 2019.29 | 6.7746 | 0.153141 | 1801. |
| 190 | 0.183841 | 1823.72 | 2044.33 | 6.8293 | 0.156912 | 1821. |
| 200 | 0.188170 | 1843.67 | 2069.48 | 6.8830 | 0.160661 | 1841. |
| 210 | 0.192480 | 1863.77 | 2094.75 | 6.9358 | 0.164391 | 1861. |
| 220 | 0.196772 | 1884.04 | 2120.16 | 6.9879 | 0.168104 | 1881. |
| 230 | 0.201049 | 1904.47 | 2145.72 | 7.0392 | 0.171801 | 1902. |
| 240 | 0.205313 | 1925.07 | 2171.45 | 7.0898 | 0.175484 | 1923. |
| 250 | 0.209563 | 1945.86 | 2197.33 | 7.1398 | 0.179154 | 1944. |
| 260 | 0.213803 | 1966.83 | 2223.39 | 7.1891 | 0.182813 | 1965. |
| 270 | 0.218032 | 1988.00 | 2249.63 | 7.2379 | 0.186461 | 1986. |
| 280 | 0.222251 | 2009.36 | 2276.06 | 7.2861 | 0.190100 | 2007. |
| 290 | 0.226461 | 2030.92 | 2302.67 | 7.3338 | 0.193729 | 2029. |
| 300 | 0.230664 | 2052.69 | 2329.48 | 7.3810 | 0.197351 | 2051. |
| 310 | 0.234859 | 2074.66 | 2356.49 | 7.4277 | 0.200965 | 2073. |
| 320 | 0.239047 | 2096.84 | 2383.70 | 7.4740 | 0.204572 | 2095. |

| T (°C) | $v$<br>m <sup>3</sup> /kg              | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 1600 kPa (Sat. T = 41.02°C)</b> |              |              |               | <b>P = 2000 kPa</b>       |              |
| Sat    | 0.080782                               | 1504.06      | 1633.31      | 5.6156        | 0.064453                  | 1505.        |
| 50     | 0.085064                               | 1527.59      | 1663.69      | 5.7110        | 0.064729                  | 1507.        |
| 60     | 0.089509                               | 1551.82      | 1695.03      | 5.8066        | 0.068754                  | 1534.        |

|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 70  | 0.093710 | 1574.63 | 1724.57 | 5.8939 | 0.072463 | 1560. |
| 80  | 0.097730 | 1596.48 | 1752.84 | 5.9751 | 0.075952 | 1583. |
| 90  | 0.101612 | 1617.64 | 1780.22 | 6.0516 | 0.079278 | 1606. |
| 100 | 0.105385 | 1638.34 | 1806.95 | 6.1242 | 0.082480 | 1628. |
| 110 | 0.109071 | 1658.71 | 1833.22 | 6.1937 | 0.085583 | 1649. |
| 120 | 0.112684 | 1678.85 | 1859.15 | 6.2605 | 0.088608 | 1670. |
| 130 | 0.116238 | 1698.86 | 1884.84 | 6.3250 | 0.091567 | 1691. |
| 140 | 0.119741 | 1718.79 | 1910.37 | 6.3876 | 0.094473 | 1711. |
| 150 | 0.123200 | 1738.69 | 1935.81 | 6.4484 | 0.097332 | 1732. |
| 160 | 0.126623 | 1758.60 | 1961.20 | 6.5077 | 0.100152 | 1752. |
| 170 | 0.130013 | 1778.56 | 1986.58 | 6.5657 | 0.102939 | 1772. |
| 180 | 0.133375 | 1798.58 | 2011.98 | 6.6223 | 0.105696 | 1793. |
| 190 | 0.136713 | 1818.70 | 2037.44 | 6.6779 | 0.108427 | 1813. |
| 200 | 0.140028 | 1838.93 | 2062.97 | 6.7324 | 0.111136 | 1834. |
| 210 | 0.143323 | 1859.28 | 2088.59 | 6.7860 | 0.113824 | 1854. |
| 220 | 0.146601 | 1879.77 | 2114.33 | 6.8387 | 0.116494 | 1875. |
| 230 | 0.149863 | 1900.40 | 2140.18 | 6.8907 | 0.119148 | 1896. |
| 240 | 0.153111 | 1921.20 | 2166.18 | 6.9418 | 0.121788 | 1917. |
| 250 | 0.156347 | 1942.16 | 2192.31 | 6.9923 | 0.124414 | 1938. |
| 260 | 0.159570 | 1963.30 | 2218.61 | 7.0420 | 0.127029 | 1959. |
| 270 | 0.162783 | 1984.61 | 2245.07 | 7.0912 | 0.129632 | 1981. |



|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 180 | 0.039128 | 1750.06 | 1945.69 | 5.9573 | 0.016629 | 1664. |
| 190 | 0.040432 | 1773.27 | 1975.43 | 6.0222 | 0.017534 | 1694. |
| 200 | 0.041706 | 1796.24 | 2004.77 | 6.0849 | 0.018386 | 1724. |
| 210 | 0.042954 | 1819.05 | 2033.82 | 6.1457 | 0.019197 | 1752. |
| 220 | 0.044180 | 1841.75 | 2062.65 | 6.2047 | 0.019975 | 1779. |
| 230 | 0.045386 | 1864.39 | 2091.32 | 6.2623 | 0.020725 | 1806. |
| 240 | 0.046575 | 1887.00 | 2119.88 | 6.3185 | 0.021451 | 1832. |
| 250 | 0.047748 | 1909.63 | 2148.37 | 6.3735 | 0.022156 | 1857. |
| 260 | 0.048908 | 1932.29 | 2176.83 | 6.4274 | 0.022844 | 1883. |
| 270 | 0.050056 | 1955.01 | 2205.29 | 6.4802 | 0.023517 | 1908. |
| 280 | 0.051192 | 1977.81 | 2233.77 | 6.5322 | 0.024176 | 1933. |
| 290 | 0.052318 | 2000.70 | 2262.29 | 6.5833 | 0.024823 | 1958. |
| 300 | 0.053435 | 2023.71 | 2290.88 | 6.6336 | 0.025459 | 1983. |
| 310 | 0.054543 | 2046.84 | 2319.55 | 6.6832 | 0.026086 | 2008. |
| 320 | 0.055644 | 2070.10 | 2348.32 | 6.7321 | 0.026704 | 2033. |
| 330 | 0.056738 | 2093.51 | 2377.20 | 6.7804 | 0.027314 | 2058. |
| 340 | 0.057825 | 2117.06 | 2406.19 | 6.8281 | 0.027916 | 2083. |
| 350 | 0.058906 | 2140.78 | 2435.31 | 6.8752 | 0.028513 | 2108. |
| 360 | 0.059982 | 2164.66 | 2464.57 | 6.9218 | 0.029103 | 2133. |
| 370 | 0.061053 | 2188.72 | 2493.98 | 6.9679 | 0.029687 | 2158. |
| 380 | 0.062119 | 2212.95 | 2523.54 | 7.0135 | 0.030267 | 2183. |

|     |          |         |         |        |          |       |
|-----|----------|---------|---------|--------|----------|-------|
| 390 | 0.063181 | 2237.36 | 2553.26 | 7.0586 | 0.030841 | 2209. |
| 400 | 0.064238 | 2261.95 | 2583.14 | 7.1034 | 0.031412 | 2234. |
| 410 | 0.065292 | 2286.74 | 2613.20 | 7.1477 | 0.031978 | 2260. |
| 420 | 0.066342 | 2311.72 | 2643.42 | 7.1916 | 0.032540 | 2286. |

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**Reference States, default for fluid**

- **Enthalpy** H = 1699.663687 kJ/kg at 26.9 C and 0.0010 MPa.
- **Entropy** S = 9.356091 kJ/kg-K at 26.9 C and 0.0010 MPa.

Source: Eric W. Lemmon, Mark O. McLinden and Daniel G. Friend, “Thermophysical Properties of Fluid Systems” in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <https://doi.org/10.18434/T4D303>, (retrieved May 2021).

# Appendix C: Thermodynamic Properties of R134a

## Table C1: Saturated R134a

| T (°C) | P (MPa) | Specific Volume<br>m <sup>3</sup> /kg |                      | Specific Internal Energy<br>kJ/kg |                      |
|--------|---------|---------------------------------------|----------------------|-----------------------------------|----------------------|
|        |         | <i>v<sub>f</sub></i>                  | <i>v<sub>g</sub></i> | <i>u<sub>f</sub></i>              | <i>u<sub>g</sub></i> |
| -70    | 0.00798 | 0.000666                              | 2.058960             | 111.19                            | 338.11               |
| -65    | 0.01138 | 0.000672                              | 1.476490             | 117.26                            | 344.26               |
| -60    | 0.01591 | 0.000678                              | 1.079030             | 123.35                            | 349.91               |
| -55    | 0.02183 | 0.000685                              | 0.802362             | 129.49                            | 355.11               |
| -50    | 0.02945 | 0.000691                              | 0.606198             | 135.65                            | 359.91               |
| -45    | 0.03912 | 0.000698                              | 0.464726             | 141.86                            | 364.26               |
| -40    | 0.05121 | 0.000705                              | 0.361076             | 148.11                            | 368.11               |
| -35    | 0.06614 | 0.000713                              | 0.284018             | 154.40                            | 371.50               |
| -30    | 0.08438 | 0.000720                              | 0.225945             | 160.73                            | 374.45               |
| -25    | 0.10640 | 0.000728                              | 0.181623             | 167.11                            | 376.91               |
| -20    | 0.13274 | 0.000736                              | 0.147395             | 173.54                            | 378.91               |
| -15    | 0.16394 | 0.000745                              | 0.120671             | 180.02                            | 380.41               |
| -10    | 0.20060 | 0.000754                              | 0.099590             | 186.55                            | 381.41               |
| -5     | 0.24334 | 0.000763                              | 0.082801             | 193.13                            | 381.91               |
| 0      | 0.29280 | 0.000772                              | 0.069309             | 199.77                            | 381.91               |
| 5      | 0.34966 | 0.000782                              | 0.058374             | 206.48                            | 381.41               |
| 10     | 0.41461 | 0.000793                              | 0.049442             | 213.25                            | 380.41               |
| 15     | 0.48837 | 0.000804                              | 0.042090             | 220.09                            | 378.91               |
| 20     | 0.57171 | 0.000816                              | 0.035997             | 227.00                            | 376.91               |
| 25     | 0.66538 | 0.000829                              | 0.030912             | 233.99                            | 374.41               |
| 30     | 0.77020 | 0.000842                              | 0.026642             | 241.07                            | 371.41               |
| 35     | 0.88698 | 0.000857                              | 0.023033             | 248.25                            | 367.91               |
| 40     | 1.01659 | 0.000872                              | 0.019966             | 255.52                            | 363.91               |
| 45     | 1.15992 | 0.000889                              | 0.017344             | 262.91                            | 359.41               |

|        |         |          |          |        |    |
|--------|---------|----------|----------|--------|----|
| 50     | 1.31791 | 0.000907 | 0.015089 | 270.43 | 40 |
| 55     | 1.49151 | 0.000927 | 0.013140 | 278.09 | 40 |
| 60     | 1.68178 | 0.000950 | 0.011444 | 285.91 | 40 |
| 65     | 1.88982 | 0.000975 | 0.009960 | 293.92 | 40 |
| 70     | 2.11683 | 0.001004 | 0.008653 | 302.16 | 41 |
| 75     | 2.36412 | 0.001037 | 0.007491 | 310.68 | 41 |
| 80     | 2.63320 | 0.001077 | 0.006448 | 319.55 | 41 |
| 85     | 2.92583 | 0.001127 | 0.005499 | 328.93 | 41 |
| 90     | 3.24418 | 0.001194 | 0.004613 | 339.06 | 41 |
| 95     | 3.59123 | 0.001294 | 0.003743 | 350.60 | 40 |
| 100    | 3.97238 | 0.001536 | 0.002681 | 367.20 | 39 |
| 101.06 | 4.05911 | 0.001954 | 0.001954 | 381.71 | 38 |

## Table C2: Superheated R134a

| T (°C) | $v$<br>m <sup>3</sup> /kg              | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 50 kPa (Sat. T = -40.45 °C)</b> |              |              |               | <b>P = 100 kPa</b>        |              |
| Sat    | 0.369253                               | 355.25       | 373.72       | 1.7650        | 0.192558                  | 363.34       |
| -20    | 0.404876                               | 368.97       | 389.21       | 1.8288        | 0.198410                  | 367.81       |
| -10    | 0.421989                               | 375.89       | 396.99       | 1.8590        | 0.207433                  | 374.89       |
| 0      | 0.438974                               | 382.98       | 404.93       | 1.8885        | 0.216303                  | 382.10       |
| 10     | 0.455859                               | 390.22       | 413.02       | 1.9176        | 0.225060                  | 389.45       |
| 20     | 0.472664                               | 397.64       | 421.27       | 1.9463        | 0.233731                  | 396.94       |
| 30     | 0.489404                               | 405.22       | 429.69       | 1.9745        | 0.242333                  | 404.59       |
| 40     | 0.506090                               | 412.97       | 438.28       | 2.0024        | 0.250878                  | 412.40       |
| 50     | 0.522731                               | 420.89       | 447.03       | 2.0299        | 0.259376                  | 420.37       |
| 60     | 0.539334                               | 428.98       | 455.94       | 2.0571        | 0.267835                  | 428.49       |
| 70     | 0.555904                               | 437.23       | 465.02       | 2.0839        | 0.276260                  | 436.78       |
| 80     | 0.572447                               | 445.64       | 474.26       | 2.1105        | 0.284657                  | 445.23       |
| 90     | 0.588966                               | 454.22       | 483.67       | 2.1367        | 0.293029                  | 453.84       |
| 100    | 0.605464                               | 462.96       | 493.24       | 2.1627        | 0.301380                  | 462.61       |
| 110    | 0.621943                               | 471.87       | 502.96       | 2.1884        | 0.309713                  | 471.53       |
| 120    | 0.638407                               | 480.93       | 512.85       | 2.2139        | 0.318029                  | 480.61       |
| 130    | 0.654857                               | 490.15       | 522.89       | 2.2391        | 0.326331                  | 489.85       |

| T (°C) | $v$<br>m <sup>3</sup> /kg               | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 150 kPa (Sat. T = -17.13 °C)</b> |              |              |               | <b>P = 200 kPa</b>        |              |
| Sat    | 0.131283                                | 368.63       | 388.32       | 1.7388        | 0.099877                  | 372.64       |
| -10    | 0.135816                                | 373.84       | 394.21       | 1.7615        | 0.099915                  | 372.70       |
| 0      | 0.142013                                | 381.19       | 402.49       | 1.7924        | 0.104811                  | 380.24       |

|     |          |        |        |        |          |        |
|-----|----------|--------|--------|--------|----------|--------|
| 10  | 0.148081 | 388.64 | 410.86 | 1.8225 | 0.109552 | 387.82 |
| 20  | 0.154053 | 396.23 | 419.33 | 1.8519 | 0.114185 | 395.49 |
| 30  | 0.159950 | 403.95 | 427.94 | 1.8808 | 0.118737 | 403.29 |
| 40  | 0.165787 | 411.82 | 436.68 | 1.9092 | 0.123226 | 411.22 |
| 50  | 0.171576 | 419.83 | 445.57 | 1.9371 | 0.127663 | 419.29 |
| 60  | 0.177323 | 428.01 | 454.60 | 1.9646 | 0.132057 | 427.51 |
| 70  | 0.183036 | 436.33 | 463.79 | 1.9918 | 0.136415 | 435.88 |
| 80  | 0.188719 | 444.82 | 473.12 | 2.0186 | 0.140744 | 444.40 |
| 90  | 0.194377 | 453.45 | 482.61 | 2.0451 | 0.145046 | 453.06 |
| 100 | 0.200014 | 462.25 | 492.25 | 2.0713 | 0.149326 | 461.88 |
| 110 | 0.205631 | 471.20 | 502.04 | 2.0972 | 0.153588 | 470.86 |
| 120 | 0.211233 | 480.30 | 511.98 | 2.1228 | 0.157832 | 479.98 |
| 130 | 0.216819 | 489.56 | 522.08 | 2.1481 | 0.162062 | 489.26 |
| 140 | 0.222394 | 498.97 | 532.33 | 2.1732 | 0.166278 | 498.69 |

| T (°C) | $v$<br>m <sup>3</sup> /kg             | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---------------------------------------|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 300 kPa (Sat. T = 0.67 °C)</b> |              |              |               | <b>P = 400 kPa</b>        |              |
| Sat    | 0.067704                              | 378.68       | 399.00       | 1.7267        | 0.051207                  | 383.24       |
| 10     | 0.070931                              | 386.06       | 407.34       | 1.7567        | 0.051506                  | 384.12       |
| 20     | 0.074254                              | 393.96       | 416.24       | 1.7876        | 0.054214                  | 392.32       |
| 30     | 0.077478                              | 401.93       | 425.18       | 1.8175        | 0.056797                  | 400.50       |
| 40     | 0.080629                              | 410.00       | 434.19       | 1.8468        | 0.059293                  | 408.73       |
| 50     | 0.083723                              | 418.19       | 443.31       | 1.8755        | 0.061724                  | 417.05       |
| 60     | 0.086770                              | 426.50       | 452.54       | 1.9036        | 0.064105                  | 425.47       |
| 70     | 0.089779                              | 434.95       | 461.89       | 1.9312        | 0.066443                  | 434.01       |

|     |          |        |        |        |          |        |
|-----|----------|--------|--------|--------|----------|--------|
| 80  | 0.092755 | 443.54 | 471.37 | 1.9585 | 0.068748 | 442.67 |
| 90  | 0.095705 | 452.27 | 480.99 | 1.9853 | 0.071023 | 451.47 |
| 100 | 0.098631 | 461.15 | 490.74 | 2.0118 | 0.073275 | 460.41 |
| 110 | 0.101537 | 470.17 | 500.63 | 2.0380 | 0.075505 | 469.48 |
| 120 | 0.104426 | 479.34 | 510.67 | 2.0638 | 0.077717 | 478.69 |
| 130 | 0.107299 | 488.66 | 520.85 | 2.0894 | 0.079914 | 488.05 |
| 140 | 0.110160 | 498.12 | 531.17 | 2.1147 | 0.082097 | 497.55 |
| 150 | 0.113009 | 507.74 | 541.64 | 2.1397 | 0.084268 | 507.20 |
| 160 | 0.115847 | 517.50 | 552.25 | 2.1645 | 0.086429 | 516.99 |

| T (°C) | $v$<br>m <sup>3</sup> /kg              | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 500 kPa (Sat. T = 15.73 °C)</b> |              |              |               | <b>P = 600 kPa</b>        |              |
| Sat    | 0.041123                               | 386.91       | 407.47       | 1.7197        | 0.034300                  | 389.99       |
| 20     | 0.042116                               | 390.55       | 411.61       | 1.7339        | -                         | -            |
| 30     | 0.044338                               | 398.99       | 421.16       | 1.7659        | 0.035984                  | 397.37       |
| 40     | 0.046456                               | 407.40       | 430.63       | 1.7967        | 0.037866                  | 406.01       |
| 50     | 0.048500                               | 415.86       | 440.11       | 1.8265        | 0.039659                  | 414.63       |
| 60     | 0.050486                               | 424.40       | 449.64       | 1.8555        | 0.041389                  | 423.30       |
| 70     | 0.052427                               | 433.04       | 459.25       | 1.8839        | 0.043070                  | 432.04       |
| 80     | 0.054332                               | 441.78       | 468.95       | 1.9118        | 0.044711                  | 440.87       |
| 90     | 0.056205                               | 450.65       | 478.76       | 1.9392        | 0.046319                  | 449.82       |
| 100    | 0.058054                               | 459.65       | 488.68       | 1.9661        | 0.047900                  | 458.88       |
| 110    | 0.059880                               | 468.78       | 498.72       | 1.9927        | 0.049459                  | 468.06       |
| 120    | 0.061688                               | 478.04       | 508.88       | 2.0189        | 0.050998                  | 477.37       |
| 130    | 0.063479                               | 487.44       | 519.18       | 2.0447        | 0.052520                  | 486.82       |

|     |          |        |        |        |          |        |
|-----|----------|--------|--------|--------|----------|--------|
| 140 | 0.065257 | 496.98 | 529.60 | 2.0703 | 0.054027 | 496.39 |
| 150 | 0.067022 | 506.66 | 540.17 | 2.0955 | 0.055522 | 506.11 |
| 160 | 0.068776 | 516.48 | 550.86 | 2.1205 | 0.057006 | 515.96 |
| 170 | 0.070521 | 526.44 | 561.70 | 2.1453 | 0.058480 | 525.95 |

| T (°C) | $v$<br>m <sup>3</sup> /kg              | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK       | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--|--------------|--------------|---------------------|---------------------------|--------------|
|        | <b>P = 800 kPa (Sat. T = 31.32 °C)</b> |              |              | <b>P = 1000 kPa</b> |                           |              |
| Sat    | 0.025625                               | 394.96       | 415.46       | 1.7140              | 0.020316                  | 398.85       |
| 40     | 0.027036                               | 402.97       | 424.59       | 1.7436              | 0.020407                  | 399.45       |
| 50     | 0.028547                               | 412.00       | 434.84       | 1.7758              | 0.021796                  | 409.09       |
| 60     | 0.029974                               | 420.98       | 444.95       | 1.8067              | 0.023068                  | 418.46       |
| 70     | 0.031340                               | 429.96       | 455.03       | 1.8365              | 0.024262                  | 427.74       |
| 80     | 0.032659                               | 438.99       | 465.12       | 1.8654              | 0.025399                  | 437.00       |
| 90     | 0.033942                               | 448.10       | 475.25       | 1.8937              | 0.026493                  | 446.30       |
| 100    | 0.035194                               | 457.30       | 485.45       | 1.9214              | 0.027552                  | 455.65       |
| 110    | 0.036420                               | 466.60       | 495.74       | 1.9486              | 0.028584                  | 465.09       |
| 120    | 0.037626                               | 476.02       | 506.12       | 1.9754              | 0.029593                  | 474.62       |
| 130    | 0.038813                               | 485.55       | 516.60       | 2.0017              | 0.030582                  | 484.25       |
| 140    | 0.039985                               | 495.21       | 527.20       | 2.0277              | 0.031554                  | 494.00       |
| 150    | 0.041144                               | 504.99       | 537.91       | 2.0533              | 0.032512                  | 503.86       |
| 160    | 0.042291                               | 514.91       | 548.74       | 2.0786              | 0.033458                  | 513.84       |
| 170    | 0.043427                               | 524.96       | 559.70       | 2.1036              | 0.034393                  | 523.95       |
| 180    | 0.044554                               | 535.14       | 570.78       | 2.1283              | 0.035318                  | 534.19       |

| T (°C) | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|---------------------------|--------------|--------------|---------------|---------------------------|--------------|
|--------|---------------------------|--------------|--------------|---------------|---------------------------|--------------|

|     | P = 1200 kPa (Sat. T = 46.31 °C) |        |        |        | P = 1400 kPa |        |
|-----|----------------------------------|--------|--------|--------|--------------|--------|
| Sat | 0.016718                         | 401.98 | 422.04 | 1.7087 | 0.014110     | 404.54 |
| 50  | 0.017201                         | 405.77 | 426.41 | 1.7223 | -            | -      |
| 60  | 0.018404                         | 415.70 | 437.79 | 1.7570 | 0.015005     | 412.61 |
| 70  | 0.019502                         | 425.36 | 448.76 | 1.7895 | 0.016060     | 422.77 |
| 80  | 0.020530                         | 434.90 | 459.53 | 1.8204 | 0.017023     | 432.65 |
| 90  | 0.021506                         | 444.41 | 470.22 | 1.8502 | 0.017923     | 442.42 |
| 100 | 0.022443                         | 453.94 | 480.87 | 1.8792 | 0.018778     | 452.16 |
| 110 | 0.023348                         | 463.53 | 491.54 | 1.9074 | 0.019597     | 461.91 |
| 120 | 0.024228                         | 473.18 | 502.25 | 1.9350 | 0.020388     | 471.70 |
| 130 | 0.025087                         | 482.92 | 513.03 | 1.9621 | 0.021156     | 481.55 |
| 140 | 0.025928                         | 492.76 | 523.87 | 1.9886 | 0.021904     | 491.49 |
| 150 | 0.026753                         | 502.70 | 534.81 | 2.0148 | 0.022637     | 501.52 |
| 160 | 0.027566                         | 512.76 | 545.84 | 2.0406 | 0.023355     | 511.65 |
| 170 | 0.028367                         | 522.93 | 556.97 | 2.0660 | 0.024062     | 521.90 |
| 180 | 0.029159                         | 533.23 | 568.22 | 2.0911 | 0.024758     | 532.25 |

| T (°C) | $v_3$<br>m <sup>3</sup> /kg      | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kgK | $v_3$<br>m <sup>3</sup> /kg | u<br>kJ/kg |
|--------|----------------------------------|------------|------------|-------------|-----------------------------|------------|
|        | P = 1600 kPa (Sat. T = 57.90 °C) |            |            |             | P = 2000 kPa                |            |
| Sat    | 0.012127                         | 406.64     | 426.04     | 1.7036      | 0.009291                    | 409.70     |
| 60     | 0.012373                         | 409.04     | 428.84     | 1.7120      | -                           | -          |
| 70     | 0.013430                         | 419.91     | 441.40     | 1.7491      | 0.009573                    | 412.91     |
| 80     | 0.014362                         | 430.24     | 453.22     | 1.7831      | 0.010539                    | 424.70     |
| 90     | 0.015216                         | 440.32     | 464.66     | 1.8150      | 0.011363                    | 435.66     |
| 100    | 0.016015                         | 450.29     | 475.91     | 1.8456      | 0.012105                    | 446.24     |

|     |          |        |        |        |          |        |
|-----|----------|--------|--------|--------|----------|--------|
| 110 | 0.016773 | 460.22 | 487.06 | 1.8751 | 0.012791 | 456.63 |
| 120 | 0.017500 | 470.16 | 498.16 | 1.9037 | 0.013436 | 466.93 |
| 130 | 0.018202 | 480.15 | 509.27 | 1.9316 | 0.014051 | 477.21 |
| 140 | 0.018882 | 490.19 | 520.40 | 1.9589 | 0.014640 | 487.49 |
| 150 | 0.019546 | 500.32 | 531.59 | 1.9856 | 0.015210 | 497.82 |
| 160 | 0.020194 | 510.53 | 542.84 | 2.0119 | 0.015764 | 508.21 |
| 170 | 0.020831 | 520.84 | 554.17 | 2.0378 | 0.016303 | 518.68 |
| 180 | 0.021456 | 531.26 | 565.59 | 2.0632 | 0.016830 | 529.23 |

| T (°C) | $v$<br>m <sup>3</sup> /kg              | $u$<br>kJ/kg | $h$<br>kJ/kg | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--------|--|--------------|--------------|---------------|---------------------------|--------------|
|        | <b>P = 3000 kPa (Sat. T = 86.20°C)</b> |              |              |               | <b>P = 4000 kPa</b>       |              |
| Sat    | 0.005281                               | 411.50       | 427.34       | 1.6748        | 0.002563                  | 395.13       |
| 90     | 0.005752                               | 418.53       | 435.78       | 1.6982        | –                         | –            |
| 100    | 0.006641                               | 433.18       | 453.10       | 1.7453        | –                         | –            |
| 110    | 0.007327                               | 445.79       | 467.77       | 1.7841        | 0.004273                  | 429.17       |
| 120    | 0.007917                               | 457.57       | 481.32       | 1.8190        | 0.004993                  | 445.13       |
| 130    | 0.008447                               | 468.92       | 494.26       | 1.8515        | 0.005549                  | 458.71       |
| 140    | 0.008937                               | 480.05       | 506.86       | 1.8824        | 0.006024                  | 471.28       |
| 150    | 0.009396                               | 491.05       | 519.24       | 1.9120        | 0.006450                  | 483.32       |
| 160    | 0.009832                               | 502.00       | 531.50       | 1.9406        | 0.006842                  | 495.07       |
| 170    | 0.010250                               | 512.93       | 543.68       | 1.9684        | 0.007208                  | 506.64       |
| 180    | 0.010652                               | 523.89       | 555.84       | 1.9956        | 0.007554                  | 518.11       |

### Reference States, IIR Convention

- **Enthalpy**  $H = 200$  kJ/kg at 0°C for saturated liquid.

- **Entropy**  $S = 1 \text{ kJ/kg-K}$  at  $0^\circ\text{C}$  for saturated liquid.

Source: Eric W. Lemmon, Mark O. McLinden and Daniel G. Friend, “Thermophysical Properties of Fluid Systems” in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <https://doi.org/10.18434/T4D303>, (retrieved May 2021).

# Appendix D: Thermodynamic Properties of Carbon Dioxide

## Table D1: Saturated CO<sub>2</sub>

| T (°C) | P (MPa) | Specific Volume<br>m <sup>3</sup> /kg |                | Specific Internal Energy<br>kJ/kg |                |
|--------|---------|---------------------------------------|----------------|-----------------------------------|----------------|
|        |         | v <sub>f</sub>                        | v <sub>g</sub> | u <sub>f</sub>                    | u <sub>g</sub> |
| -50    | 0.68234 | 0.000866                              | 0.055789       | 92.35                             |                |
| -48    | 0.73949 | 0.000872                              | 0.051618       | 96.26                             |                |
| -46    | 0.80015 | 0.000878                              | 0.047819       | 100.18                            |                |
| -44    | 0.86445 | 0.000883                              | 0.044352       | 104.11                            |                |
| -42    | 0.93252 | 0.000889                              | 0.041184       | 108.05                            |                |
| -40    | 1.00450 | 0.000896                              | 0.038284       | 112.00                            |                |
| -38    | 1.08051 | 0.000902                              | 0.035624       | 115.97                            |                |
| -36    | 1.16071 | 0.000909                              | 0.033181       | 119.96                            |                |
| -34    | 1.24522 | 0.000915                              | 0.030935       | 123.96                            |                |
| -32    | 1.33419 | 0.000922                              | 0.028865       | 127.97                            |                |
| -30    | 1.42776 | 0.000930                              | 0.026956       | 132.01                            |                |
| -28    | 1.52607 | 0.000937                              | 0.025192       | 136.07                            |                |
| -26    | 1.62926 | 0.000945                              | 0.023560       | 140.15                            |                |
| -24    | 1.73749 | 0.000953                              | 0.022048       | 144.25                            |                |
| -22    | 1.85089 | 0.000961                              | 0.020645       | 148.38                            |                |
| -20    | 1.96963 | 0.000969                              | 0.019343       | 152.54                            |                |
| -18    | 2.09384 | 0.000978                              | 0.018131       | 156.73                            |                |
| -16    | 2.22370 | 0.000987                              | 0.017002       | 160.95                            |                |
| -14    | 2.35935 | 0.000997                              | 0.015950       | 165.20                            |                |
| -12    | 2.50095 | 0.001007                              | 0.014967       | 169.49                            |                |
| -10    | 2.64868 | 0.001017                              | 0.014048       | 173.83                            |                |
| -8     | 2.80269 | 0.001028                              | 0.013188       | 178.20                            |                |
| -6     | 2.96316 | 0.001040                              | 0.012381       | 182.63                            |                |
| -4     | 3.13027 | 0.001052                              | 0.011624       | 187.11                            |                |

|         |         |          |          |        |  |
|---------|---------|----------|----------|--------|--|
| -2      | 3.30420 | 0.001065 | 0.010912 | 191.64 |  |
| 0       | 3.48514 | 0.001078 | 0.010241 | 196.24 |  |
| 2       | 3.67329 | 0.001093 | 0.009609 | 200.91 |  |
| 4       | 3.86884 | 0.001108 | 0.009011 | 205.66 |  |
| 6       | 4.07202 | 0.001124 | 0.008445 | 210.50 |  |
| 8       | 4.28306 | 0.001142 | 0.007909 | 215.44 |  |
| 10      | 4.50218 | 0.001161 | 0.007399 | 220.50 |  |
| 12      | 4.72966 | 0.001182 | 0.006912 | 225.69 |  |
| 14      | 4.96577 | 0.001205 | 0.006447 | 231.05 |  |
| 16      | 5.21080 | 0.001231 | 0.006000 | 236.59 |  |
| 18      | 5.46511 | 0.001260 | 0.005569 | 242.38 |  |
| 20      | 5.72905 | 0.001293 | 0.005149 | 248.46 |  |
| 22      | 6.00308 | 0.001332 | 0.004737 | 254.93 |  |
| 24      | 6.28773 | 0.001379 | 0.004327 | 261.94 |  |
| 26      | 6.58368 | 0.001440 | 0.003908 | 269.78 |  |
| 28      | 6.89182 | 0.001526 | 0.003459 | 279.11 |  |
| 30      | 7.21369 | 0.001685 | 0.002898 | 292.40 |  |
| 30.9782 | 7.37730 | 0.002139 | 0.002139 | 316.47 |  |

## Table D2: Superheated CO<sub>2</sub>

| T (°C) | $v^3$<br>m <sup>3</sup> /kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kgK | $v^3$<br>m <sup>3</sup> /kg | u<br>kJ/kg |
|--------|-----------------------------|------------|------------|-------------|-----------------------------|------------|
|        | <b>P = 400 kPa</b>          |            |            |             | <b>P = 800 kPa</b>          |            |
| Sat    | -                           | -          | -          | -           | 0.046807                    | 395.73     |
| -40    | 0.10499                     | 405.37     | 447.36     | 2.2603      | 0.049662                    | 399.96     |
| -20    | 0.11538                     | 418.21     | 464.36     | 2.3302      | 0.055455                    | 414.03     |
| 0      | 0.12552                     | 431.21     | 481.42     | 2.3951      | 0.060937                    | 427.82     |
| 20     | 0.13551                     | 444.47     | 498.67     | 2.4561      | 0.066231                    | 441.64     |
| 40     | 0.14538                     | 458.04     | 516.19     | 2.5139      | 0.071401                    | 455.61     |
| 60     | 0.15518                     | 471.93     | 534.00     | 2.5690      | 0.076484                    | 469.81     |
| 80     | 0.16491                     | 486.15     | 552.12     | 2.6218      | 0.081503                    | 484.27     |
| 100    | 0.17460                     | 500.70     | 570.54     | 2.6725      | 0.086474                    | 499.02     |
| 120    | 0.18425                     | 515.57     | 589.28     | 2.7214      | 0.091408                    | 514.05     |
| 140    | 0.19388                     | 530.76     | 608.31     | 2.7687      | 0.096313                    | 529.37     |
| 160    | 0.20348                     | 546.25     | 627.64     | 2.8143      | 0.101194                    | 544.97     |
| 180    | 0.21307                     | 562.04     | 647.26     | 2.8586      | 0.106056                    | 560.86     |
| 200    | 0.22264                     | 578.11     | 667.16     | 2.9016      | 0.110902                    | 577.01     |
| 220    | 0.23219                     | 594.45     | 687.33     | 2.9433      | 0.115734                    | 593.43     |
| 240    | 0.24174                     | 611.06     | 707.75     | 2.9839      | 0.120555                    | 610.10     |
| 260    | 0.25127                     | 627.92     | 728.43     | 3.0235      | 0.125367                    | 627.02     |

| T (°C) | $v^3$<br>m <sup>3</sup> /kg              | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kgK | $v^3$<br>m <sup>3</sup> /kg | u<br>kJ/kg |
|--------|--|------------|------------|-------------|-----------------------------|------------|
|        | <b>P = 1000 kPa (Sat. T = -40.12 °C)</b> |            |            |             | <b>P = 1400 kPa</b>         |            |
| Sat    | 0.03779                                  | 396.93     | 435.40     | 2.0467      | 0.027145                    | 398.31     |
| -20    | 0.04342                                  | 411.80     | 455.21     | 2.1312      | 0.029569                    | 406.95     |
| 0      | 0.04799                                  | 426.05     | 474.04     | 2.2028      | 0.033153                    | 422.32     |
| 20     | 0.05236                                  | 440.17     | 492.53     | 2.2681      | 0.036483                    | 437.13     |

|     |         |        |        |        |          |        |
|-----|---------|--------|--------|--------|----------|--------|
| 40  | 0.05660 | 454.36 | 510.96 | 2.3289 | 0.039661 | 451.80 |
| 60  | 0.06074 | 468.73 | 529.47 | 2.3862 | 0.042739 | 466.52 |
| 80  | 0.06482 | 483.32 | 548.14 | 2.4406 | 0.045746 | 481.38 |
| 100 | 0.06885 | 498.17 | 567.01 | 2.4926 | 0.048700 | 496.44 |
| 120 | 0.07284 | 513.28 | 586.12 | 2.5425 | 0.051615 | 511.73 |
| 140 | 0.07680 | 528.67 | 605.47 | 2.5905 | 0.054499 | 527.26 |
| 160 | 0.08074 | 544.33 | 625.07 | 2.6368 | 0.057358 | 543.04 |
| 180 | 0.08465 | 560.26 | 644.92 | 2.6816 | 0.060197 | 559.07 |
| 200 | 0.08856 | 576.46 | 665.02 | 2.7250 | 0.063019 | 575.36 |
| 220 | 0.09244 | 592.91 | 685.36 | 2.7671 | 0.065828 | 591.89 |
| 240 | 0.09632 | 609.62 | 705.94 | 2.8080 | 0.068625 | 608.66 |
| 260 | 0.10019 | 626.57 | 726.76 | 2.8478 | 0.071413 | 625.67 |
| 280 | 0.10405 | 643.76 | 747.81 | 2.8866 | 0.074192 | 642.91 |

| T (°C)                                   | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg | $h$<br>kJ/kg        | $s$<br>kJ/kgK | $v$<br>m <sup>3</sup> /kg | $u$<br>kJ/kg |
|--|---------------------------|--------------|---------------------|---------------|---------------------------|--------------|
| <b>P = 2000 kPa (Sat. T = -19.50 °C)</b> |                           |              | <b>P = 3000 kPa</b> |               |                           |              |
| Sat                                      | 0.01885                   | 398.78       | 436.83              | 1.9446        | 0.012124                  | 396.93       |
| 0  | 0.02193                   | 416.15       | 460.00              | 2.0341        | 0.012931                  | 403.43       |
| 20                                       | 0.02453                   | 432.27       | 481.32              | 2.1095        | 0.015116                  | 423.12       |
| 40                                       | 0.02693                   | 447.78       | 501.65              | 2.1766        | 0.016980                  | 440.52       |
| 60                                       | 0.02922                   | 463.09       | 521.54              | 2.2381        | 0.018683                  | 457.04       |
| 80                                       | 0.03143                   | 478.40       | 541.27              | 2.2956        | 0.020287                  | 473.21       |
| 100                                      | 0.03359                   | 493.80       | 560.97              | 2.3499        | 0.021824                  | 489.25       |
| 120                                      | 0.03570                   | 509.36       | 580.76              | 2.4016        | 0.023313                  | 505.32       |
| 140                                      | 0.03777                   | 525.12       | 600.67              | 2.4509        | 0.024766                  | 521.48       |
| 160                                      | 0.03982                   | 541.09       | 620.73              | 2.4984        | 0.026191                  | 537.77       |

|     |         |        |        |        |          |        |
|-----|---------|--------|--------|--------|----------|--------|
| 180 | 0.04186 | 557.27 | 640.99 | 2.5441 | 0.027594 | 554.24 |
| 200 | 0.04387 | 573.69 | 661.43 | 2.5882 | 0.028979 | 570.89 |
| 220 | 0.04587 | 590.34 | 682.08 | 2.6310 | 0.030350 | 587.74 |
| 240 | 0.04786 | 607.21 | 702.92 | 2.6724 | 0.031708 | 604.79 |
| 260 | 0.04983 | 624.31 | 723.98 | 2.7127 | 0.033057 | 622.04 |
| 280 | 0.05180 | 641.63 | 745.24 | 2.7518 | 0.034396 | 639.49 |
| 300 | 0.05377 | 659.17 | 766.70 | 2.7899 | 0.035729 | 657.15 |

| T (°C)                                  | $v_3$<br>m <sup>3</sup> /kg | u<br>kJ/kg | h<br>kJ/kg | s<br>kJ/kgK | $v_3$<br>m <sup>3</sup> /kg | u<br>kJ/kg |
|---|-----------------------------|------------|------------|-------------|-----------------------------|------------|
| <b>P = 6000 kPa (Sat. T = 21.97 °C)</b> |                             |            |            | <b>P =</b>  |                             |            |
| Sat                                     | 0.00474                     | 374.87     | 403.32     | 1.6862      | -                           | -          |
| 20                                      | -                           | -          | -          | -           | 0.001168                    | 231.02     |
| 40                                      | 0.00670                     | 411.53     | 451.72     | 1.8462      | 0.001591                    | 297.13     |
| 60                                      | 0.00801                     | 435.41     | 483.45     | 1.9445      | 0.003449                    | 390.53     |
| 80                                      | 0.00908                     | 455.64     | 510.12     | 2.0223      | 0.004513                    | 425.72     |
| 100                                     | 0.01004                     | 474.37     | 534.60     | 2.0898      | 0.005303                    | 451.11     |
| 120                                     | 0.01092                     | 492.37     | 557.92     | 2.1507      | 0.005977                    | 473.09     |
| 140                                     | 0.01176                     | 510.00     | 580.59     | 2.2069      | 0.006584                    | 493.44     |
| 160                                     | 0.01257                     | 527.46     | 602.88     | 2.2596      | 0.007147                    | 512.90     |
| 180                                     | 0.01335                     | 544.87     | 624.96     | 2.3094      | 0.007679                    | 531.85     |
| 200                                     | 0.01411                     | 562.31     | 646.95     | 2.3569      | 0.008188                    | 550.51     |
| 220                                     | 0.01485                     | 579.81     | 668.91     | 2.4024      | 0.008679                    | 569.03     |
| 240                                     | 0.01558                     | 597.43     | 690.90     | 2.4461      | 0.009156                    | 587.48     |
| 260                                     | 0.01630                     | 615.17     | 712.95     | 2.4882      | 0.009622                    | 605.94     |
| 280                                     | 0.01701                     | 633.05     | 735.09     | 2.5290      | 0.010078                    | 624.44     |
| 300                                     | 0.01771                     | 651.09     | 757.34     | 2.5685      | 0.010527                    | 643.01     |

|     |         |        |        |        |          |        |
|-----|---------|--------|--------|--------|----------|--------|
| 320 | 0.01840 | 669.28 | 779.70 | 2.6069 | 0.010969 | 661.67 |
|-----|---------|--------|--------|--------|----------|--------|

### Reference States, IIR Convention

- **Enthalpy**  $H = 200 \text{ kJ/kg}$  at  $0^\circ\text{C}$  for saturated liquid.
- **Entropy**  $S = 1 \text{ kJ/kg-K}$  at  $0^\circ\text{C}$  for saturated liquid.

Source: Eric W. Lemmon, Mark O. McLinden and Daniel G. Friend, "Thermophysical Properties of Fluid Systems" in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <https://doi.org/10.18434/T4D303>, (retrieved May 2021).

# Appendix E: Critical Properties of Selected Fluids

**Table E1: Critical Constants of Selected Fluids**

| Substance          | Formula                           | Molecular Mass (g/mol) | Temperature (K) |
|--------------------|-----------------------------------|------------------------|-----------------|
| Water              | H <sub>2</sub> O                  | 18.015                 | 647.1           |
| Ammonia            | NH <sub>3</sub>                   | 17.031                 | 405.4           |
| Nitrogen           | N <sub>2</sub>                    | 28.013                 | 126.2           |
| Hydrogen           | H <sub>2</sub>                    | 2.0160                 | 33.1            |
| Oxygen             | O <sub>2</sub>                    | 31.999                 | 154.6           |
| Carbon Dioxide     | CO <sub>2</sub>                   | 44.010                 | 304.1           |
| Methane            | CH <sub>4</sub>                   | 16.043                 | 190.6           |
| Ethane             | C <sub>2</sub> H <sub>6</sub>     | 30.069                 | 305.3           |
| Propane            | C <sub>3</sub> H <sub>8</sub>     | 44.096                 | 369.8           |
| Refrigerant, R12   | CCl <sub>2</sub> F <sub>2</sub>   | 120.914                | 385.1           |
| Refrigerant, R22   | CHClF <sub>2</sub>                | 86.468                 | 369.3           |
| Refrigerant, R134a | CF <sub>3</sub> CH <sub>2</sub> F | 102.03                 | 374.2           |

Source: Eric W. Lemmon, Mark O. McLinden and Daniel G. Friend, “Thermophysical Properties of Fluid Systems” in **NIST Chemistry WebBook, NIST Standard Reference Database Number 69**, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, <https://doi.org/10.18434/T4D303>, (retrieved May 2021).

# Appendix F: Triple Point of Selected Substances

## Table F1: Triple Point of Selected Fluids

| Substance            | Temperature<br>K (°C)       | Pressure<br>kPa (atm)   |
|----------------------|-----------------------------|---|
| Acetylene            | 192.4 K (-80.7 °C)          | 120 kPa (1.2 atm)   |
| Ammonia              | 195.40 K (-77.75 °C)        | 6.060 kPa (0.05981 atm)                                       |
| Argon                | 83.8058 K<br>(-189.3442 °C) | 68.9 kPa (0.680 atm)  |
| Butane               | 134.6 K (-138.6 °C)         | $7 \times 10^{-4}$ kPa ( $6.9 \times 10^{-6}$ atm)            |
| Carbon dioxide       | 216.55 K (-56.60 °C)        | 517 kPa (5.10 atm)  |
| Carbon monoxide      | 68.10 K (-205.05 °C)        | 15.37 kPa (0.1517 atm)  |
| Ethane               | 89.89 K (-183.26 °C)        | $1.1 \times 10^{-3}$ kPa ( $1.1 \times 10^{-5}$ atm)          |
| Ethanol              | 150 K (-123 °C)             | $4.3 \times 10^{-7}$ kPa ( $4.2 \times 10^{-9}$ atm)          |
| Ethylene             | 104.0 K (-169.2 °C)         | 0.12 kPa (0.0012 atm)   |
| Hexafluoroethane     | 173.08 K (-100.07 °C)       | 26.60 kPa (0.2625 atm)  |
| Hydrogen             | 13.8033 K<br>(-259.3467 °C) | 7.04 kPa (0.0695 atm)   |
| Hydrogen<br>chloride | 158.96 K (-114.19 °C)       | 13.9 kPa (0.137 atm)  |
| Isobutane            | 113.55 K (-159.60 °C)       | $1.9481 \times 10^{-5}$ kPa<br>( $1.9226 \times 10^{-7}$ atm) |
| Krypton              | 115.76 K (-157.39 °C)       | 74.12 kPa (0.7315 atm)  |
| Mercury              | 234.3156 K<br>(-38.8344 °C) | $1.65 \times 10^{-7}$ kPa ( $1.63 \times 10^{-9}$ atm)        |

|               |                          |                               |
|---------------|--------------------------|-------------------------------|
| Methane       | 90.68 K (-182.47 °C)     | 11.7 kPa (0.115 atm)          |
| Neon          | 24.5561 K (-248.5939 °C) | 43.332 kPa (0.42765 atm)      |
| Nitric oxide  | 109.50 K (-163.65 °C)    | 21.92 kPa (0.2163 atm)        |
| Nitrogen      | 63.18 K (-209.97 °C)     | 12.6 kPa (0.124 atm)          |
| Nitrous oxide | 182.34 K (-90.81 °C)     | 87.85 kPa (0.8670 atm)        |
| Oxygen        | 54.3584 K (-218.7916 °C) | 0.14625 kPa (0.0014434 atm)   |
| Radon         | 202 K (-71 °C)           | 70 kPa (0.69 atm)             |
| Water         | 273.16 K (0.01 °C)       | 0.611657 kPa (0.00603659 atm) |
| Xenon         | 161.3 K (-111.8 °C)      | 81.5 kPa (0.804 atm)          |

Source: Wikipedia contributors. (2021b, June 8). Triple point. Wikipedia. [https://en.wikipedia.org/wiki/Triple\\_point](https://en.wikipedia.org/wiki/Triple_point), (retrieved June 10, 2021).

# Appendix G: Properties of Various Substances

**Table G1: Properties of various ideal gases (at 300K)**

| Gas                | Formula                        | R<br>(kJ/<br>kgK) | C <sub>p</sub><br>(kJ/<br>kgK) | C <sub>v</sub><br>(kJ/<br>kgK) | k = C <sub>p</sub> /C <sub>v</sub> |
|--------------------|--------------------------------|-------------------|--------------------------------|--------------------------------|------------------------------------|
| Air                | —                              | 0.287             | 1.005                          | 0.718                          | 1.4                                |
| Argon              | Ar                             | 0.2081            | 0.5203                         | 0.3122                         | 1.667                              |
| Butane             | C <sub>4</sub> H <sub>10</sub> | 0.1433            | 1.7164                         | 1.5734                         | 1.091                              |
| Carbon<br>Dioxide  | CO <sub>2</sub>                | 0.1889            | 0.846                          | 0.657                          | 1.289                              |
| Carbon<br>Monoxide | CO                             | 0.2968            | 1.04                           | 0.744                          | 1.4                                |
| Ethane             | C <sub>2</sub> H <sub>6</sub>  | 0.2765            | 1.7662                         | 1.4897                         | 1.186                              |
| Ethylene           | C <sub>2</sub> H <sub>4</sub>  | 0.2964            | 1.5482                         | 1.2518                         | 1.237                              |
| Helium             | He                             | 2.0769            | 5.1926                         | 3.1156                         | 1.667                              |
| Hydrogen           | H <sub>2</sub>                 | 4.124             | 14.307                         | 10.183                         | 1.405                              |
| Methane            | CH <sub>4</sub>                | 0.5182            | 2.2537                         | 1.7354                         | 1.299                              |
| Neon               | Ne                             | 0.4119            | 1.0299                         | 0.6179                         | 1.667                              |
| Nitrogen           | N <sub>2</sub>                 | 0.2968            | 1.039                          | 0.743                          | 1.4                                |
| Octane             | C <sub>8</sub> H <sub>18</sub> | 0.0729            | 1.7113                         | 1.6385                         | 1.044                              |
| Oxygen             | O <sub>2</sub>                 | 0.2598            | 0.918                          | 0.658                          | 1.395                              |
| Propane            | C <sub>3</sub> H <sub>8</sub>  | 0.1885            | 1.6794                         | 1.4909                         | 1.126                              |
| Steam              | H <sub>2</sub> O               | 0.4615            | 1.8723                         | 1.4108                         | 1.327                              |

**Table G2: Properties of various liquids (at 300K)**

| <b>Liquid</b> | <b><math>C_p</math><br/>(kJ/kgK)</b> |
|---------------|--------------------------------------|
| Ammonia       | 4.700                                |
| Ethanol       | 2.440                                |
| Gasoline      | 2.220                                |
| Mercury       | 0.1395                               |
| Methanol      | 2.140                                |
| Water         | 4.181                                |

## Table G3: Properties of various solids (at 300K)

| <b>Solid</b>     | <b><math>C_p</math><br/>(kJ/kgK)</b> |
|------------------|--------------------------------------|
| Aluminum         | 0.897                                |
| Brick            | 0.840                                |
| Carbon, graphite | 0.790                                |
| Concrete         | 0.880                                |
| Copper           | 0.385                                |
| Gold             | 0.129                                |
| Glass, silica    | 0.840                                |
| Glass, crown     | 0.670                                |
| Glass, flint     | 0.503                                |
| Glass, pyrex     | 0.753                                |
| Granite          | 0.790                                |
| Gypsum           | 1.090                                |
| Lead             | 0.129                                |
| Marble, mica     | 0.880                                |
| Magnesium        | 1.020                                |
| Sand             | 0.835                                |
| Silver           | 0.233                                |

|          |       |
|----------|-------|
| Soil     | 0.800 |
| Steel    | 0.466 |
| Tin      | 0.227 |
| Tungsten | 0.134 |
| Wood     | 1.70  |
| Zinc     | 0.387 |

Source: Wikipedia contributors. (May 1, 2021). Table of specific heat capacities. Wikipedia. [https://en.wikipedia.org/wiki/Table\\_of\\_specific\\_heat\\_capacities](https://en.wikipedia.org/wiki/Table_of_specific_heat_capacities), (retrieved June 10, 2021).

# Glossary

## **Absolute pressure**

Absolute pressure is a pressure that is measured relative to an ideal reference, or absolute vacuum. It is the sum of the atmospheric pressure and the gauge pressure. Absolute pressure is ALWAYS a positive number.

## **Absolute temperature**

Absolute temperature, also called thermodynamic temperature, is the temperature expressed on the **Kelvin** or **Rankine** scale. Absolute zero (0 K or 0 R) is the minimum possible temperature. Matter at absolute zero is in the state of lowest possible (minimum) energy.

## **Adiabatic process**

An adiabatic process is a process, in which heat transfer does NOT occur between a system and its surroundings.

## **Boundary**

Boundary or system boundary refers to the surface that separates the system and its surroundings.

## **Boundary work**

Boundary work refers to the work done by a substance at the system boundary due to the expansion or compression of the substance.

## **Chemical equilibrium**

Chemical equilibrium is a state in which the forward and backward reactions proceed at the same rate, causing no net

change of the concentrations in either the reactants or the products. A system free from chemical reactions is in chemical equilibrium.

### **Clausius statement**

It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body (heat sink) to a higher-temperature body (heat source).

### **Closed system**

A closed system is a system of a fixed mass. Mass transfer cannot happen between a closed system and its surroundings.

### **Constant-pressure specific heat**

Constant-pressure specific heat is a property of a substance. It equals to the amount of energy required to raise the temperature of one unit mass (i.e., 1 kg) of the substance by one degree in an isobaric process.

### **Constant-volume specific heat**

Constant-volume specific heat is a property of a substance. It equals to the amount of energy required to raise the temperature of one unit mass of the substance by one degree in an isochoric process.

### **Continuum**

Continuum refers to a continuous homogeneous matter distributed throughout a system.

### **Control volume**

Control volume is also called open system. It is a selected region

in space, which allows mass and energy to transfer across the boundary between the system and its surroundings.

### **Cycle**

A cycle consists of a series of processes. The final state of a cycle is always identical to its initial state.

### **Density**

Density is the mass per unit volume of a body or a system.

### **Enthalpy**

Enthalpy is a thermodynamic property. It is defined as the sum of the internal energy of a system and the flow work associated with the flowing fluid.

### **Entropy**

Entropy is a thermodynamic property, which quantifies the degree of disorder of a system resulting from the dispersal of energy and matter in a process.

### **Equation of state**

An equation of state is an expression that relates pressure, temperature and specific volume of a gas.

### **Equilibrium**

Equilibrium refers to a uniform condition throughout a system.

### **Equilibrium state**

An equilibrium state refers to a state of a system in equilibrium.

### **Extensive property**

An extensive property refers to a thermodynamic property of a

system, whose magnitude depends on the mass of the system. Examples of extensive properties include mass, volume, internal energy, enthalpy, and entropy.

### **Fusion line**

Fusion line is a curve that represents the transition between the solid and liquid phases of a substance.

### **Heat**

Heat is a form of energy. Heat transfer will take place between two objects if they are at different temperatures.

### **Heat engine**

Heat engine is a device that produces work by absorbing heat from a high-temperature body (heat source) and rejecting the waste heat to a low-temperature body (heat sink).

### **Heat sink**

A heat engine, refrigerator or heat pump must operate between a high-temperature body and a low-temperature body. The low-temperature body is called heat sink.

### **Heat source**

A heat engine, refrigerator or heat pump must operate between a high-temperature body and a low temperature body. The high-temperature body is called heat source.

### **Ideal gas**

An ideal gas is a gas that obeys the ideal gas equation of state,  $Pv=RT$ .

### **Intensive property**

An intensive property is a thermodynamic property that does

not depend on the mass of a system. Examples of intensive properties include pressure, temperature, density, specific volume, specific internal energy, specific enthalpy, and specific entropy.

### **Internal energy**

Internal energy is a form of thermal energy. From a macroscopic level, it is strongly associated with the temperature of a system. From a microscopic level, it is associated with the motions and structure of the molecules of a system.

### **Irreversibilities**

Irreversibilities refer to factors that render a process irreversible.

### **Isentropic process**

An isentropic process refers to a process that is reversible and adiabatic. The entropy remains constant in an isentropic process.

### **Isobaric process**

An isobaric process refers to a process whose pressure remains constant.

### **Isochoric process**

An isochoric process refers to a process of constant specific volume.

### **Isolated system**

An isolated system cannot exchange mass or energy with its surroundings.

## **Isothermal process**

An isothermal process refers to a process whose temperature remains constant.

## **Kelvin-Planck Statement**

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

## **Mechanical equilibrium**

Mechanical equilibrium refers to an equilibrium condition, in which the pressure of a system has no tendency to change over time.

## **Open system**

Open system is also called control volume. It is a selected region in space, which allows mass and energy to transfer across the boundary between the system and its surroundings.

## **Phase diagram**

Phase diagram is a graphical representation of a substance's state (solid, liquid or vapour) under different conditions of temperature and pressure.

## **Phase equilibrium**

Phase equilibrium is an equilibrium condition. For a system consisting of a mixture of multiple phases, if the composition of the mixture remains constant over time, the system is in phase equilibrium.

## **Pressure**

Pressure is the normal force exerted by an object on a surface per unit area of the surface.

**Process**

A process refers to the change in a system from one state to another state.

**Pure substance**

A pure substance refers to a matter that has a homogeneous and definite chemical composition. A pure substance may exist in a single phase or as a multi-phase mixture.

**Quasi-equilibrium process**

A quasi-equilibrium process refers to a process, in which all states are equilibrium states.

**Real gas**

A real gas refers to a gas, whose pressure, temperature and specific volume behaviour cannot be represented by the ideal gas equation of state.

**Reversible process**

A reversible process refers to a process that can be reversed without leaving any changes in either the system or its surroundings. In a reversible process, both the system and its surroundings can always return to their original states.

**Single phase**

Single phase refers to the solid, liquid or vapour (or gaseous) phase that a substance exists at a certain condition.

**Specific boundary work**

Specific boundary work is the boundary work done by one unit mass of a substance.

**Specific enthalpy**

Specific enthalpy is the enthalpy per unit mass of a system.

**Specific entropy**

Specific entropy is the entropy per unit mass of a system.

**Specific heat**

Specific heat, also called heat capacity, is a thermodynamic property to quantify the energy storage capacity of a substance. It is defined as the amount of heat required to raise the temperature of one unit mass of a substance by one degree.

**Specific internal energy**

Specific internal energy is the internal energy per unit mass of a system.

**Specific property**

A specific property is the corresponding extensive property per unit mass. Examples of specific properties include specific volume, specific internal energy, specific enthalpy, and specific entropy. Specific properties are intensive properties.

**Specific volume**

Specific volume is the volume per unit mass of a system. It is the reciprocal of density.

**State**

A state refers to a specific condition of a system that is described by a unique set of thermodynamic properties, such as pressure, temperature, specific volume, specific enthalpy, and so on.

**Steady flow**

A steady flow through a control volume refers to a flow, in which the properties, such as the mass and energy of the control volume remain unchanged over time.

**Sublimation line**

The sublimation line is the curve that represents the transition between the solid and vapour phases of a substance in a phase diagram.

**Surroundings**

In thermodynamic analysis, the universe is divided into two parts: a system and its surroundings. Surroundings refer to the rest of the universe outside of the system.

**System**

In thermodynamic analysis, the universe is divided into two parts: a system and its surroundings. A system refers to a selected quantity of matter or a region in space.

**Temperature**

Temperature is a measurable thermodynamic property that indicates the hotness or coldness of a body.

**Thermal equilibrium**

Thermal equilibrium is an equilibrium condition. A system in thermal equilibrium has a uniform temperature everywhere.

**Thermodynamics**

Thermodynamics is a branch of science. It originally focused on the scientific theories of heat-work conversion, and the operations and efficiency improvement of heat engines.

Nowadays, the applications of thermodynamics have extended to all fields related to energy conversion and conservation.

### **Transient flow**

A transient flow refers to a flow through a control volume, in which the properties, such as the mass and energy of the control volume change over time.

### **Triple point**

The triple point refers to a unique state of a substance, at which the three phases, solid, liquid and vapour, coexist in equilibrium.

### **Vapourization line**

The vapourization line refers to the curve that represents the transition between the liquid and vapour phases of a substance in a phase diagram.

### **Work**

Work is a form of energy that is transferred to or from a body by applying a force on that body along a displacement.

# Versioning History

We are always seeking to improve our open textbooks. Please submit your suggestions, recommendations, and/or corrections to the author Dr. Claire Yu Yan at [yu.yan@ubc.ca](mailto:yu.yan@ubc.ca).

This page lists major changes to this book with major changes marked with a 1.0 increase in the version number and minor changes marked with a 0.1 increase.

| <b>Version</b> | <b>Date</b>        | <b>Change</b>     |
|----------------|--------------------|-------------------|
| 1.0            | August 31,<br>2022 | Pressbook Created |