**UNIVERSITY OF ABERDEEN SESSION 2011-2012**

**Degree Examination in EG3020 PROCESS THERMODYNAMICS**

**Tuesday 25th January 2012 9.00a.m. – 12.00noon**

***Notes: (i) Candidates ARE permitted to use an approved calculator***

***(ii) Candidates ARE permitted to use Engineering Mathematics Handbook***

***(iii) Data sheets are attached to the paper***

***Candidates should attempt ALL FIVE questions. All questions carry 20 marks.***

**PLEASE NOTE THE FOLLOWING**

(i) You **must not** have in your possession any material other than that expressly permitted in the rules appropriate to this examination. Where this is permitted, such material **must not** be amended, annotated or modified in any way.

(ii) You **must not** have in your possession any material that could be determined as giving you an advantage in the examination.

(iii) You **must not** attempt to communicate with any candidate during the exam, either orally or by passing written material, or by showing material to another candidate, nor must you attempt to view another candidate's work.

**Failure to comply with the above will be regarded as cheating and may lead to disciplinary action as indicated in the Academic Quality Handbook (www.abdn.ac.uk/registry/quality/appendix7x1.pdf) Section 4.14 and 5.**

***Question 1***

Rapid Compression Machines (RCM) are often used to study engine combustion processes under idealised conditions. In an RCM the gas inside the cylinder can be considered as closed system. The initial pressure and temperature conditions of the working fluid air (molar mass $M$ = 28.97 g $mol^{-1}$, adiabatic coefficient $\gamma$ = 1.4) are $P_1$ = 1000 Torr and $T_1$ = 298 K. Air can be considered as an ideal gas with constant composition.

In the first step the gas is compressed rapidly in order to avoid any heat losses (compression ratio $r$ = 9.9); hence the compression can be considered to be adiabatic. In the second step the gas is heated in an isochoric process when combustion takes place reaching a temperature $T_3$ = 960 K. Then it expands adiabatically to the initial volume. In the last step, the gas returns to its initial condition.

a) Calculate pressure, temperature and specific volume for all states. Give your results in SI units.

[13 marks]

b) Sketch the cycle on a *PV* diagram.

[5 marks]

c) What is the requirement for the combustion step to be isochoric?

[2 marks]

***Question 2***

In a chemical plant the malfunction of a safety valve results in superheated steam at pressure $P$ = 70 bar and temperature $T$ = 500°C being discharged through a nozzle. The process can be considered to be reversible and adiabatic.

a) Assuming the steam is expanded to an ambient pressure of 1 bar, calculate the vapour quality and the temperature of the exhaust. Give the calculated temperature in °C with two decimal places precision.

[10 marks]

b) Determine the exhaust pressure at which saturated steam would exist.

[4 marks]

c) Draw the expansion process for both cases a) and b) in a *TS* diagram each. Indicate isobaric lines of the pressure levels involved in the process.

[6 marks]

***Question 3***

Mixtures and mixing processes are of great importance in any kind of chemical plant.

a) A stream of nitrogen (molar mass $M$ = 28.014 g mol$^{-1}$) flowing at the rate of 2 kg s$^{-1}$ and a stream of hydrogen (molar mass $M$ = 2.016 g mol$^{-1}$) flowing at a rate of 0.5 kg s$^{-1}$ mix adiabatically in a steady-flow process. If the gases are assumed ideal, what is the rate of entropy increase as a result of the process?

[7 marks]

b) The volume change of mixing (cm$^3$ mol$^{-1}$) for a binary system at 25°C is given by the equation:

$$\Delta V = x_1 x_2 \left[ -1.026 + 0.220\left(x_1 - x_2\right) \right]$$

Given that $V_1$ = 58.6 cm$^3$ mol$^{-1}$ and $V_2$ = 118.5 cm$^3$ mol$^{-1}$, what volume of mixture is formed when 700 cm$^3$ of pure species 1 is mixed with 1,400 cm$^3$ of species 2 at 25°C? What would be the volume if an ideal solution were formed?

[9 marks]

c) Explain in your own words the term ‘excess property’ and give an example.

[4 marks]

***Question 4***

A binary system of species 1 and 2 consists of vapour and liquid phases in equilibrium with each other at temperature *T*. In addition, the following information is given:

- $\ln \gamma_1 = 1.8x_2^2$ and $\ln \gamma_2 = 1.8x_1^2$
- At temperature *T*, the saturation pressures are $P_1^{sat}$ = 1.24 bar and $P_2^{sat}$ = 0.89 bar
- The modified Raoult's law is valid.

a) Determine the composition of the vapour and the pressure for which the two-phase system can exist with a liquid mole fraction $x_1$ = 0.65.

[6 marks]

b) Determine the range of values of the overall mole fraction $z_1$ for which the two-phase system can exist with a liquid mole fraction $x_1$ = 0.65.

[5 marks]

c) The system exhibits an azeotrope. Draw a schematic *P-xy* diagram showing an azeotropic behaviour. Indicate how the *P-x* relationship would look like for Raoult's law.

[6 marks]

d) Which is the main problem that is associated with azeotropic mixtures in technical processes? How can it be overcome (give one example)?

[3 marks]

***Question 5***

Equations of state allow determining *PVT* properties of fluids.

a) What are the main assumptions for an ideal gas? Under which conditions can the ideal gas law be used in practice?

[5 marks]

b) What do the parameters *a* and *b* account for in the van der Waals equation of state?

$$P = \frac{RT}{V-b} - \frac{a}{V^2}$$

[2 marks]

c) For an ideal gas show that in a *PV* diagram the curve representing an adiabatic process exhibits a steeper slope than the one representing an isothermal process.

[8 marks]

d) One form of the virial equation is

$$Z = 1 + B'P + C'P^2 + D'P^3 + \cdots$$

What is the physical meaning of the virial coefficients *B', C', D'*? What is the definition of the compressibility factor *Z*, and how can the given virial equation be used to describe an ideal gas?

[5 marks]

**Data Sheet**

### *Conversions*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | m | = | 3.281 | ft | | | | | |
| 1 | kg | = | 2.205 | lb | | | | | |
| 1 | J | = | 0.2388 | cal | | | | | |
| 1 | bar | = | 100000 | $N.m^{-2}$ | = | 14.50 | Psi | = | 0.986923 atm |
| 1 | bar | | 750.06 | Torr | | 750.06 | mmHg | | |
| 1 | acre ft | = | 43560 | $ft^3$ | = | 7758 | bbl | | |
| 1 | square mile | = | 640 | acre | | | | | |
| 1 | bbl | = | 5.615 | $ft^3$ | = | 0.159 | $m^3$ | = | 42 US Gal |

### *Temperature Conversions*

°R = °F + 460
K = °C + 273
°R = 1.8×K

### *Universal Gas Constant*

8.314 $J.mol^{-1}.K^{-1}$
10.73 $psia.ft^3.lb\text{-}mol^{-1}.°R^{-1}$

### *Standard Conditions*

Stock-tank or Standard Conditions are 60°F and 14.7 psia.

### *Equations of State*

The Generic Cubic Equation of State

$$P = \frac{RT}{V-b} - \frac{a(T)}{(V+\varepsilon b)(V+\sigma b)}$$

$$a(T) = \Psi \frac{\alpha(T_r) R^2 T_c^2}{P_c}$$

$$b = \Omega \frac{RT_c}{P_c}$$

| Eq. of State | $\alpha(T_r)$ | $\sigma$ | $\varepsilon$ | $\Omega$ | $\Psi$ |
|---|---|---|---|---|---|
| vdW | 1 | 0 | 0 | 1/8 | 27/64 |
| RK | $T_r^{-0.5}$ | 1 | 0 | 0.08664 | 0.42748 |
| SRK | $\alpha_{SRK}(T_r;\omega)^{\dagger}$ | 1 | 0 | 0.08664 | 0.42748 |
| PR | $\alpha_{PR}(T_r;\omega)^{\ddagger}$ | $1+\sqrt{2}$ | $1-\sqrt{2}$ | 0.07780 | 0.30740 |

† $\alpha_{SRK}(T_r;\omega) = \left[1+\left(0.480+1.574\omega-0.176\omega^2\right)\left(1-T_r^{0.5}\right)\right]^2$

‡ $\alpha_{PR}(T_r;\omega) = \left[1+\left(0.37464+1.54226\omega-0.26992\omega^2\right)\left(1-T_r^{0.5}\right)\right]^2$

Vapour & Vapour–like Roots of The Generic Cubic Equation of State

$$V = \frac{RT}{P} + b - \frac{a(T)}{P}\frac{V-b}{(V+\varepsilon b)(V+\sigma b)}$$

$$Z = 1 + \beta - q\beta\frac{Z-\beta}{(Z+\varepsilon\beta)(Z+\sigma\beta)}$$

$$\beta = \Omega\frac{P_r}{T_r}$$

$$q = \frac{\Psi\alpha(T_r)}{\Omega T_r}$$

Liquid & Liquid–like Roots of The Generic Cubic Equation of State

$$V = b + (V+\varepsilon b)(V+\sigma b)\left[\frac{RT + bP - VP}{a(T)}\right]$$

$$Z = \beta + (Z+\varepsilon\beta)(Z+\sigma\beta)\left(\frac{1+\beta-Z}{q\beta}\right)$$

### *Raoult's Law*

$y_i P = x_i P_i^{SAT} \qquad i = 1,2,3\ldots N$

$y_i P = x_i \gamma_i P_i^{SAT}$

### *Henry's Law*

$x_i H_i = y_i P \qquad i = 1,2,3\ldots N$

### *Antoine equation*

$\log_{10} P^* = A - \frac{B}{T+C}$ $\qquad P^*$ in mm Hg, $T$ in °C

| Compound | Formula | *A* | *B* | *C* |
|---|---|---|---|---|
| | | | | |
| Acetone | C3H6O | 7.11714 | 1210.595 | 229.664 |
| Benzene | C6H6 | 6.89272 | 1203.531 | 219.888 |
| Formaldehyde | CH2O | 7.19578 | 970.595 | 244.124 |
| Methyl Benzene | C7H8 | 6.95805 | 1345.773 | 219.693 |

$V$ = SPECIFIC VOLUME $cm^3\ g^{-1}$
$U$ = SPECIFIC INTERNAL ENERGY $kJ\ kg^{-1}$
$H$ = SPECIFIC ENTHALPY $kJ\ kg^{-1}$
$S$ = SPECIFIC ENTROPY $kJ\ kg^{-1}\ K^{-1}$

## Table F.1. Saturated Steam, SI Units (Continued)

| | | | SPECIFIC VOLUME $V$ | | | INTERNAL ENERGY $U$ | | | ENTHALPY $H$ | | | ENTROPY $S$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $t$ °C | $T$ K | $P$ kPa | sat. liq. | evap. | sat. vap. | sat. liq. | evap. | sat. vap. | sat. liq. | evap. | sat. vap. | sat. liq. | evap. | sat. vap. |
| 75 | 348.15 | 38.55 | 1.026 | 4133.1 | 4134.1 | 313.9 | 2162.1 | 2476.0 | 313.9 | 2321.5 | 2635.4 | 1.0154 | 6.6681 | 7.6835 |
| 76 | 349.15 | 40.19 | 1.027 | 3974.6 | 3975.7 | 318.1 | 2159.2 | 2477.3 | 318.1 | 2318.9 | 2637.1 | 1.0275 | 6.6418 | 7.6693 |
| 77 | 350.15 | 41.89 | 1.027 | 3823.3 | 3824.3 | 322.3 | 2156.3 | 2478.5 | 322.3 | 2316.4 | 2638.7 | 1.0395 | 6.6156 | 7.6551 |
| 78 | 351.15 | 43.65 | 1.028 | 3678.6 | 3679.6 | 326.5 | 2153.3 | 2479.8 | 326.5 | 2313.9 | 2640.4 | 1.0514 | 6.5896 | 7.6410 |
| 79 | 352.15 | 45.47 | 1.029 | 3540.3 | 3541.3 | 330.7 | 2150.4 | 2481.1 | 330.7 | 2311.4 | 2642.1 | 1.0634 | 6.5637 | 7.6271 |
| 80 | 353.15 | 47.36 | 1.029 | 3408.1 | 3409.1 | 334.9 | 2147.4 | 2482.3 | 334.9 | 2308.8 | 2643.8 | 1.0753 | 6.5380 | 7.6132 |
| 81 | 354.15 | 49.31 | 1.030 | 3281.6 | 3282.6 | 339.1 | 2144.5 | 2483.5 | 339.1 | 2306.3 | 2645.4 | 1.0871 | 6.5123 | 7.5995 |
| 82 | 355.15 | 51.33 | 1.031 | 3160.6 | 3161.6 | 343.3 | 2141.5 | 2484.8 | 343.3 | 2303.8 | 2647.1 | 1.0990 | 6.4868 | 7.5858 |
| 83 | 356.15 | 53.42 | 1.031 | 3044.8 | 3045.8 | 347.5 | 2138.6 | 2486.0 | 347.5 | 2301.2 | 2648.7 | 1.1108 | 6.4615 | 7.5722 |
| 84 | 357.15 | 55.57 | 1.032 | 2933.9 | 2935.0 | 351.7 | 2135.6 | 2487.3 | 351.7 | 2298.6 | 2650.4 | 1.1225 | 6.4362 | 7.5587 |
| 85 | 358.15 | 57.80 | 1.033 | 2827.8 | 2828.8 | 355.9 | 2132.6 | 2488.5 | 355.9 | 2296.1 | 2652.0 | 1.1343 | 6.4111 | 7.5454 |
| 86 | 359.15 | 60.11 | 1.033 | 2726.1 | 2727.2 | 360.1 | 2129.7 | 2489.7 | 360.1 | 2293.5 | 2653.6 | 1.1460 | 6.3861 | 7.5321 |
| 87 | 360.15 | 62.49 | 1.034 | 2628.8 | 2629.8 | 364.3 | 2126.7 | 2490.9 | 364.3 | 2290.9 | 2655.3 | 1.1577 | 6.3612 | 7.5189 |
| 88 | 361.15 | 64.95 | 1.035 | 2535.4 | 2536.5 | 368.5 | 2123.7 | 2492.2 | 368.5 | 2288.4 | 2656.9 | 1.1693 | 6.3365 | 7.5058 |
| 89 | 362.15 | 67.49 | 1.035 | 2446.0 | 2447.0 | 372.7 | 2120.7 | 2493.4 | 372.7 | 2285.8 | 2658.5 | 1.1809 | 6.3119 | 7.4928 |
| 90 | 363.15 | 70.11 | 1.036 | 2360.3 | 2361.3 | 376.9 | 2117.7 | 2494.6 | 376.9 | 2283.2 | 2660.1 | 1.1925 | 6.2873 | 7.4799 |
| 91 | 364.15 | 72.81 | 1.037 | 2278.0 | 2279.1 | 381.1 | 2114.7 | 2495.8 | 381.1 | 2280.6 | 2661.7 | 1.2041 | 6.2629 | 7.4670 |
| 92 | 365.15 | 75.61 | 1.038 | 2199.2 | 2200.2 | 385.3 | 2111.7 | 2497.0 | 385.4 | 2278.0 | 2663.4 | 1.2156 | 6.2387 | 7.4543 |
| 93 | 366.15 | 78.49 | 1.038 | 2123.5 | 2124.5 | 389.5 | 2108.7 | 2498.2 | 389.6 | 2275.4 | 2665.0 | 1.2271 | 6.2145 | 7.4416 |
| 94 | 367.15 | 81.46 | 1.039 | 2050.9 | 2051.9 | 393.7 | 2105.7 | 2499.4 | 393.8 | 2272.8 | 2666.6 | 1.2386 | 6.1905 | 7.4291 |
| 95 | 368.15 | 84.53 | 1.040 | 1981.2 | 1982.2 | 397.9 | 2102.7 | 2500.6 | 398.0 | 2270.2 | 2668.1 | 1.2501 | 6.1665 | 7.4166 |
| 96 | 369.15 | 87.69 | 1.041 | 1914.3 | 1915.3 | 402.1 | 2099.7 | 2501.8 | 402.2 | 2267.5 | 2669.7 | 1.2615 | 6.1427 | 7.4042 |
| 97 | 370.15 | 90.94 | 1.041 | 1850.0 | 1851.0 | 406.3 | 2096.6 | 2503.0 | 406.4 | 2264.9 | 2671.3 | 1.2729 | 6.1190 | 7.3919 |
| 98 | 371.15 | 94.30 | 1.042 | 1788.3 | 1789.3 | 410.5 | 2093.6 | 2504.1 | 410.6 | 2262.2 | 2672.9 | 1.2842 | 6.0954 | 7.3796 |
| 99 | 372.15 | 97.76 | 1.043 | 1729.0 | 1730.0 | 414.7 | 2090.6 | 2505.3 | 414.8 | 2259.6 | 2674.4 | 1.2956 | 6.0719 | 7.3675 |
| 100 | 373.15 | 101.33 | 1.044 | 1672.0 | 1673.0 | 419.0 | 2087.5 | 2506.5 | 419.1 | 2256.9 | 2676.0 | 1.3069 | 6.0485 | 7.3554 |
| 102 | 375.15 | 108.78 | 1.045 | 1564.5 | 1565.5 | 427.4 | 2081.4 | 2508.8 | 427.5 | 2251.6 | 2679.1 | 1.3294 | 6.0021 | 7.3315 |
| 104 | 377.15 | 116.68 | 1.047 | 1465.1 | 1466.2 | 435.8 | 2075.3 | 2511.1 | 435.9 | 2246.3 | 2682.2 | 1.3518 | 5.9560 | 7.3078 |
| 106 | 379.15 | 125.04 | 1.049 | 1373.1 | 1374.2 | 444.3 | 2069.2 | 2513.4 | 444.4 | 2240.9 | 2685.3 | 1.3742 | 5.9104 | 7.2845 |
| 108 | 381.15 | 133.90 | 1.050 | 1287.9 | 1288.9 | 452.7 | 2063.0 | 2515.7 | 452.9 | 2235.4 | 2688.3 | 1.3964 | 5.8651 | 7.2615 |
| 110 | 383.15 | 143.27 | 1.052 | 1208.9 | 1209.9 | 461.2 | 2056.8 | 2518.0 | 461.3 | 2230.0 | 2691.3 | 1.4185 | 5.8203 | 7.2388 |
| 112 | 385.15 | 153.16 | 1.054 | 1135.6 | 1136.6 | 469.6 | 2050.6 | 2520.2 | 469.8 | 2224.5 | 2694.3 | 1.4405 | 5.7758 | 7.2164 |
| 114 | 387.15 | 163.62 | 1.055 | 1067.5 | 1068.5 | 478.1 | 2044.3 | 2522.4 | 478.3 | 2219.0 | 2697.2 | 1.4624 | 5.7318 | 7.1942 |
| 116 | 389.15 | 174.65 | 1.057 | 1004.2 | 1005.2 | 486.6 | 2038.1 | 2524.6 | 486.7 | 2213.4 | 2700.2 | 1.4842 | 5.6881 | 7.1723 |
| 118 | 391.15 | 186.28 | 1.059 | 945.3 | 946.3 | 495.0 | 2031.8 | 2526.8 | 495.2 | 2207.9 | 2703.1 | 1.5060 | 5.6447 | 7.1507 |
| 120 | 393.15 | 198.54 | 1.061 | 890.5 | 891.5 | 503.5 | 2025.4 | 2529.0 | 503.7 | 2202.2 | 2706.0 | 1.5276 | 5.6017 | 7.1293 |
| 122 | 395.15 | 211.45 | 1.062 | 839.4 | 840.5 | 512.0 | 2019.1 | 2531.1 | 512.2 | 2196.6 | 2708.8 | 1.5491 | 5.5590 | 7.1082 |
| 124 | 397.15 | 225.04 | 1.064 | 791.8 | 792.8 | 520.5 | 2012.7 | 2533.2 | 520.7 | 2190.9 | 2711.6 | 1.5706 | 5.5167 | 7.0873 |
| 126 | 399.15 | 239.33 | 1.066 | 747.3 | 748.4 | 529.0 | 2006.3 | 2535.3 | 529.2 | 2185.2 | 2714.4 | 1.5919 | 5.4747 | 7.0666 |
| 128 | 401.15 | 254.35 | 1.068 | 705.8 | 706.9 | 537.5 | 1999.9 | 2537.4 | 537.8 | 2179.4 | 2717.2 | 1.6132 | 5.4330 | 7.0462 |
| 130 | 403.15 | 270.13 | 1.070 | 667.1 | 668.1 | 546.0 | 1993.4 | 2539.4 | 546.3 | 2173.6 | 2719.9 | 1.6344 | 5.3917 | 7.0261 |
| 132 | 405.15 | 286.70 | 1.072 | 630.8 | 631.9 | 554.5 | 1986.9 | 2541.4 | 554.8 | 2167.8 | 2722.6 | 1.6555 | 5.3507 | 7.0061 |
| 134 | 407.15 | 304.07 | 1.074 | 596.9 | 598.0 | 563.1 | 1980.4 | 2543.4 | 563.4 | 2161.9 | 2725.3 | 1.6765 | 5.3099 | 6.9864 |
| 136 | 409.15 | 322.29 | 1.076 | 565.1 | 566.2 | 571.6 | 1973.8 | 2545.4 | 572.0 | 2155.9 | 2727.9 | 1.6974 | 5.2695 | 6.9669 |
| 138 | 411.15 | 341.38 | 1.078 | 535.3 | 536.4 | 580.2 | 1967.2 | 2547.4 | 580.5 | 2150.0 | 2730.5 | 1.7182 | 5.2293 | 6.9475 |
| 140 | 413.15 | 361.38 | 1.080 | 507.4 | 508.5 | 588.7 | 1960.6 | 2549.3 | 589.1 | 2144.0 | 2733.1 | 1.7390 | 5.1894 | 6.9284 |
| 142 | 415.15 | 382.31 | 1.082 | 481.2 | 482.3 | 597.3 | 1953.9 | 2551.2 | 597.7 | 2137.9 | 2735.6 | 1.7597 | 5.1499 | 6.9095 |
| 144 | 417.15 | 404.20 | 1.084 | 456.6 | 457.7 | 605.9 | 1947.2 | 2553.1 | 606.3 | 2131.8 | 2738.1 | 1.7803 | 5.1105 | 6.8908 |
| 146 | 419.15 | 427.09 | 1.086 | 433.5 | 434.6 | 614.4 | 1940.5 | 2554.9 | 614.9 | 2125.7 | 2740.6 | 1.8008 | 5.0715 | 6.8723 |
| 148 | 421.15 | 451.01 | 1.089 | 411.8 | 412.9 | 623.0 | 1933.7 | 2556.8 | 623.5 | 2119.5 | 2743.0 | 1.8213 | 5.0327 | 6.8539 |
| 150 | 423.15 | 476.00 | 1.091 | 391.4 | 392.4 | 631.6 | 1926.9 | 2558.6 | 632.1 | 2113.2 | 2745.4 | 1.8416 | 4.9941 | 6.8358 |
| 152 | 425.15 | 502.08 | 1.093 | 372.1 | 373.2 | 640.2 | 1920.1 | 2560.3 | 640.8 | 2106.9 | 2747.7 | 1.8619 | 4.9558 | 6.8178 |
| 154 | 427.15 | 529.29 | 1.095 | 354.0 | 355.1 | 648.9 | 1913.2 | 2562.1 | 649.4 | 2100.6 | 2750.0 | 1.8822 | 4.9178 | 6.8000 |
| 156 | 429.15 | 557.67 | 1.098 | 336.9 | 338.0 | 657.5 | 1906.3 | 2563.8 | 658.1 | 2094.2 | 2752.3 | 1.9023 | 4.8800 | 6.7823 |
| 158 | 431.15 | 587.25 | 1.100 | 320.8 | 321.9 | 666.1 | 1899.3 | 2565.5 | 666.8 | 2087.7 | 2754.5 | 1.9224 | 4.8424 | 6.7648 |
| 160 | 433.15 | 618.06 | 1.102 | 305.7 | 306.8 | 674.8 | 1892.3 | 2567.1 | 675.5 | 2081.3 | 2756.7 | 1.9425 | 4.8050 | 6.7475 |
| 162 | 435.15 | 650.16 | 1.105 | 291.3 | 292.4 | 683.5 | 1885.3 | 2568.8 | 684.2 | 2074.7 | 2758.9 | 1.9624 | 4.7679 | 6.7303 |
| 164 | 437.15 | 683.56 | 1.107 | 277.8 | 278.9 | 692.1 | 1878.2 | 2570.4 | 692.9 | 2068.1 | 2761.0 | 1.9823 | 4.7309 | 6.7133 |
| 166 | 439.15 | 718.31 | 1.109 | 265.0 | 266.1 | 700.8 | 1871.1 | 2571.9 | 701.6 | 2061.4 | 2763.1 | 2.0022 | 4.6942 | 6.6964 |
| 168 | 441.15 | 754.45 | 1.112 | 252.9 | 254.0 | 709.5 | 1863.9 | 2573.4 | 710.4 | 2054.7 | 2765.1 | 2.0219 | 4.6577 | 6.6796 |
| 170 | 443.15 | 792.02 | 1.114 | 241.4 | 242.6 | 718.2 | 1856.7 | 2574.9 | 719.1 | 2047.9 | 2767.1 | 2.0416 | 4.6214 | 6.6630 |
| 172 | 445.15 | 831.06 | 1.117 | 230.6 | 231.7 | 727.0 | 1849.5 | 2576.4 | 727.9 | 2041.1 | 2769.0 | 2.0613 | 4.5853 | 6.6465 |
| 174 | 447.15 | 871.60 | 1.120 | 220.3 | 221.5 | 735.7 | 1842.2 | 2577.8 | 736.7 | 2034.2 | 2770.9 | 2.0809 | 4.5493 | 6.6302 |
| 176 | 449.15 | 913.68 | 1.122 | 210.6 | 211.7 | 744.4 | 1834.8 | 2579.3 | 745.5 | 2027.3 | 2772.7 | 2.1004 | 4.5136 | 6.6140 |
| 178 | 451.15 | 957.36 | 1.125 | 201.4 | 202.5 | 753.2 | 1827.4 | 2580.6 | 754.3 | 2020.2 | 2774.5 | 2.1199 | 4.4780 | 6.5979 |
| 180 | 453.15 | 1002.7 | 1.128 | 192.7 | 193.8 | 762.0 | 1820.0 | 2581.9 | 763.1 | 2013.1 | 2776.3 | 2.1393 | 4.4426 | 6.5819 |
| 182 | 455.15 | 1049.6 | 1.130 | 184.4 | 185.5 | 770.8 | 1812.5 | 2583.2 | 772.0 | 2006.0 | 2778.0 | 2.1587 | 4.4074 | 6.5660 |
| 184 | 457.15 | 1098.3 | 1.133 | 176.5 | 177.6 | 779.6 | 1804.9 | 2584.5 | 780.8 | 1998.8 | 2779.6 | 2.1780 | 4.3723 | 6.5503 |
| 186 | 459.15 | 1148.8 | 1.136 | 169.0 | 170.2 | 788.4 | 1797.3 | 2585.7 | 789.7 | 1991.5 | 2781.2 | 2.1972 | 4.3374 | 6.5346 |
| 188 | 461.15 | 1201.0 | 1.139 | 161.9 | 163.1 | 797.2 | 1789.7 | 2586.9 | 798.6 | 1984.2 | 2782.8 | 2.2164 | 4.3026 | 6.5191 |
| 190 | 463.15 | 1255.1 | 1.142 | 155.2 | 156.3 | 806.1 | 1782.0 | 2588.1 | 807.5 | 1976.7 | 2784.3 | 2.2356 | 4.2680 | 6.5036 |
| 192 | 465.15 | 1311.1 | 1.144 | 148.8 | 149.9 | 814.9 | 1774.2 | 2589.2 | 816.5 | 1969.3 | 2785.7 | 2.2547 | 4.2336 | 6.4883 |
| 194 | 467.15 | 1369.0 | 1.147 | 142.6 | 143.8 | 823.8 | 1766.4 | 2590.2 | 825.4 | 1961.7 | 2787.1 | 2.2738 | 4.1993 | 6.4730 |
| 196 | 469.15 | 1428.9 | 1.150 | 136.8 | 138.0 | 832.7 | 1758.6 | 2591.3 | 834.4 | 1954.1 | 2788.4 | 2.2928 | 4.1651 | 6.4578 |
| 198 | 471.15 | 1490.9 | 1.153 | 131.3 | 132.4 | 841.6 | 1750.6 | 2592.3 | 843.4 | 1946.4 | 2789.7 | 2.3117 | 4.1310 | 6.4428 |
| 200 | 473.15 | 1554.9 | 1.156 | 126.0 | 127.2 | 850.6 | 1742.6 | 2593.2 | 852.4 | 1938.6 | 2790.9 | 2.3307 | 4.0971 | 6.4278 |
| 202 | 475.15 | 1621.0 | 1.160 | 121.0 | 122.1 | 859.5 | 1734.6 | 2594.1 | 861.4 | 1930.7 | 2792.1 | 2.3495 | 4.0633 | 6.4128 |
| 204 | 477.15 | 1689.3 | 1.163 | 116.2 | 117.3 | 868.5 | 1726.5 | 2595.0 | 870.5 | 1922.8 | 2793.2 | 2.3684 | 4.0296 | 6.3980 |
| 206 | 479.15 | 1759.8 | 1.166 | 111.6 | 112.8 | 877.5 | 1718.3 | 2595.8 | 879.5 | 1914.7 | 2794.3 | 2.3872 | 3.9961 | 6.3832 |
| 208 | 481.15 | 1832.6 | 1.169 | 107.2 | 108.4 | 886.5 | 1710.1 | 2596.6 | 888.6 | 1906.6 | 2795.3 | 2.4059 | 3.9626 | 6.3686 |
| 210 | 483.15 | 1907.7 | 1.173 | 103.1 | 104.2 | 895.5 | 1701.8 | 2597.3 | 897.7 | 1898.5 | 2796.2 | 2.4247 | 3.9293 | 6.3539 |
| 212 | 485.15 | 1985.2 | 1.176 | 99.09 | 100.26 | 904.5 | 1693.5 | 2598.0 | 906.9 | 1890.2 | 2797.1 | 2.4434 | 3.8960 | 6.3394 |
| 214 | 487.15 | 2065.1 | 1.179 | 95.28 | 96.46 | 913.6 | 1685.1 | 2598.7 | 916.0 | 1881.8 | 2797.9 | 2.4620 | 3.8629 | 6.3249 |
| 216 | 489.15 | 2147.5 | 1.183 | 91.65 | 92.83 | 922.7 | 1676.6 | 2599.3 | 925.2 | 1873.4 | 2798.6 | 2.4806 | 3.8298 | 6.3104 |
| 218 | 491.15 | 2232.4 | 1.186 | 88.17 | 89.36 | 931.8 | 1668.0 | 2599.8 | 934.4 | 1864.9 | 2799.3 | 2.4992 | 3.7968 | 6.2960 |

## Table F.2. Superheated Steam, SI Units (Continued)

| $P$/kPa ($t^{sat}$/°C) | | sat. liq. | sat. vap. | TEMPERATURE: $t$ °C (TEMPERATURE: $T$ kelvins) 450 (723.15) | 475 (748.15) | 500 (773.15) | 525 (798.15) | 550 (823.15) | 575 (848.15) | 600 (873.15) | 650 (923.15) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *V* | 1.312 | 33.651 | 54.026 | 56.357 | 58.644 | 60.896 | 63.120 | 65.320 | 67.500 | 71.807 |
| 5800 | *U* | 1194.7 | 2591.9 | 2992.9 | 3038.8 | 3084.4 | 3129.8 | 3175.2 | 3220.7 | 3266.4 | 3358.5 |
| (273.35) | *H* | 1202.3 | 2787.0 | 3306.3 | 3365.7 | 3424.5 | 3483.0 | 3541.2 | 3599.5 | 3657.9 | 3775.0 |
| | *S* | 3.0071 | 5.9066 | 6.7416 | 6.8223 | 6.8996 | 6.9740 | 7.0460 | 7.1157 | 7.1835 | 7.3139 |
| | *V* | 1.315 | 33.034 | 53.048 | 55.346 | 57.600 | 59.819 | 62.010 | 64.176 | 66.322 | 70.563 |
| 5900 | *U* | 1200.3 | 2591.1 | 2991.9 | 3037.9 | 3083.5 | 3129.0 | 3174.4 | 3220.0 | 3265.7 | 3357.9 |
| (274.46) | *H* | 1208.0 | 2786.0 | 3304.9 | 3364.4 | 3423.3 | 3481.9 | 3540.3 | 3598.6 | 3657.0 | 3774.3 |
| | *S* | 3.0172 | 5.8986 | 6.7322 | 6.8132 | 6.8906 | 6.9652 | 7.0372 | 7.1070 | 7.1749 | 7.3054 |
| | *V* | 1.319 | 32.438 | 52.103 | 54.369 | 56.592 | 58.778 | 60.937 | 63.071 | 65.184 | 69.359 |
| 6000 | *U* | 1205.8 | 2590.4 | 2990.8 | 3036.9 | 3082.6 | 3128.2 | 3173.7 | 3219.3 | 3265.1 | 3357.4 |
| (275.55) | *H* | 1213.7 | 2785.0 | 3303.5 | 3363.2 | 3422.2 | 3480.8 | 3539.3 | 3597.7 | 3656.2 | 3773.5 |
| | *S* | 3.0273 | 5.8908 | 6.7230 | 6.8041 | 6.8818 | 6.9564 | 7.0285 | 7.0985 | 7.1664 | 7.2971 |
| | *V* | 1.322 | 31.860 | 51.189 | 53.424 | 55.616 | 57.771 | 59.898 | 62.001 | 64.083 | 68.196 |
| 6100 | *U* | 1211.2 | 2589.6 | 2989.8 | 3036.0 | 3081.8 | 3127.4 | 3173.0 | 3218.6 | 3264.5 | 3356.8 |
| (276.63) | *H* | 1219.3 | 2783.9 | 3302.0 | 3361.9 | 3421.0 | 3479.8 | 3538.3 | 3596.8 | 3655.4 | 3772.8 |
| | *S* | 3.0372 | 5.8830 | 6.7139 | 6.7952 | 6.8730 | 6.9478 | 7.0200 | 7.0900 | 7.1581 | 7.2889 |
| | *V* | 1.325 | 31.300 | 50.304 | 52.510 | 54.671 | 56.797 | 58.894 | 60.966 | 63.018 | 67.069 |
| 6200 | *U* | 1216.6 | 2588.8 | 2988.7 | 3035.0 | 3080.9 | 3126.6 | 3172.2 | 3218.0 | 3263.8 | 3356.3 |
| (277.70) | *H* | 1224.8 | 2782.9 | 3300.6 | 3360.6 | 3419.9 | 3478.7 | 3537.4 | 3595.9 | 3654.5 | 3772.1 |
| | *S* | 3.0471 | 5.8753 | 6.7049 | 6.7864 | 6.8644 | 6.9393 | 7.0116 | 7.0817 | 7.1498 | 7.2808 |
| | *V* | 1.328 | 30.757 | 49.447 | 51.624 | 53.757 | 55.853 | 57.921 | 59.964 | 61.986 | 65.979 |
| 6300 | *U* | 1221.9 | 2588.0 | 2987.7 | 3034.1 | 3080.1 | 3125.8 | 3171.5 | 3217.3 | 3263.2 | 3355.7 |
| (278.75) | *H* | 1230.3 | 2781.8 | 3299.2 | 3359.3 | 3418.7 | 3477.7 | 3536.4 | 3595.0 | 3653.7 | 3771.4 |
| | *S* | 3.0568 | 5.8677 | 6.6960 | 6.7778 | 6.8559 | 6.9309 | 7.0034 | 7.0735 | 7.1417 | 7.2728 |
| | *V* | 1.332 | 30.230 | 48.617 | 50.767 | 52.871 | 54.939 | 56.978 | 58.993 | 60.987 | 64.922 |
| 6400 | *U* | 1227.2 | 2587.2 | 2986.6 | 3033.1 | 3079.2 | 3125.0 | 3170.8 | 3216.6 | 3262.6 | 3355.2 |
| (279.79) | *H* | 1235.7 | 2780.6 | 3297.7 | 3358.0 | 3417.6 | 3476.6 | 3535.4 | 3594.1 | 3652.9 | 3770.7 |
| | *S* | 3.0664 | 5.8601 | 6.6872 | 6.7692 | 6.8475 | 6.9226 | 6.9952 | 7.0655 | 7.1337 | 7.2649 |
| | *V* | 1.335 | 29.719 | 47.812 | 49.935 | 52.012 | 54.053 | 56.065 | 58.052 | 60.018 | 63.898 |
| 6500 | *U* | 1232.5 | 2586.3 | 2985.5 | 3032.2 | 3078.3 | 3124.2 | 3170.0 | 3215.9 | 3261.9 | 3354.6 |
| (280.82) | *H* | 1241.1 | 2779.5 | 3296.3 | 3356.8 | 3416.4 | 3475.6 | 3534.4 | 3593.2 | 3652.1 | 3770.0 |
| | *S* | 3.0759 | 5.8527 | 6.6786 | 6.7608 | 6.8392 | 6.9145 | 6.9871 | 7.0575 | 7.1258 | 7.2572 |
| | *V* | 1.338 | 29.223 | 47.031 | 49.129 | 51.180 | 53.194 | 55.179 | 57.139 | 59.079 | 62.905 |
| 6600 | *U* | 1237.6 | 2585.5 | 2984.5 | 3031.2 | 3077.4 | 3123.4 | 3169.3 | 3215.2 | 3261.3 | 3354.1 |
| (281.84) | *H* | 1246.5 | 2778.3 | 3294.9 | 3355.5 | 3415.2 | 3474.5 | 3533.5 | 3592.3 | 3651.2 | 3769.2 |
| | *S* | 3.0853 | 5.8452 | 6.6700 | 6.7524 | 6.8310 | 6.9064 | 6.9792 | 7.0497 | 7.1181 | 7.2495 |
| | *V* | 1.342 | 28.741 | 46.274 | 48.346 | 50.372 | 52.361 | 54.320 | 56.254 | 58.168 | 61.942 |
| 6700 | *U* | 1242.8 | 2584.6 | 2983.4 | 3030.3 | 3076.6 | 3122.6 | 3168.6 | 3214.5 | 3260.7 | 3353.5 |
| (282.84) | *H* | 1251.8 | 2777.1 | 3293.4 | 3354.2 | 3414.1 | 3473.4 | 3532.5 | 3591.4 | 3650.4 | 3768.5 |
| | *S* | 3.0946 | 5.8379 | 6.6616 | 6.7442 | 6.8229 | 6.8985 | 6.9714 | 7.0419 | 7.1104 | 7.2420 |
| | *V* | 1.345 | 28.272 | 45.539 | 47.587 | 49.588 | 51.552 | 53.486 | 55.395 | 57.283 | 61.007 |
| 6800 | *U* | 1247.9 | 2583.7 | 2982.3 | 3029.3 | 3075.7 | 3121.8 | 3167.8 | 3213.9 | 3260.0 | 3353.0 |
| (283.84) | *H* | 1257.0 | 2775.9 | 3292.0 | 3352.9 | 3412.9 | 3472.4 | 3531.5 | 3590.5 | 3649.6 | 3767.8 |
| | *S* | 3.1038 | 5.8306 | 6.6532 | 6.7361 | 6.8150 | 6.8907 | 6.9636 | 7.0343 | 7.1028 | 7.2345 |
| | *V* | 1.351 | 27.373 | 44.131 | 46.133 | 48.086 | 50.003 | 51.889 | 53.750 | 55.590 | 59.217 |
| 7000 | *U* | 1258.0 | 2581.8 | 2980.1 | 3027.4 | 3074.0 | 3120.2 | 3166.3 | 3212.5 | 3258.8 | 3351.9 |
| (285.79) | *H* | 1267.4 | 2773.5 | 3289.1 | 3350.3 | 3410.6 | 3470.2 | 3529.6 | 3588.7 | 3647.9 | 3766.4 |
| | *S* | 3.1219 | 5.8162 | 6.6368 | 6.7201 | 6.7993 | 6.8753 | 6.9485 | 7.0193 | 7.0880 | 7.2200 |
| | *V* | 1.358 | 26.522 | 42.802 | 44.759 | 46.668 | 48.540 | 50.381 | 52.197 | 53.991 | 57.527 |
| 7200 | *U* | 1267.9 | 2579.9 | 2978.0 | 3025.4 | 3072.2 | 3118.6 | 3164.9 | 3211.1 | 3257.5 | 3350.7 |
| (287.70) | *H* | 1277.6 | 2770.9 | 3286.1 | 3347.7 | 3408.2 | 3468.1 | 3527.6 | 3586.9 | 3646.2 | 3764.9 |
| | *S* | 3.1397 | 5.8020 | 6.6208 | 6.7044 | 6.7840 | 6.8602 | 6.9337 | 7.0047 | 7.0735 | 7.2058 |
| | *V* | 1.364 | 25.715 | 41.544 | 43.460 | 45.327 | 47.156 | 48.954 | 50.727 | 52.478 | 55.928 |
| 7400 | *U* | 1277.6 | 2578.0 | 2975.8 | 3023.5 | 3070.4 | 3117.0 | 3163.4 | 3209.8 | 3256.2 | 3349.6 |
| (289.57) | *H* | 1287.7 | 2768.3 | 3283.2 | 3345.1 | 3405.9 | 3466.0 | 3525.7 | 3585.1 | 3644.5 | 3763.5 |
| | *S* | 3.1571 | 5.7880 | 6.6050 | 6.6892 | 6.7691 | 6.8456 | 6.9192 | 6.9904 | 7.0594 | 7.1919 |
| | *V* | 1.371 | 24.949 | 40.351 | 42.228 | 44.056 | 45.845 | 47.603 | 49.335 | 51.045 | 54.413 |
| 7600 | *U* | 1287.2 | 2575.9 | 2973.6 | 3021.5 | 3068.7 | 3115.4 | 3161.9 | 3208.4 | 3254.9 | 3348.5 |
| (291.41) | *H* | 1297.6 | 2765.5 | 3280.3 | 3342.5 | 3403.5 | 3463.8 | 3523.7 | 3583.3 | 3642.9 | 3762.1 |
| | *S* | 3.1742 | 5.7742 | 6.5896 | 6.6742 | 6.7545 | 6.8312 | 6.9051 | 6.9765 | 7.0457 | 7.1784 |
| | *V* | 1.378 | 24.220 | 39.220 | 41.060 | 42.850 | 44.601 | 46.320 | 48.014 | 49.686 | 52.976 |
| 7800 | *U* | 1296.7 | 2573.8 | 2971.4 | 3019.6 | 3066.9 | 3113.8 | 3160.4 | 3207.0 | 3253.7 | 3347.4 |
| (293.21) | *H* | 1307.4 | 2762.8 | 3277.3 | 3339.8 | 3401.1 | 3461.7 | 3521.7 | 3581.5 | 3641.2 | 3760.6 |
| | *S* | 3.1911 | 5.7605 | 6.5745 | 6.6596 | 6.7402 | 6.8172 | 6.8913 | 6.9629 | 7.0322 | 7.1652 |
| | *V* | 1.384 | 23.525 | 38.145 | 39.950 | 41.704 | 43.419 | 45.102 | 46.759 | 48.394 | 51.611 |
| 8000 | *U* | 1306.0 | 2571.7 | 2969.2 | 3017.6 | 3065.1 | 3112.2 | 3158.9 | 3205.6 | 3252.4 | 3346.3 |
| (294.97) | *H* | 1317.1 | 2759.9 | 3274.3 | 3337.2 | 3398.8 | 3459.5 | 3519.7 | 3579.7 | 3639.5 | 3759.2 |
| | *S* | 3.2076 | 5.7471 | 6.5597 | 6.6452 | 6.7262 | 6.8035 | 6.8778 | 6.9496 | 7.0191 | 7.1523 |