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|---|---|---|
| **PROGRAM** | : | BACHELOR OF ENGINEERING TECHNOLOGY<br>*CHEMICAL ENGINEERING* |
| **SUBJECT** | : | **APPLIED THERMODYNAMICS 2B** |
| **CODE** | : | **ATDCHB2** |
| **DATE** | : | SSA SUMMER EXAMINATION<br>JANUARY 2020 |
| **DURATION** | : | (SESSION X) 3 hours |
| **WEIGHT** | : | 40: 60 |
| **TOTAL MARKS** | : | 100 |
| **FULL MARKS** | : | 100 |
| **EXAMINER** | : | Mr G PAHLA and Prof C NARASIGADU |
| **MODERATOR** | : | DR R HUBERTS |
| **NUMBER OF PAGES** | : | 10 PAGES |
| **REQUIREMENTS** | : | Use of scientific (non-programmable) calculator is permitted (only one per candidate). |

## HINTS AND INSTRUCTIONS TO CANDIDATE(S):

- Purpose of assessment is to determine not only if you can write down an answer, but also to assess whether you understand the concepts, principles and expressions involved. Set out solutions in a logical and concise manner with justification for the steps followed.
- **ATTEMPT ALL QUESTIONS**. Please answer each question to the best of your ability.
- Write your details (module name and code, ID number, student number etc.) on script(s).
- Number each question clearly; questions may be answered in any order.
- Make sure that you read each question carefully before attempting to answer the question.
- Show all steps (and units) in calculations; this is a 'closed book' assessment.
- Ensure your responses are legible, clear and include relevant units (where appropriate).

**Question One** **[Total: 20 marks]**

An air-standard Otto cycle has a compression ratio of 9.5. Prior to the isentropic compression process, the air is at 100 kPa, 35 °C, and 600 $cm^3$. The temperature at the end of the isentropic expansion process is 527 $^oC$. Calculate the thermal efficiency for this cycle.

For air; $C_p$ = 1.005 kJ/kg·K, $C_v$ = 0.718 kJ/kg·K, R = 0.287 kJ/kg·K, and $\gamma$ = 1.4.

**Question Two** **[Total: 30 Marks]**

A gas turbine draws in air from the atmosphere at 1 bar and 15$^o$C and compresses it to 4.5 bar with an isentropic efficiency of 82%. The air is heated to 1100 K at constant pressure and then expanded through two stages in series back to 1 bar. The high pressure turbine is connected to the compressor and produces just enough power to drive it. The low pressure stage is connected to an external load and produces 100 kW of power. The isentropic efficiency is 85% for both stages. For the compressor $\gamma$ = 1.4 and for the turbines $\gamma$ = 1.3. The gas constant R is 0.287 kJ/kg K for both.

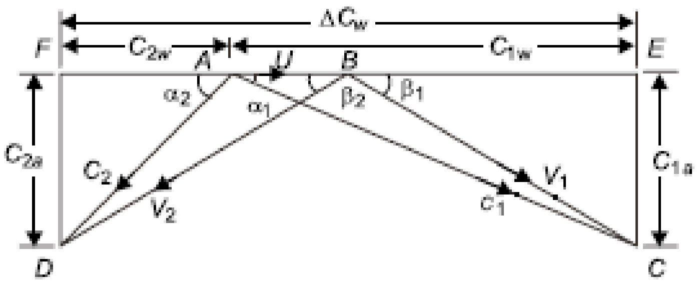
Neglecting increase in mass during fuel injection, calculate the mass flow of air, the inter-stage pressure of the turbines and the thermal efficiency of the cycle.

**Question Three** **[Total: 20 Marks]**

Steam enters the blade row of an impulse turbine with a velocity of 600 m/s at an angle of 25$^o$to the plane of rotation of the blades. The mean blade speed is 250 m/s. the plant angle at the exit side is 30$^o$. Take the value of k as 0.9. With the aid of Figure 3.1, determine;

3.1. The blade angle at the inlet. **[8]**

3.2. The work done per kg of steam. **[12]**




Combined inlet and outlet velocity diagrams.

Figure 3.1. Combined inlet and outlet velocity diagram.

**Question Four** **[Total: 15 Marks]**

In a single acting, two-stage reciprocating air compressor 5 kg/min of air is compressed from 1.013 bar and 15 °C through a pressure ratio of 9/1. The compression follows $pV^{1.3}$ = constant and the two stages have the same pressure ratio. The P-V plot is shown in Figure 4.1. If intercooling is complete, calculate the indicated power. Assume that the clearance volumes of both stages are 6 % of their respective swept volumes and that the compressor runs at 300 rev/min.

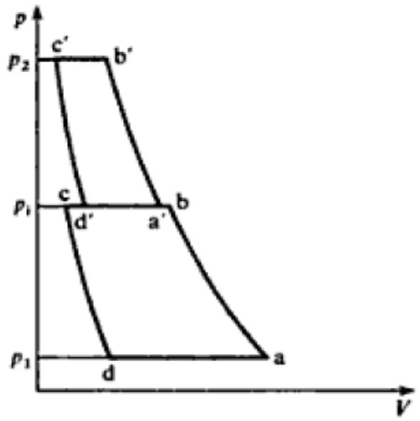



Figure 4.1. Pressure-volume diagram for two-stage reciprocating air compressor.

**Question Five** **[Total: 15 Marks]**

A steady-flow Carnot refrigeration cycle uses refrigerant-134a as the working fluid. The refrigerant changes from saturated vapour to saturated liquid at 30°C in the condenser as it rejects heat. The evaporator pressure is 160 kPa.

5.1. Show the cycle on a T-S diagram relative to saturation lines. **[3]**

5.2. Determine the coefficient of performance. **[4]**

5.3. Calculate the net-work input. **[8]**

**END** **[Total:100 Marks]**

**USEFUL EQUATIONS AND FORMULAE**

$PV = nRT$; $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$; $v = \frac{V^t}{m}$; $v = \frac{V^t}{n}$;$\dot{m} = uA\rho$; $\dot{n} = \frac{uA}{vM}$; $\rho = v^{-1}$; $\dot{V} = \frac{V}{t}$

t(ºC) = T(K) – 273.15; t(ºF) = T(R) – 459.67; t(ºF) = 1.8t(ºC) + 32;

$P_g = \frac{F}{A} = \frac{mg}{A} = \frac{\rho Vg}{A} = \frac{Ah\rho g}{A}$; $P_{abs} = P_g(or \rho gh) + P_{atm}$

Interpolation: $M = \left(\frac{X_2-X}{X_2-X_1}\right)M_1 + \left(\frac{X-X_1}{X_2-X_1}\right)M_2$ OR $M = \frac{M_1(X_2-X)+M_2(X-X_1)}{X_2-X_1}$

$\Delta E_{univ} = \Delta E_{syst} + \Delta E_{surr} = 0$; $\eta = \frac{W_{irreversible}}{W_{reversible}}$; $\frac{dm_{cv}}{dt} = \Delta m = \dot{m}_{out} - \dot{m}_{in}$; $\gamma = \frac{C_P}{C_V}$

EB for open systems: $\frac{d(mU)_{cv}}{dt} = -\dot{m}\Delta\left[U + \frac{1}{2}u^2 + gh\right] + \dot{Q} + \dot{W}$

EB for steady-state flow processes: $\Delta\dot{m}\left(H + \frac{1}{2}u^2 + gh\right) = \dot{Q} + \dot{W}_s$

Mechanically reversible closed system processes:

Constant V: $Q = n\Delta U = n\int_{T_1}^{T_2} C_v dT = nC_v\Delta T$

Constant P: $Q = n\Delta H = n\int_{T_1}^{T_2} C_p dT = nC_p\Delta T$; $W = -R(T_2 - T_1)$

Constant T: $Q = -W = RT_1 \ln\frac{V_2}{V_1} = -RT_1 \ln\frac{P_2}{P_1} = P_1V_1 \ln\frac{V_2}{V_1} = -P_1V_1 \ln\frac{P_2}{P_1}$

Adiabatic: $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{R/C_V}$; $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/C_P}$; $\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{C_P/C_V}$;

Carnot cycle: $\eta = \frac{W_{net}}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$

Constant-pressure (Joule) cycle: $\eta = 1 - \frac{1}{\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}}$

Work ratio: $W = \frac{Net\ work\ output}{Gross\ work\ output} = 1 - \frac{T_1}{T_3}\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$

Compression ratio: $\frac{sweptvolume + clearancevolume}{clearancevolume} = \frac{v_1}{v_2}$

Otto cycle: $\eta = 1 - \frac{1}{\left(\frac{V_1}{V_2}\right)^{\gamma-1}}$

Diesel cycle: $\eta = 1 - \left(\frac{T_4-T_1}{\gamma(T_3-T_2)}\right)$ $OR$ $\eta = 1 - \left(\frac{1}{V_1/V_2}\right)^{\gamma-1}\left\{\frac{(V_3/V_2)^{\gamma}-1}{\gamma[(V_3/V_2)-1]}\right\}$

Dual-combustion cycle: $\eta = 1 - \frac{C_v(T_5-T_1)}{C_v(T_3-T_2) + C_p(T_4-T_3)}$

Mean effective pressure (MEP): $-W_{net} = P_m(V_1 - V_2)$

Stirling and Ericsson cycles: $\eta_{Stirling} = \eta_{Ericsson} = \eta_{Carnot} = 1 - \frac{T_2}{T_1}$

Steam rate: $\dot{m} = \frac{\dot{W}_{net}}{W_{net}} = \frac{\dot{W}_{net}}{W_{turbine}-W_{pump}}$

Rankine cycle (pump work input): $W = v_i(P_{i+1} - P_i)$

Rankine efficiency: $\eta = \frac{Net\ work\ output}{Heat\ supplied\ in\ boiler}$

Efficiency ratio = $\frac{cycle\ efficiency}{Rankine\ efficiency}$ ; $ssc = \frac{1}{Net\ work\ output}$ ; $CHL = ssc(\Delta H_{condenser})$

Isentropic efficiency: $\frac{ratio\ of\ work\ input\ required}{actual\ work\ required}$

Gross work output: $work\ output\ of\ HP\ turbine + work\ output\ of\ LP\ turbine$

Work ratio: $W = \frac{Net\ work\ output}{Gross\ work\ output} = 1 - \frac{T_1}{T_3}\left(\frac{P_2}{P_1}\right)^{(\gamma-1)/\gamma}$

Mass flow rate: $\dot{m} = \frac{\dot{W}_{net}}{W_{net}}$; Cycle efficiency: $\eta = \frac{W_{turbine}}{Q_1}$

For steam turbines: $\Delta C_w = C_{wi} + C_{we} = C_{re}\cos\beta_e + C_{ri}\cos\beta_i$

Velocity coefficient: $k = \frac{C_{re}}{C_{ri}}$ ; Driving force: $F_D = \dot{m}\Delta C_w$

Diagram efficiency: $\eta_d = \frac{2C_b\Delta C_w}{C_{ai}^2}$ ; $Energy\ supplied\ per\ unit\ mass\ of\ steam = \frac{1}{2}\dot{m}C_{ai}^2$

Power output: $\dot{W}_{output} = \dot{m}C_b\Delta C_w$

End (Axial) thrust: $\dot{m}\Delta C_f$ ; Where: $\Delta C_f = C_{fi} - C_{fe} = C_{ri}\sin\beta_i - C_{re}\sin\beta_e$

For Nozzles (EB): $H_1 + \frac{C_1^2}{2} = H_2 + \frac{C_2^2}{2}$

Critical pressure: $\frac{P_c}{P_1} = \left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}$ Critical temperature: $\frac{T_c}{T_1} = \left(\frac{P_c}{P_1}\right)^{(\gamma-1)/\gamma}$

Critical specific volume: $v_c = \frac{(R/M)T_c}{P_c}$ Critical velocity: $C_c = \sqrt{\frac{\gamma R T_c}{M}} = \sqrt{2(H_1 - H_c)} = \sqrt{2C_p(T_1 - T_c)}$

Exit specific volume: $v_2 = \frac{(R/M)T_2}{P_2}$ Exit velocity: $C_2 = \sqrt{2(H_1 - H_2)}$

Mass flowrate per unit area: $\frac{\dot{m}}{A_2} = \frac{C_2}{v_2}$ Nozzle efficiency: $\frac{H_1 - H_2}{H_1 - H_{2s}} = \frac{C_p(T_1 - T_2)}{C_p(T_1 - T_{2s})} = \frac{T_1 - T_2}{T_1 - T_{2s}}$

Velocity coefficient: $\frac{C_2}{C_{2s}}$ Coefficient of discharge: $\frac{\dot{m}}{\dot{m}_s}$

For dry saturated steam, $\gamma = 1.135$ For superheated steam, $\gamma = 1.3$

Refrigeration (Engine efficiency): $\eta_{carnot} = \frac{W_{netcarnotengine}}{Q_1} = 1 - \frac{T_2}{T_1}$

Coefficient of Performance: $COP_{carnot} = \frac{Q_{1\ refrigerator}}{W_{refrigeratorinput}} = \frac{T_2}{T_1 - T_2}$

Indicated Power: $IP = \frac{n}{n-1}\dot{m}R(T_2 - T_1)$, $IP = \frac{n}{n-1}\dot{m}RT_1\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\}$, $IP = \frac{n}{n-1}\dot{V}p_1\{\left(\frac{p_2}{p_1}\right)^{\frac{(n-1)}{n}} - 1\}$

Isothermal Power: $Isothermal\ Power = \dot{m}RT\ln\frac{p_2}{p_1}$

Volumetric Efficiency: $\cap_v = 1 - \frac{V_c}{V_s}\{\left(\frac{p_2}{p_1}\right)^{1/n} - 1\}$, $\cap_v = \frac{V}{V_s}$, $\frac{FAD}{cycle} = (V_a - V_d)\frac{T}{T_1}\frac{p_1}{p}$

Roots Efficiency: $RE = \frac{C_p}{R}\{\frac{r^{(\gamma-1)\gamma} - 1}{r-1}\}$

**Table A.1: Conversion Factors**

| Quantity | Conversion |
|---|---|
| Length | $1\ m = 100\ cm$<br>$= 3.28084(ft) = 39.3701(in)$ |
| Mass | $1\ kg = 10^3\ g$<br>$= 2.20462(lb_m)$ |
| Force | $1\ N = 1\ kg\ m\ s^{-2}$<br>$= 10^5(dyne)$<br>$= 0.224809(lb_f)$ |
| Pressure | $1\ bar = 10^5\ kg\ m^{-1}\ s^{-2} = 10^5\ N\ m^{-2}$<br>$= 10^5\ Pa = 10^2\ kPa$<br>$= 10^6(dyne)\ cm^{-2}$<br>$= 0.986923(atm)$<br>$= 14.5038(psia)$<br>$= 750.061(torr)$ |
| Volume | $1\ m^3 = 10^6\ cm^3 = 10^3$ liters<br>$= 35.3147(ft)^3$<br>$= 264.172(gal)$ |
| Density | $1\ g\ cm^{-3} = 10^3\ kg\ m^{-3}$<br>$= 62.4278(lb_m)(ft)^{-3}$ |
| Energy | $1\ J = 1\ kg\ m^2\ s^{-2} = 1\ N\ m$<br>$= 1\ m^3\ Pa = 10^{-5}\ m^3\ bar = 10\ cm^3\ bar$<br>$= 9.86923\ cm^3(atm)$<br>$= 10^7(dyne)\ cm = 10^7(erg)$<br>$= 0.239006(cal)$<br>$= 5.12197 \times 10^{-3}(ft)^3(psia) = 0.737562(ft)(lb_f)$<br>$= 9.47831 \times 10^{-4}(Btu) = 2.77778 \times 10^{-7}\ kWhr$ |
| Power | $1\ kW = 10^3\ W = 10^3\ kg\ m^2\ s^{-3} = 10^3\ J\ s^{-1}$<br>$= 239.006(cal)\ s^{-1}$<br>$= 737.562(ft)(lb_f)\ s^{-1}$<br>$= 0.947831(Btu)\ s^{-1}$<br>$= 1.34102(hp)$ |

**Table A.2: Values of the Universal Gas Constant**

$R = 8.314\ J\ mol^{-1}\ K^{-1} = 8.314\ m^3\ Pa\ mol^{-1}\ K^{-1}$
$= 83.14\ cm^3\ bar\ mol^{-1}\ K^{-1} = 8{,}314\ cm^3\ kPa\ mol^{-1}\ K^{-1}$
$= 82.06\ cm^3(atm)\ mol^{-1}\ K^{-1} = 62{,}356\ cm^3(torr)\ mol^{-1}\ K^{-1}$
$= 1.987(cal)\ mol^{-1}\ K^{-1} = 1.986(Btu)(lb\ mole)^{-1}(R)^{-1}$
$= 0.7302(ft)^3(atm)(lb\ mol)^{-1}(R)^{-1} = 10.73(ft)^3(psia)(lb\ mol)^{-1}(R)^{-1}$
$= 1{,}545(ft)(lb_f)(lb\ mol)^{-1}(R)^{-1}$

**Table 9.1** Thermodynamic Properties of Saturated Tetrafluoroethane†

| Temperature °C | K | Saturation pressure MPa | Liquid density kg m$^{-3}$ | Specific volume of vapor m$^3$ kg$^{-1}$ | Enthalpy kJ kg$^{-1}$ | | Entropy kJ kg$^{-1}$ K$^{-1}$ | |
|---|---|---|---|---|---|---|---|---|
| | | $P$ | $\rho^l$ | $V^v$ | $H^l$ | $H^v$ | $S^l$ | $S^v$ |
| −40 | 233.15 | 0.051 22 | 1414.8 | 0.360 95 | 148.57 | 374.16 | 0.7973 | 1.7649 |
| −30 | 243.15 | 0.084 36 | 1385.9 | 0.225 96 | 161.10 | 380.45 | 0.8498 | 1.7519 |
| **−26.07**[b] | **247.08** | **0.101 33** | **1374.3** | **0.190 16** | **166.07** | **382.90** | **0.8701** | **1.7476** |
| −24 | 249.15 | 0.111 27 | 1368.2 | 0.174 10 | 168.70 | 384.19 | 0.8806 | 1.7455 |
| −22 | 251.15 | 0.121 60 | 1362.2 | 0.160 10 | 171.26 | 385.43 | 0.8908 | 1.7436 |
| −20 | 253.15 | 0.132 68 | 1356.2 | 0.147 44 | 173.82 | 386.66 | 0.9009 | 1.7417 |
| −18 | 255.15 | 0.144 54 | 1350.2 | 0.135 97 | 176.39 | 387.89 | 0.9110 | 1.7399 |
| −16 | 257.15 | 0.157 21 | 1344.1 | 0.125 56 | 178.97 | 389.11 | 0.9211 | 1.7383 |
| −14 | 259.15 | 0.170 74 | 1338.0 | 0.116 10 | 181.56 | 390.33 | 0.9311 | 1.7367 |
| −12 | 261.15 | 0.185 16 | 1331.8 | 0.107 49 | 184.16 | 391.55 | 0.9410 | 1.7351 |
| −10 | 263.15 | 0.200 52 | 1325.6 | 0.099 63 | 186.78 | 392.75 | 0.9509 | 1.7337 |
| −8 | 265.15 | 0.216 84 | 1319.3 | 0.092 46 | 189.40 | 393.95 | 0.9608 | 1.7323 |
| −6 | 267.15 | 0.234 18 | 1313.0 | 0.085 91 | 192.03 | 393.15 | 0.9707 | 1.7310 |
| −4 | 269.15 | 0.252 57 | 1306.6 | 0.079 91 | 194.68 | 396.33 | 0.9805 | 1.7297 |
| −2 | 271.15 | 0.272 06 | 1300.2 | 0.074 40 | 197.33 | 397.51 | 0.9903 | 1.7285 |
| 0 | 273.15 | 0.292 69 | 1293.7 | 0.069 35 | 200.00 | 398.68 | 1.0000 | 1.7274 |
| 2 | 275.15 | 0.314 50 | 1287.1 | 0.064 70 | 202.68 | 399.84 | 1.0097 | 1.7263 |
| 4 | 277.15 | 0.337 55 | 1280.5 | 0.060 42 | 205.37 | 401.00 | 1.0194 | 1.7252 |
| 6 | 279.15 | 0.361 86 | 1273.8 | 0.056 48 | 208.08 | 402.14 | 1.0291 | 1.7242 |
| 8 | 281.15 | 0.387 49 | 1267.0 | 0.052 84 | 210.80 | 403.27 | 1.0387 | 1.7233 |
| 10 | 283.15 | 0.414 49 | 1260.2 | 0.049 48 | 213.53 | 404.40 | 1.0483 | 1.7224 |
| 12 | 285.15 | 0.442 89 | 1253.3 | 0.046 36 | 216.27 | 405.51 | 1.0579 | 1.7215 |
| 14 | 287.15 | 0.472 76 | 1246.3 | 0.043 48 | 219.03 | 406.61 | 1.0674 | 1.7207 |
| 16 | 289.15 | 0.504 13 | 1239.3 | 0.040 81 | 221.80 | 407.70 | 1.0770 | 1.7199 |
| 18 | 291.15 | 0.537 06 | 1232.1 | 0.038 33 | 224.59 | 408.78 | 1.0865 | 1.7191 |
| 20 | 293.15 | 0.571 59 | 1224.9 | 0.036 03 | 227.40 | 409.84 | 1.0960 | 1.7183 |
| 24 | 297.15 | 0.645 66 | 1210.1 | 0.031 89 | 233.05 | 411.93 | 1.1149 | 1.7169 |
| 28 | 301.15 | 0.726 76 | 1194.9 | 0.028 29 | 238.77 | 413.95 | 1.1338 | 1.7155 |
| 32 | 305.15 | 0.815 30 | 1179.3 | 0.025 16 | 244.55 | 415.90 | 1.1527 | 1.7142 |
| 36 | 309.15 | 0.911 72 | 1163.2 | 0.022 41 | 250.41 | 417.78 | 1.1715 | 1.7129 |
| 40 | 313.15 | 1.016 5 | 1146.5 | 0.019 99 | 256.35 | 419.58 | 1.1903 | 1.7115 |
| 44 | 317.15 | 1.130 0 | 1129.2 | 0.017 86 | 262.38 | 421.28 | 1.2091 | 1.7101 |
| 48 | 321.15 | 1.252 7 | 1111.3 | 0.015 98 | 268.49 | 422.88 | 1.2279 | 1.7086 |
| 52 | 325.15 | 1.385 2 | 1092.6 | 0.014 30 | 274.71 | 424.35 | 1.2468 | 1.7070 |
| 56 | 329.15 | 1.528 0 | 1073.0 | 0.012 80 | 281.04 | 425.68 | 1.2657 | 1.7051 |
| 60 | 333.15 | 1.681 5 | 1052.4 | 0.011 46 | 287.49 | 426.86 | 1.2847 | 1.7031 |
| 64 | 337.15 | 1.846 4 | 1030.7 | 0.010 26 | 294.08 | 427.84 | 1.3039 | 1.7007 |
| 68 | 341.15 | 2.023 4 | 1007.7 | 0.009 17 | 300.84 | 428.61 | 1.3234 | 1.6979 |
| 72 | 345.15 | 2.213 0 | 983.1 | 0.008 18 | 307.79 | 429.10 | 1.3430 | 1.6945 |
| 76 | 349.15 | 2.415 9 | 956.5 | 0.007 28 | 314.96 | 429.27 | 1.3631 | 1.6905 |

[b] normal boiling point

†Reproduced with permission from *ASHRAE Handbook: Fundamentals*, p. 17.29, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, 1993.

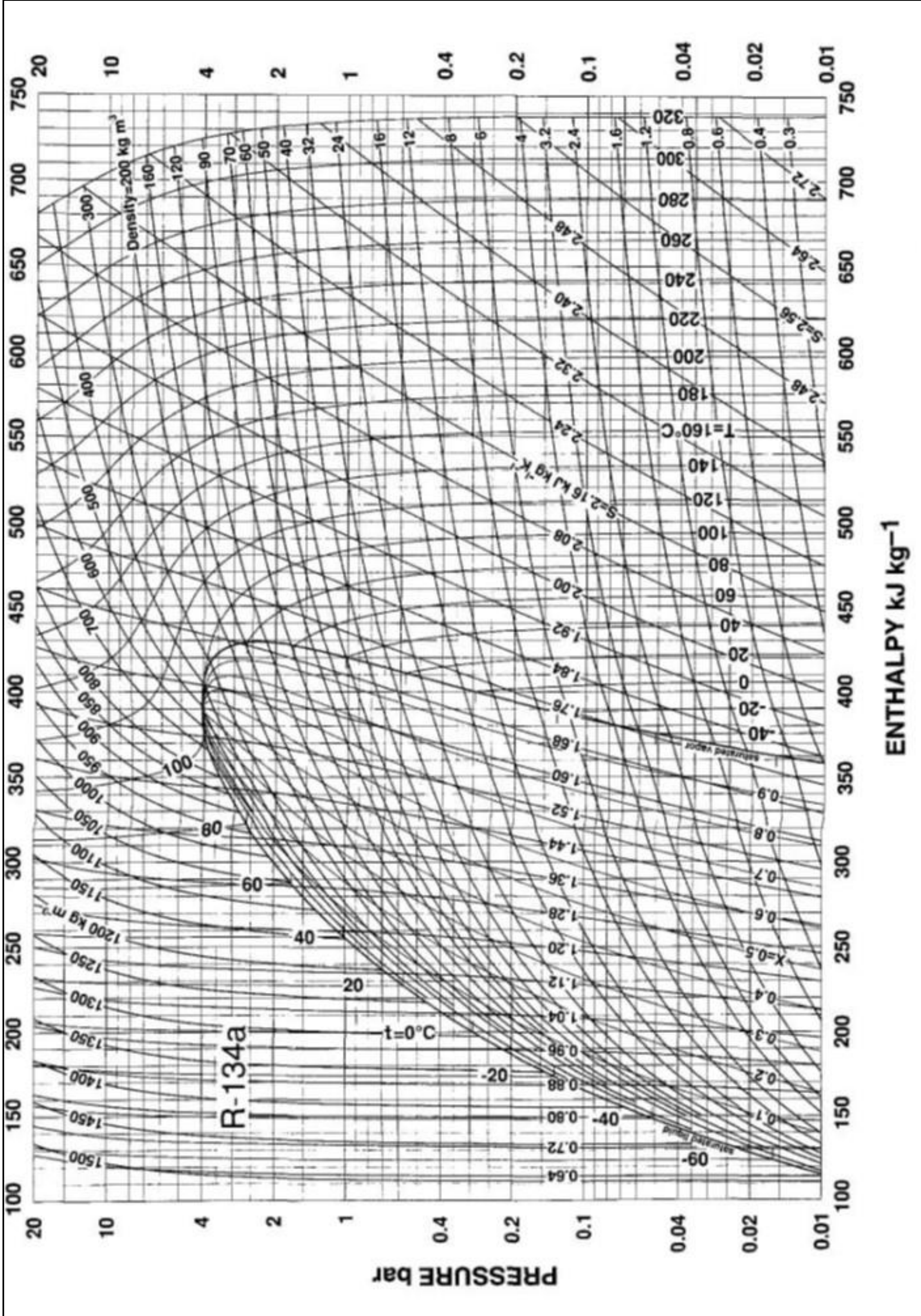



**Figure G.2:** *PH* diagram for tetrafluroethane (HFC-134a). (Reproduced by permission, ASHRAE Handbook : Fundamentals, p.17.28, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., USA, 1993.

**TABLE A–13**

Superheated refrigerant-134a

| $T$ °C | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg·K | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg·K | $v$ m³/kg | $u$ kJ/kg | $h$ kJ/kg | $s$ kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $P$ = 0.06 MPa ($T_{sat}$ = −36.95°C) | | | | $P$ = 0.10 MPa ($T_{sat}$ = −26.37°C) | | | | $P$ = 0.14 MPa ($T_{sat}$ = −18.77°C) | | | |
| Sat. | 0.31121 | 209.12 | 227.79 | 0.9644 | 0.19254 | 215.19 | 234.44 | 0.9518 | 0.14014 | 219.54 | 239.16 | 0.9446 |
| −20 | 0.33608 | 220.60 | 240.76 | 1.0174 | 0.19841 | 219.66 | 239.50 | 0.9721 | | | | |
| −10 | 0.35048 | 227.55 | 248.58 | 1.0477 | 0.20743 | 226.75 | 247.49 | 1.0030 | 0.14605 | 225.91 | 246.36 | 0.9724 |
| 0 | 0.36476 | 234.66 | 256.54 | 1.0774 | 0.21630 | 233.95 | 255.58 | 1.0332 | 0.15263 | 233.23 | 254.60 | 1.0031 |
| 10 | 0.37893 | 241.92 | 264.66 | 1.1066 | 0.22506 | 241.30 | 263.81 | 1.0628 | 0.15908 | 240.66 | 262.93 | 1.0331 |
| 20 | 0.39302 | 249.35 | 272.94 | 1.1353 | 0.23373 | 248.79 | 272.17 | 1.0918 | 0.16544 | 248.22 | 271.38 | 1.0624 |
| 30 | 0.40705 | 256.95 | 281.37 | 1.1636 | 0.24233 | 256.44 | 280.68 | 1.1203 | 0.17172 | 255.93 | 279.97 | 1.0912 |
| 40 | 0.42102 | 264.71 | 289.97 | 1.1915 | 0.25088 | 264.25 | 289.34 | 1.1484 | 0.17794 | 263.79 | 288.70 | 1.1195 |
| 50 | 0.43495 | 272.64 | 298.74 | 1.2191 | 0.25937 | 272.22 | 298.16 | 1.1762 | 0.18412 | 271.79 | 297.57 | 1.1474 |
| 60 | 0.44883 | 280.73 | 307.66 | 1.2463 | 0.26783 | 280.35 | 307.13 | 1.2035 | 0.19025 | 279.96 | 306.59 | 1.1749 |
| 70 | 0.46269 | 288.99 | 316.75 | 1.2732 | 0.27626 | 288.64 | 316.26 | 1.2305 | 0.19635 | 288.28 | 315.77 | 1.2020 |
| 80 | 0.47651 | 297.41 | 326.00 | 1.2997 | 0.28465 | 297.08 | 325.55 | 1.2572 | 0.20242 | 296.75 | 325.09 | 1.2288 |
| 90 | 0.49032 | 306.00 | 335.42 | 1.3260 | 0.29303 | 305.69 | 334.99 | 1.2836 | 0.20847 | 305.38 | 334.57 | 1.2553 |
| 100 | 0.50410 | 314.74 | 344.99 | 1.3520 | 0.30138 | 314.46 | 344.60 | 1.3096 | 0.21449 | 314.17 | 344.20 | 1.2814 |
| | $P$ = 0.18 MPa ($T_{sat}$ = −12.73°C) | | | | $P$ = 0.20 MPa ($T_{sat}$ = −10.09°C) | | | | $P$ = 0.24 MPa ($T_{sat}$ = −5.38°C) | | | |
| Sat. | 0.11041 | 222.99 | 242.86 | 0.9397 | 0.09987 | 224.48 | 244.46 | 0.9377 | 0.08390 | 227.14 | 247.28 | 0.9346 |
| −10 | 0.11189 | 225.02 | 245.16 | 0.9484 | 0.09991 | 224.55 | 244.54 | 0.9380 | | | | |
| 0 | 0.11722 | 232.48 | 253.58 | 0.9798 | 0.10481 | 232.09 | 253.05 | 0.9698 | 0.08617 | 231.29 | 251.97 | 0.9519 |
| 10 | 0.12240 | 240.00 | 262.04 | 1.0102 | 0.10955 | 239.67 | 261.58 | 1.0004 | 0.09026 | 238.98 | 260.65 | 0.9831 |
| 20 | 0.12748 | 247.64 | 270.59 | 1.0399 | 0.11418 | 247.35 | 270.18 | 1.0303 | 0.09423 | 246.74 | 269.36 | 1.0134 |
| 30 | 0.13248 | 255.41 | 279.25 | 1.0690 | 0.11874 | 255.14 | 278.89 | 1.0595 | 0.09812 | 254.61 | 278.16 | 1.0429 |
| 40 | 0.13741 | 263.31 | 288.05 | 1.0975 | 0.12322 | 263.08 | 287.72 | 1.0882 | 0.10193 | 262.59 | 287.06 | 1.0718 |
| 50 | 0.14230 | 271.36 | 296.98 | 1.1256 | 0.12766 | 271.15 | 296.68 | 1.1163 | 0.10570 | 270.71 | 296.08 | 1.1001 |
| 60 | 0.14715 | 279.56 | 306.05 | 1.1532 | 0.13206 | 279.37 | 305.78 | 1.1441 | 0.10942 | 278.97 | 305.23 | 1.1280 |
| 70 | 0.15196 | 287.91 | 315.27 | 1.1805 | 0.13641 | 287.73 | 315.01 | 1.1714 | 0.11310 | 287.36 | 314.51 | 1.1554 |
| 80 | 0.15673 | 296.42 | 324.63 | 1.2074 | 0.14074 | 296.25 | 324.40 | 1.1983 | 0.11675 | 295.91 | 323.93 | 1.1825 |
| 90 | 0.16149 | 305.07 | 334.14 | 1.2339 | 0.14504 | 304.92 | 333.93 | 1.2249 | 0.12038 | 304.60 | 333.49 | 1.2092 |
| 100 | 0.16622 | 313.88 | 343.80 | 1.2602 | 0.14933 | 313.74 | 343.60 | 1.2512 | 0.12398 | 313.44 | 343.20 | 1.2356 |
| | $P$ = 0.28 MPa ($T_{sat}$ = −1.25°C) | | | | $P$ = 0.32 MPa ($T_{sat}$ = 2.46°C) | | | | $P$ = 0.40 MPa ($T_{sat}$ = 8.91°C) | | | |
| Sat. | 0.07235 | 229.46 | 249.72 | 0.9321 | 0.06360 | 231.52 | 251.88 | 0.9301 | 0.051201 | 235.07 | 255.55 | 0.9269 |
| 0 | 0.07282 | 230.44 | 250.83 | 0.9362 | | | | | | | | |
| 10 | 0.07646 | 238.27 | 259.68 | 0.9680 | 0.06609 | 237.54 | 258.69 | 0.9544 | 0.051506 | 235.97 | 256.58 | 0.9305 |
| 20 | 0.07997 | 246.13 | 268.52 | 0.9987 | 0.06925 | 245.50 | 267.66 | 0.9856 | 0.054213 | 244.18 | 265.86 | 0.9628 |
| 30 | 0.08338 | 254.06 | 277.41 | 1.0285 | 0.07231 | 253.50 | 276.65 | 1.0157 | 0.056796 | 252.36 | 275.07 | 0.9937 |
| 40 | 0.08672 | 262.10 | 286.38 | 1.0576 | 0.07530 | 261.60 | 285.70 | 1.0451 | 0.059292 | 260.58 | 284.30 | 1.0236 |
| 50 | 0.09000 | 270.27 | 295.47 | 1.0862 | 0.07823 | 269.82 | 294.85 | 1.0739 | 0.061724 | 268.90 | 293.59 | 1.0528 |
| 60 | 0.09324 | 278.56 | 304.67 | 1.1142 | 0.08111 | 278.15 | 304.11 | 1.1021 | 0.064104 | 277.32 | 302.96 | 1.0814 |
| 70 | 0.09644 | 286.99 | 314.00 | 1.1418 | 0.08395 | 286.62 | 313.48 | 1.1298 | 0.066443 | 285.86 | 312.44 | 1.1094 |
| 80 | 0.09961 | 295.57 | 323.46 | 1.1690 | 0.08675 | 295.22 | 322.98 | 1.1571 | 0.068747 | 294.53 | 322.02 | 1.1369 |
| 90 | 0.10275 | 304.29 | 333.06 | 1.1958 | 0.08953 | 303.97 | 332.62 | 1.1840 | 0.071023 | 303.32 | 331.73 | 1.1640 |
| 100 | 0.10587 | 313.15 | 342.80 | 1.2222 | 0.09229 | 312.86 | 342.39 | 1.2105 | 0.073274 | 312.26 | 341.57 | 1.1907 |
| 110 | 0.10897 | 322.16 | 352.68 | 1.2483 | 0.09503 | 321.89 | 352.30 | 1.2367 | 0.075504 | 321.33 | 351.53 | 1.2171 |
| 120 | 0.11205 | 331.32 | 362.70 | 1.2742 | 0.09775 | 331.07 | 362.35 | 1.2626 | 0.077717 | 330.55 | 361.63 | 1.2431 |
| 130 | 0.11512 | 340.63 | 372.87 | 1.2997 | 0.10045 | 340.39 | 372.54 | 1.2882 | 0.079913 | 339.90 | 371.87 | 1.2688 |
| 140 | 0.11818 | 350.09 | 383.18 | 1.3250 | 0.10314 | 349.86 | 382.87 | 1.3135 | 0.082096 | 349.41 | 382.24 | 1.2942 |

**TABLE A–13**

Superheated refrigerant-134a (*Continued*)

| *T* °C | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg·K | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg·K | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *P* = 0.50 MPa ($T_{sat}$ = 15.71°C) | | | | *P* = 0.60 MPa ($T_{sat}$ = 21.55°C) | | | | *P* = 0.70 MPa ($T_{sat}$ = 26.69°C) | | | |
| Sat. | 0.041118 | 238.75 | 259.30 | 0.9240 | 0.034295 | 241.83 | 262.40 | 0.9218 | 0.029361 | 244.48 | 265.03 | 0.9199 |
| 20 | 0.042115 | 242.40 | 263.46 | 0.9383 | | | | | | | | |
| 30 | 0.044338 | 250.84 | 273.01 | 0.9703 | 0.035984 | 249.22 | 270.81 | 0.9499 | 0.029966 | 247.48 | 268.45 | 0.9313 |
| 40 | 0.046456 | 259.26 | 282.48 | 1.0011 | 0.037865 | 257.86 | 280.58 | 0.9816 | 0.031696 | 256.39 | 278.57 | 0.9641 |
| 50 | 0.048499 | 267.72 | 291.96 | 1.0309 | 0.039659 | 266.48 | 290.28 | 1.0121 | 0.033322 | 265.20 | 288.53 | 0.9954 |
| 60 | 0.050485 | 276.25 | 301.50 | 1.0599 | 0.041389 | 275.15 | 299.98 | 1.0417 | 0.034875 | 274.01 | 298.42 | 1.0256 |
| 70 | 0.052427 | 284.89 | 311.10 | 1.0883 | 0.043069 | 283.89 | 309.73 | 1.0705 | 0.036373 | 282.87 | 308.33 | 1.0549 |
| 80 | 0.054331 | 293.64 | 320.80 | 1.1162 | 0.044710 | 292.73 | 319.55 | 1.0987 | 0.037829 | 291.80 | 318.28 | 1.0835 |
| 90 | 0.056205 | 302.51 | 330.61 | 1.1436 | 0.046318 | 301.67 | 329.46 | 1.1264 | 0.039250 | 300.82 | 328.29 | 1.1114 |
| 100 | 0.058053 | 311.50 | 340.53 | 1.1705 | 0.047900 | 310.73 | 339.47 | 1.1536 | 0.040642 | 309.95 | 338.40 | 1.1389 |
| 110 | 0.059880 | 320.63 | 350.57 | 1.1971 | 0.049458 | 319.91 | 349.59 | 1.1803 | 0.042010 | 319.19 | 348.60 | 1.1658 |
| 120 | 0.061687 | 329.89 | 360.73 | 1.2233 | 0.050997 | 329.23 | 359.82 | 1.2067 | 0.043358 | 328.55 | 358.90 | 1.1924 |
| 130 | 0.063479 | 339.29 | 371.03 | 1.2491 | 0.052519 | 338.67 | 370.18 | 1.2327 | 0.044688 | 338.04 | 369.32 | 1.2186 |
| 140 | 0.065256 | 348.83 | 381.46 | 1.2747 | 0.054027 | 348.25 | 380.66 | 1.2584 | 0.046004 | 347.66 | 379.86 | 1.2444 |
| 150 | 0.067021 | 358.51 | 392.02 | 1.2999 | 0.055522 | 357.96 | 391.27 | 1.2838 | 0.047306 | 357.41 | 390.52 | 1.2699 |
| 160 | 0.068775 | 368.33 | 402.72 | 1.3249 | 0.057006 | 367.81 | 402.01 | 1.3088 | 0.048597 | 367.29 | 401.31 | 1.2951 |
| | *P* = 0.80 MPa ($T_{sat}$ = 31.31°C) | | | | *P* = 0.90 MPa ($T_{sat}$ = 35.51°C) | | | | *P* = 1.00 MPa ($T_{sat}$ = 39.37°C) | | | |
| Sat. | 0.025621 | 246.79 | 267.29 | 0.9183 | 0.022683 | 248.85 | 269.26 | 0.9169 | 0.020313 | 250.68 | 270.99 | 0.9156 |
| 40 | 0.027035 | 254.82 | 276.45 | 0.9480 | 0.023375 | 253.13 | 274.17 | 0.9327 | 0.020406 | 251.30 | 271.71 | 0.9179 |
| 50 | 0.028547 | 263.86 | 286.69 | 0.9802 | 0.024809 | 262.44 | 284.77 | 0.9660 | 0.021796 | 260.94 | 282.74 | 0.9525 |
| 60 | 0.029973 | 272.83 | 296.81 | 1.0110 | 0.026146 | 271.60 | 295.13 | 0.9976 | 0.023068 | 270.32 | 293.38 | 0.9850 |
| 70 | 0.031340 | 281.81 | 306.88 | 1.0408 | 0.027413 | 280.72 | 305.39 | 1.0280 | 0.024261 | 279.59 | 303.85 | 1.0160 |
| 80 | 0.032659 | 290.84 | 316.97 | 1.0698 | 0.028630 | 289.86 | 315.63 | 1.0574 | 0.025398 | 288.86 | 314.25 | 1.0458 |
| 90 | 0.033941 | 299.95 | 327.10 | 1.0981 | 0.029806 | 299.06 | 325.89 | 1.0860 | 0.026492 | 298.15 | 324.64 | 1.0748 |
| 100 | 0.035193 | 309.15 | 337.30 | 1.1258 | 0.030951 | 308.34 | 336.19 | 1.1140 | 0.027552 | 307.51 | 335.06 | 1.1031 |
| 110 | 0.036420 | 318.45 | 347.59 | 1.1530 | 0.032068 | 317.70 | 346.56 | 1.1414 | 0.028584 | 316.94 | 345.53 | 1.1308 |
| 120 | 0.037625 | 327.87 | 357.97 | 1.1798 | 0.033164 | 327.18 | 357.02 | 1.1684 | 0.029592 | 326.47 | 356.06 | 1.1580 |
| 130 | 0.038813 | 337.40 | 368.45 | 1.2061 | 0.034241 | 336.76 | 367.58 | 1.1949 | 0.030581 | 336.11 | 366.69 | 1.1846 |
| 140 | 0.039985 | 347.06 | 379.05 | 1.2321 | 0.035302 | 346.46 | 378.23 | 1.2210 | 0.031554 | 345.85 | 377.40 | 1.2109 |
| 150 | 0.041143 | 356.85 | 389.76 | 1.2577 | 0.036349 | 356.28 | 389.00 | 1.2467 | 0.032512 | 355.71 | 388.22 | 1.2368 |
| 160 | 0.042290 | 366.76 | 400.59 | 1.2830 | 0.037384 | 366.23 | 399.88 | 1.2721 | 0.033457 | 365.70 | 399.15 | 1.2623 |
| 170 | 0.043427 | 376.81 | 411.55 | 1.3080 | 0.038408 | 376.31 | 410.88 | 1.2972 | 0.034392 | 375.81 | 410.20 | 1.2875 |
| 180 | 0.044554 | 386.99 | 422.64 | 1.3327 | 0.039423 | 386.52 | 422.00 | 1.3221 | 0.035317 | 386.04 | 421.36 | 1.3124 |
| | *P* = 1.20 MPa ($T_{sat}$ = 46.29°C) | | | | *P* = 1.40 MPa ($T_{sat}$ = 52.40°C) | | | | *P* = 1.60 MPa ($T_{sat}$ = 57.88°C) | | | |
| Sat. | 0.016715 | 253.81 | 273.87 | 0.9130 | 0.014107 | 256.37 | 276.12 | 0.9105 | 0.012123 | 258.47 | 277.86 | 0.9078 |
| 50 | 0.017201 | 257.63 | 278.27 | 0.9267 | | | | | | | | |
| 60 | 0.018404 | 267.56 | 289.64 | 0.9614 | 0.015005 | 264.46 | 285.47 | 0.9389 | 0.012372 | 260.89 | 280.69 | 0.9163 |
| 70 | 0.019502 | 277.21 | 300.61 | 0.9938 | 0.016060 | 274.62 | 297.10 | 0.9733 | 0.013430 | 271.76 | 293.25 | 0.9535 |
| 80 | 0.020529 | 286.75 | 311.39 | 1.0248 | 0.017023 | 284.51 | 308.34 | 1.0056 | 0.014362 | 282.09 | 305.07 | 0.9875 |
| 90 | 0.021506 | 296.26 | 322.07 | 1.0546 | 0.017923 | 294.28 | 319.37 | 1.0364 | 0.015215 | 292.17 | 316.52 | 1.0194 |
| 100 | 0.022442 | 305.80 | 332.73 | 1.0836 | 0.018778 | 304.01 | 330.30 | 1.0661 | 0.016014 | 302.14 | 327.76 | 1.0500 |
| 110 | 0.023348 | 315.38 | 343.40 | 1.1118 | 0.019597 | 313.76 | 341.19 | 1.0949 | 0.016773 | 312.07 | 338.91 | 1.0795 |
| 120 | 0.024228 | 325.03 | 354.11 | 1.1394 | 0.020388 | 323.55 | 352.09 | 1.1230 | 0.017500 | 322.02 | 350.02 | 1.1081 |
| 130 | 0.025086 | 334.77 | 364.88 | 1.1664 | 0.021155 | 333.41 | 363.02 | 1.1504 | 0.018201 | 332.00 | 361.12 | 1.1360 |
| 140 | 0.025927 | 344.61 | 375.72 | 1.1930 | 0.021904 | 343.34 | 374.01 | 1.1773 | 0.018882 | 342.05 | 372.26 | 1.1632 |
| 150 | 0.026753 | 354.56 | 386.66 | 1.2192 | 0.022636 | 353.37 | 385.07 | 1.2038 | 0.019545 | 352.17 | 383.44 | 1.1900 |
| 160 | 0.027566 | 364.61 | 397.69 | 1.2449 | 0.023355 | 363.51 | 396.20 | 1.2298 | 0.020194 | 362.38 | 394.69 | 1.2163 |
| 170 | 0.028367 | 374.78 | 408.82 | 1.2703 | 0.024061 | 373.75 | 407.43 | 1.2554 | 0.020830 | 372.69 | 406.02 | 1.2421 |
| 180 | 0.029158 | 385.08 | 420.07 | 1.2954 | 0.024757 | 384.10 | 418.76 | 1.2807 | 0.021456 | 383.11 | 417.44 | 1.2676 |