UNIVERSITI SAINS MALAYSIA

Second Semester Examination
Academic Session 2007/2008

April 2008

# EKC 222 – Chemical Engineering Thermodynamic
# *[Termodinamik Kejuruteraan Kimia]*

Duration : 3 hours
*[Masa : 3 jam]*

Please check that this examination paper consists of SEVEN pages of printed material and FOUR pages of Appendix before you begin the examination.

*[Sila pastikan bahawa kertas peperiksaan ini mengandungi TUJUH muka surat yang bercetak dan EMPAT muka surat Lampiran sebelum anda memulakan peperiksaan ini.]*

**Instructions**: Answer **FOUR** (4) questions. Answer **TWO** (2) questions from Section A. Answer **TWO** (2) questions from Section B.

*[**Arahan**: Jawab **EMPAT** (4) soalan. Jawab **DUA** (2) soalan dari Bahagian A. Jawab **DUA** (2) soalan dari Bahagian B.]*

You may answer your questions either in Bahasa Malaysia or in English.

*[Anda dibenarkan menjawab soalan sama ada dalam Bahasa Malaysia atau Bahasa Inggeris.]*

Section A : Answer any TWO questions.
*Section A : Answer any TWO questions.*

1. [a] An inventor proposes an engine that operates between a 27°C warm surface layer of the ocean and a 10°C layer a few meters down. The inventor claims that the engine produces 100 kW by pumping 20 kg/s of sea water. Is this possible? Assume $(C_p)_{seawater} \cong 4.18$ kJ/kg.K. Support your answer with calculations.

*Seorang pencipta mencadangkan sebuah enjin yang beroperasi antara lapisan permukaan lautan yang bersuhu 27°C dengan lapisan bersuhu 10°C beberapa meter bawah permukaan. Pencipta tersebut menyatakan yang enjin berkenaan boleh menghasilkan 100 kW dengan mengepam 20 kg/s air laut. Bolehkah ini berlaku? Andaikan $(C_p)_{air\ laut} \cong 4.18$ kJ/kg.K. Jawapan anda perlu disokong dengan pengiraan.*

*[10 marks/markah]*

[b] Two kg of superheated steam at 400°C and 600 kPa is cooled at constant pressure by transferring heat from a cylinder until the steam is completely condensed. The surroundings are at 25°C. Determine the net entropy change of the universe due to this process.

*Dua kg stim panas lampau pada 400°C dan 600 kPa disejukkan pada tekanan malar dengan memindahkan haba dari sebatang silinder sehingga stim tersebut terpeluwap sepenuhnya. Suhu persekitaran ialah 25°C. Tentukan perubahan entropi bersih semesta yang disebabkan oleh proses tersebut.*

*[5 marks/markah]*

[c] Define the following terms:
*Takrifkan terma-terma berikut:*

[i] Polytropic process
*Proses politropik*

[ii] Pure substance
*Bahan tulen*

[iii] Beyond critical point
*Selepas titik genting*

[iv] Reversible process
*Proses berbalik*

[v] Second law of thermodynamics
*Hukum kedua termodinamik*

*[10 marks/markah]*

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2. [a] For the cycle in Figure Q.2. [a], find the work output and the net heat transfer if 0.1 kg of air is contained in a piston-cylinder arrangement.
*Carikan kerja keluaran dan pemindahan haba bersih bagi kitaran dalam Rajah S.2. [a], jika 0.1 kg udara diisi dalam susunan omboh-silinder.*

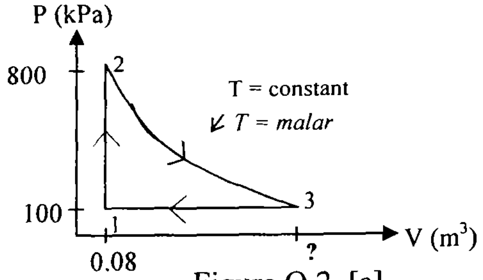



Figure Q.2. [a]
*Rajah S.2. [a]*

*[6 marks/markah]*

[b] Water vapor is contained in a rigid vessel of 5 $m^3$ at a quality of 0.8 and a pressure of 2 MPa. If the pressure is reduced to 400 kPa by cooling the vessel, find the final mass of vapor ($m_g$) and mass of liquid ($m_f$).
*Wap air diisi dalam sebuah bekas tegar 5 $m^3$ pada kualiti 0.8 dan tekanan 2 MPa. Jika tekanan dikurangkan ke 400 kPa dengan menyejukkan bekas tersebut, carikan jisim akhir wap ($m_g$) dan jisim cecair ($m_f$).*

*[8 marks/markah]*

[c] Four kg of water is heated at a pressure of 220 kPa to produce a mixture with a quality x = 0.8. Determine the final volume occupied by the mixture.
*Empat kg air dipanaskan pada tekanan 220 kPa untuk menghasilkan suatu campuran dengan kualiti x = 0.8. Tentukan isipadu akhir campuran tersebut.*

*[6 marks/markah]*

[d] Verify the Clapeyron equation of $\left(\frac{\partial P}{\partial T}\right)_V = h_{fg}/T_{v\,fg}$ for referigerant (R134a) at 500 kPa.
*Sahkan persamaan Clapeyron $\left(\frac{\partial P}{\partial T}\right)_V = h_{fg}/T_{v\,fg}$ untuk bahan pendingin (R134a) pada 500 kPa.*

*[5 marks/markah]*

3. [a] Five kg of water is placed in an enclosed volume of 1 $m^3$. Heat is added until the temperature is 150°C. Find:
*Lima kg air diisi dalam sebuah isipadu tertutup 1 $m^3$. Haba ditambah sehingga suhu mencapai 150°C. Carikan:*

[i] The pressure
*Tekanan*

[ii] The mass of vapor
*Jisim wap*

[iii] The volume of the vapor
*Isipadu wap*

*[8 marks/markah]*

[b] The cycle associated with the Carnot engine is compossed of four processes. Using an ideal gas as the working substance, explain the four processes and draw the Pv diagram of the four processes.

*Kitaran yang berkaitan dengan enjin Carnot mengandungi empat proses. Dengan menggunakan gas unggul sebagai bahan kerja, terangkan serta lukiskan gambarajah Pv bagi keempat-empat proses tersebut.*

*[4 marks/markah]*

[c] Energy is added to a piston-cylinder arrangement, and the piston is withdrawn in such a way that the quantity PV remains constant. The initial pressure and volume are 200 kPa and 2 $m^3$, respectively. If the final pressure is 100 kPa, calculate the work done by the gas on the piston.

*Tenaga telah ditambah ke suatu susunan omboh-silinder dan omboh tersebut telah diundurkan supaya kuantiti PV kekal malar. Tekanan awal dan isipadu masing-masing ialah 200 kPa dan 2 $m^3$. Jika tekanan akhir ialah 100 kPa, kirakan kerja yang dilakukan oleh gas ke atas omboh.*

*[3 marks/markah]*

[d] A 1.5 $m^3$ insulated rigid tank contains 2.7 kg of pure carbon dioxide at 100 kPa. A work is done using a paddle wheel on the system until the pressure in the tank rises to 150 kPa. Determine the entropy change of carbon dioxide during this process. Assume constant specific heats.

*Suatu tangki tegar tertebat 1.5 $m^3$ mengandungi 2.7 kg karbon dioksida tulen pada 100 kPa. Kerja dilakukan oleh suatu roda pengayuh ke atas sistem sehingga tekanan dalam tangki meningkat ke 150 kPa. Tentukan perubahan entropi karbon dioksida semasa proses ini berlaku. Andaikan haba tentu adalah malar.*

*[4 marks/markah]*

[e] Determine the missing properties and the phase description in the following table of water.

*Tentukan sifat-sifat dan huraian fasa yang tertinggal di dalam jadual air berikut.*

| P, kPa<br>*P, kPa* | T,°C<br>*T,°C* | v $m^3$/kg<br>*v $m^3$/kg* | u kJ/kg<br>*u kJ/kg* | Phase description<br>*Huraian fasa* |
|---|---|---|---|---|
| 200 | 30 | | | |
| | | | | |
| 500 | | | 3084 | |

*[6 marks/markah]*

Section B : Answer any TWO questions.
*Bahagian B : Jawab mana-mana DUA soalan.*

4. [a] It is desired to produce 10 kW of refrigeration from a vapor-compression refrigeration cycle. The working fluid is refrigerant (R134a). The cycle operates between 120 kPa and 900 kPa. Assuming an ideal cycle, determine the coefficient of performance and the mass flow rate of refrigerant needed.

*Adalah diperlukan untuk menghasilkan 10 kW penyejukkan dari satu kitar penyejukan mampatan wap. Cecair yang digunakan ialah bahan pendingin (R134a). Kitaran ini beroperasi antara 120 kPa dan 900 kPa. Andaikan satu kitar unggul, hitungkan pekali prestasi dan kadar aliran jisim untuk bahan pendingin yang diperlukan.*

*[8 marks/markah]*

[b] Consider a system with liquid containing 30 mole % *n*-pentane (1), 30 mole % cyclohexane (2), 20 mole % *n*-hexane (3), and 20 mole % *n*-heptane (4) at 1 bar. Determine the temperature at which this liquid develops the first bubble of vapor. What is the vapor composition?

*Satu sistem cecair mengandungi 30% mol n-pentana (1), 30% mol sikloheksana (2), 20% mol n-heksana (3), dan 20% mol n-heptana (4) pada 1 bar. Hitungkan suhu di mana cecair ini mula menghasilkan gelembung wap. Apakah komposisi wap tersebut?*

*[8 marks/markah]*

[c] Steam flow at 350°C into a porous plug in a pipe line at a pressure of 10 MPa. It exits at 1 bar. What is the **exit** temperature?

*Aliran stim pada 350°C mengalir ke dalam palam berliang dari satu paip 10 MPa. Ia keluar pada 1 bar. Apakah suhu **keluarnya?***

*[5 marks/markah]*

[d] Briefly discuss the term equilibrium.
*Bincangkan secara ringkas terma keseimbangan.*

*[4 marks/markah]*

5. [a] Determine the fugacity and fugacity coefficient for saturated steam at 1 atm.

*Hitungkan fugasiti dan pekali fugasiti untuk stim tepu pada 1 atm.*

*[10 marks/markah]*

[b] Fuel cells produce electricity from hydrogen. The life of the fuel cell depends on producing relatively pure hydrogen. Methane (natural gas) is often used as a feed to produce hydrogen. Consider the production of hydrogen ($H_2$) by dissociation of methane ($CH_4$) into solid carbon (C). The process can be described by the following chemical reaction:

*Sel-sel bahan api menghasilkan elektrik daripada hidrogen. Jangka hayat sel bahan api bergantung kepada penghasilan hidrogen yang tulen. Metana (gas asli) selalunya digunakan sebagai suapan untuk menghasilkan hidrogen. Pertimbangkan penghasilan hidrogen ($H_2$) dengan penceraian metana ($CH_4$) kepada karbon pejal (C). Proses boleh diperihalkan oleh tindakbalas kimia di bawah:*

$$CH_4\,(g) \rightleftharpoons C(s) + 2H_2(g)$$

The temperature is 1000 K and the pressure is 1000 Pa. You may assume that $\Delta h^o_{rxn}$ does not change with temperature.

*Suhu ialah 1000 K dan tekanan ialah 1000 Pa. Anda boleh mengandaikan bahawa $\Delta h^o_{tb}$ tidak berubah dengan suhu.*

[i] What is the equilibrium constant at 298 K?

*Apakah pemalar keseimbangan pada 298 K?*

[ii] What is the equilibrium constant at 1000 K?

*Apakah pemalar keseimbangan pada 1000 K?*

[iii] What is the maximum amount of $H_2$ that can be produced per mole of $CH_4$ in the feed at 1000 K?

*Apakah jumlah $H_2$ yang boleh dihasilkan oleh setiap mol suapan $CH_4$ pada 1000 K?*

[iv] Why is this reaction conducted at 1000 K instead of 298 K?

*Kenapakah tindakbalas ini dijalankan pada 1000 K bukannya pada 298 K?*

[v] Why is this reaction conducted at 1000 Pa instead of 1 bar?

*Kenapakah tindakbalas ini dijalankan pada 1000 Pa bukannya pada 1 bar?*

*[15 marks/markah]*

6. [a] Consider a binary mixture of A and B at T=300 K and P= 20 kPa. A graph of the fugacity of species A as a function of mole fraction is shown below. Use Henry's law as the reference state for species A and the Lewis/Randall rule for species B.

*Satu campuran perduaan A dan B pada T=300 K dan P= 20 kPa. Satu graf fugasiti untuk spesis A sebagai fungsi pecahan mol ditunjukkan di bawah. Gunakan Hukum Henry sebagai keadaan rujukan untuk spesis A dan peraturan-peraturan Lewis/Randall untuk spesis B.*

[i] What is the Henry's law constant for species A?

*Apakah pemalar Henry untuk spesis A?*

[ii] What is the activity coefficient for species A at $x_a = 0.4$? at $x_A = 0.8$?

*Apakah pekali aktiviti untuk spesis A pada $x_a = 0.4$? pada $x_A = 0.8$?*

[iii] Is the activity coefficient for species B at $x_A = 0.4$ greater than or less than 1? Explain.

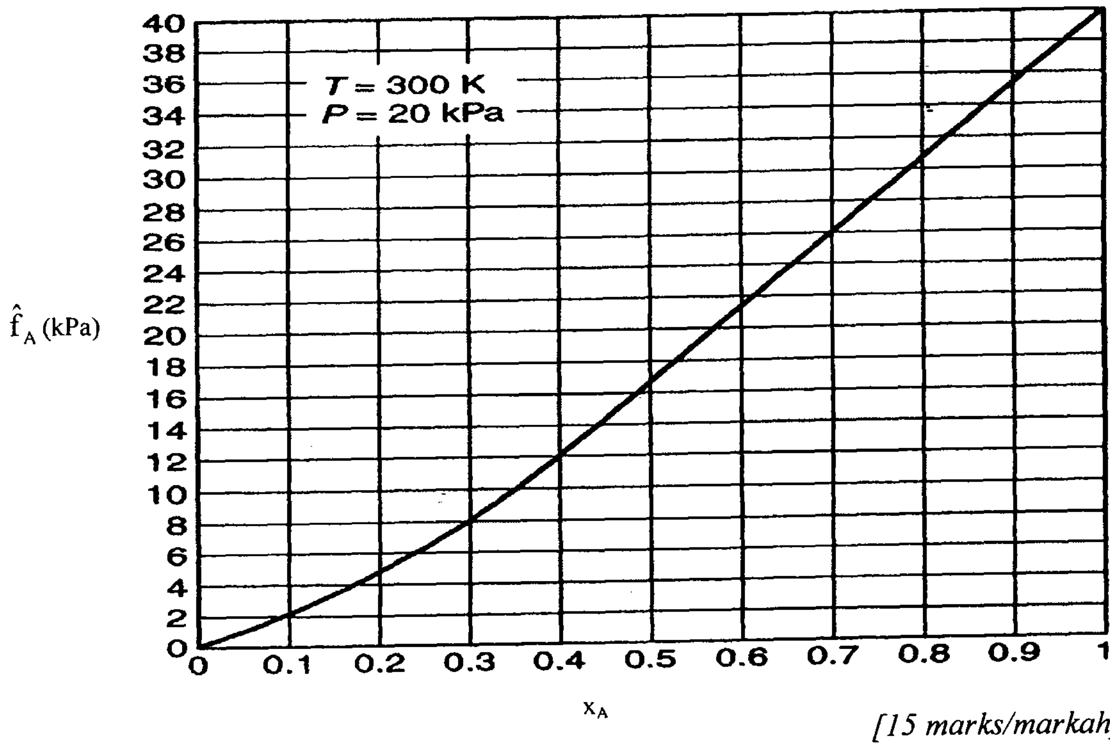
*Adakah pekali aktiviti untuk spesis B pada $x_A = 0.4$ lebih besar atau lebih kecil daripada 1? Terangkan.*

[iv] Is the A-B interaction stronger than the pure species interaction? Explain.

*Adakah interaksi A-B lebih kuat dibandingkan dengan interaksi spesis tulen? Terangkan.*

[v] Consider the vapor phase to be ideal. What is the vapor-phase mole fraction of A in equilibrium with 40% liquid A?

*Andaikan fasa wap adalah unggul. Apakah pecahan mol fasa-wap untuk A dalam keseimbangan dengan 40% cecair A?*




*[15 marks/markah]*

[b] [i] Briefly explain the term azeotrope in relation to VLE.

*Terangkan dengan ringkas terma azeotrop bila dikaitkan dengan VLE.*

*[5 marks/markah]*

[ii] Briefly discuss how the natural gas liquefaction process can be accomplished.

*Bincangkan dengan ringkas bagaimana proses pencecairan boleh dilakukan.*

*[5 marks/markah]*

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Appendix
*Lampiran*

## Thermodynamic Properties of Saturated Tetrafluoroethane†

| Temperature °C | K | Saturation pressure MPa $P$ | Liquid density kg $m^{-3}$ $\rho^l$ | Specific volume of vapor $m^3$ $kg^{-1}$ $V^v$ | Enthalpy kJ $kg^{-1}$ $H^l$ | $H^v$ | Entropy kJ $kg^{-1}$ $K^{-1}$ $S^l$ | $S^v$ |
|---|---|---|---|---|---|---|---|---|
| −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

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# CRITICAL CONSTANTS, ACENTRIC FACTORS AND ANTOINE COEFFICIENTS:[1]

The Antoine equation is of the form: $\ln(P^{sat}[\text{bar}]) = A - \dfrac{B}{T\,[\text{K}] + C}$

**Organic compounds**

| Formula | Name | $MW_{[g/mol]}$ | $T_c$ [K] | $P_c$ [bar] | $\omega$ | A | B | C | $T_{min}$ | $T_{max}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| $CH_2O$ | Formaldehyde | 30.026 | 408 | 65.86 | 0.253 | 9.8573 | 2204.13 | −30.15 | 185 | 271 |
| $CH_4$ | Methane | 16.042 | 190.6 | 46.00 | 0.008 | 8.6041 | 597.84 | −7.16 | 93 | 120 |
| $CH_4O$ | Methanol | 32.042 | 512.6 | 80.96 | 0.559 | 11.9673 | 3626.55 | −34.29 | 257 | 364 |
| $C_2H_4$ | Acetylene | 26.038 | 308.3 | 61.40 | 0.184 | 9.7279 | 1637.14 | −19.77 | 194 | 202 |
| $C_2H_3N$ | Acetonitrile | 41.052 | 548 | 48.33 | 0.321 | 9.6672 | 2945.47 | −49.15 | 260 | 390 |
| $C_2H_4$ | Ethylene | 28.053 | 282.4 | 50.36 | 0.085 | 8.9166 | 1347.01 | −18.15 | 120 | 182 |
| $C_2H_4O$ | Acetaldehyde | 44.053 | 461 | 55.73 | 0.303 | 9.6279 | 2465.15 | −37.15 | 210 | 320 |
| $C_2H_4O$ | Ethylene oxide | 44.053 | 469 | 71.94 | 0.200 | 10.1198 | 2567.61 | −29.01 | 300 | 310 |
| $C_2H_4O_2$ | Acetic acid | 60.052 | 594.4 | 57.86 | 0.454 | 10.1878 | 3405.57 | −56.34 | 290 | 430 |
| $C_2H_6$ | Ethane | 30.069 | 305.4 | 48.74 | 0.099 | 9.0435 | 1511.42 | −17.16 | 130 | 199 |
| $C_2H_6O$ | Ethanol | 46.068 | 516.2 | 63.83 | 0.635 | 12.2917 | 3803.98 | −41.68 | 270 | 369 |
| $C_3H_6$ | Propylene | 42.080 | 365.0 | 46.20 | 0.148 | 9.0825 | 1807.53 | −26.15 | 160 | 240 |
| $C_3H_6O$ | Acetone | 58.079 | 508.1 | 47.01 | 0.309 | 10.0311 | 2940.46 | −35.93 | 241 | 350 |
| $C_3H_8$ | Propane | 44.096 | 370.0 | 42.44 | 0.152 | 9.1058 | 1872.46 | −25.16 | 164 | 249 |
| $C_3H_8O$ | 1-Propanol | 60.095 | 536.7 | 51.68 | 0.624 | 10.9237 | 3166.38 | −80.15 | 285 | 400 |
| $C_4H_6$ | 1,3-Butadiene | 54.090 | 425 | 43.27 | 0.195 | 9.1525 | 2142.66 | −34.30 | 215 | 290 |
| $C_4H_8$ | *cis*-2-Butene | 56.106 | 435.6 | 42.05 | 0.202 | 9.1969 | 2210.71 | −36.15 | 200 | 305 |
| $C_4H_8$ | *trans*-2-Butene | 56.106 | 428.6 | 41.04 | 0.214 | 9.1975 | 2212.32 | −33.15 | 200 | 300 |
| $C_4H_8O_2$ | Ethyl acetate | 88.105 | 523.2 | 38.30 | 0.363 | 9.5314 | 2790.50 | −57.15 | 260 | 385 |
| $C_4H_{10}$ | *n*-Butane | 58.122 | 425.2 | 37.90 | 0.193 | 9.0580 | 2154.90 | −34.42 | 195 | 290 |
| $C_4H_{10}$ | Isobutane | 58.122 | 408.1 | 36.48 | 0.176 | 8.9179 | 2032.76 | −33.15 | 187 | 280 |
| $C_4H_{10}O$ | *n*-Butanol | 74.122 | 562.9 | 44.18 | 0.590 | 10.5958 | 3137.02 | −94.43 | 288 | 404 |
| $C_5H_{10}$ | 1-Pentene | 70.133 | 464.7 | 40.53 | 0.245 | 9.1444 | 2405.96 | −39.63 | 220 | 325 |
| $C_5H_{12}$ | *n*-Pentane | 72.149 | 469.6 | 33.74 | 0.251 | 9.2131 | 2477.07 | −39.94 | 220 | 330 |
| $C_6H_6$ | Benzene | 78.112 | 562.1 | 48.94 | 0.212 | 9.2806 | 2788.51 | −52.36 | 280 | 377 |
| $C_6H_6O$ | Phenol | 94.111 | 694.2 | 61.30 | 0.440 | 9.8077 | 3490.89 | −98.59 | 345 | 481 |
| $C_6H_7N$ | Aniline | 93.127 | 699 | 53.09 | 0.382 | 10.0546 | 3857.52 | −73.15 | 340 | 500 |
| $C_6H_{12}$ | Cyclohexane | 84.159 | 553.4 | 40.73 | 0.213 | 9.1325 | 2766.63 | −50.50 | 280 | 380 |
| $C_6H_{12}$ | 1-Hexene | 84.159 | 504.0 | 31.71 | 0.285 | 9.1887 | 2654.81 | −47.30 | 240 | 360 |
| $C_6H_{14}$ | *n*-Hexane | 86.175 | 507.4 | 29.69 | 0.296 | 9.2164 | 2697.55 | −48.78 | 245 | 370 |
| $C_7H_8$ | Toluene | 92.138 | 591.7 | 41.14 | 0.257 | 9.3935 | 3096.52 | −53.67 | 280 | 410 |
| $C_7H_{14}$ | 1-Heptene | 98.186 | 537.2 | 28.37 | 0.358 | 9.2692 | 2895.51 | −53.97 | 265 | 400 |
| $C_7H_{16}$ | *n*-Heptane | 100.202 | 540.2 | 27.36 | 0.351 | 9.2535 | 2911.32 | −56.51 | 270 | 400 |
| $C_8H_8$ | Styrene | 104.149 | 647.0 | 39.92 | 0.257 | 9.3991 | 3328.57 | −63.72 | 305 | 460 |
| $C_8H_{10}$ | *o*-Xylene | 106.165 | 630.2 | 37.29 | 0.314 | 9.4954 | 3395.57 | −59.46 | 305 | 445 |
| $C_8H_{10}$ | *m*-Xylene | 106.165 | 617.0 | 35.46 | 0.331 | 9.5188 | 3366.99 | −58.04 | 300 | 440 |
| $C_8H_{10}$ | *p*-Xylene | 106.165 | 616.2 | 35.16 | 0.324 | 9.4761 | 3346.65 | −57.84 | 300 | 440 |
| $C_8H_{10}$ | Ethylbenzene | 106.165 | 617.1 | 36.07 | 0.301 | 9.3993 | 3279.47 | −59.95 | 300 | 450 |
| $C_8H_{16}$ | 1-Octene | 112.213 | 566.6 | 26.24 | 0.386 | 9.3428 | 3116.52 | −60.39 | 288 | 420 |
| $C_8H_{18}$ | *n*-Octane | 114.229 | 568.8 | 24.82 | 0.394 | 9.3224 | 3120.29 | −63.63 | 292 | 425 |
| $C_9H_{20}$ | *n*-Nonane | 128.255 | 594.6 | 23.10 | 0.444 | 9.3469 | 3291.45 | −71.33 | 312 | 452 |
| $C_{10}H_8$ | Naphthalene | 128.171 | 748.4 | 40.53 | 0.302 | 9.5224 | 3992.01 | −71.29 | 360 | 545 |
| $C_{10}H_{22}$ | *n*-Decane | 142.282 | 617.6 | 21.08 | 0.490 | 9.3912 | 3456.80 | −78.67 | 330 | 476 |

# ENTHALPY AND GIBBS ENERGY OF FORMATION AT 298 K AND 1 BAR

**Organic Compounds**

| Formula | Name | Phase | $\Delta h^{o}_{f,298}$ [kJ/mol] | $\Delta g^{o}_{f,298}$ [kJ/mol] |
|---|---|---|---|---|
| $CH_2O$ | Formaldehyde | G | −115.97 | −109.99 |
| $CH_4$ | Methane | G | −74.81 | −50.72 |
| $CH_4O$ | Methanol | L | −238.73 | −166.34 |
| $CH_4O$ | Methanol | G | −200.66 | −161.96 |
| $C_2H_2$ | Acetylene | G | 226.88 | 209.24 |
| $C_2H_3N$ | Acetonitrile | L | 53.17 | 98.93 |
| $C_2H_3N$ | Acetonitrile | G | 87.92 | 105.67 |
| $C_2H_4$ | Ethylene | G | 52.26 | 68.15 |
| $C_2H_4Cl_2$ | 1,1-Dichloroethane | L | −160.86 | −76.20 |
| $C_2H_4Cl_2$ | 1,1-Dichloroethane | G | −130.00 | −73.14 |
| $C_2H_4O$ | Acetaldehyde | G | −166.47 | −133.39 |
| $C_2H_4O$ | Ethylene oxide | L | −77.46 | −11.43 |
| $C_2H_4O$ | Ethylene oxide | G | −52.67 | −13.10 |
| $C_2H_4O_2$ | Acetic acid | L | −484.41 | −389.62 |
| $C_2H_4O_2$ | Acetic acid | G | −435.13 | −376.94 |
| $C_2H_6$ | Ethane | G | −84.68 | −32.84 |
| $C_2H_6O$ | Ethanol | L | −277.17 | −174.25 |
| $C_2H_6O$ | Ethanol | G | −234.96 | −168.39 |
| $C_3H_6$ | Propylene | G | 20.43 | 62.76 |
| $C_3H_6O$ | Acetone | L | −248.28 | −155.50 |
| $C_3H_6O$ | Acetone | G | −217.71 | −153.15 |
| $C_3H_6O$ | Propylene oxide | L | −120.75 | −26.75 |
| $C_3H_6O$ | Propylene oxide | G | −92.82 | −25.79 |
| $C_3H_8$ | Propane | G | −103.85 | −23.49 |
| $C_3H_8O$ | 1-Propanol | L | −304.76 | −170.78 |
| $C_3H_8O$ | 1-Propanol | G | −257.70 | −163.08 |
| $C_4H_6$ | 1,3-Butadiene | L | 85.41 | 149.68 |
| $C_4H_6$ | 1,3-Butadiene | G | 110.24 | 150.77 |
| $C_4H_8$ | 1-Butene | G | −0.13 | 71.34 |
| $C_4H_8$ | *cis*-2-Butene | G | −6.99 | 65.90 |
| $C_4H_8$ | *trans*-2-Butene | G | −11.18 | 63.01 |
| $C_4H_8O_2$ | Ethyl acetate | L | −479.35 | −332.93 |
| $C_4H_8O_2$ | Ethyl acetate | G | −443.21 | −327.62 |
| $C_4H_{10}$ | *n*-Butane | L | −147.75 | −15.07 |
| $C_4H_{10}$ | *n*-Butane | G | −126.23 | −17.17 |
| $C_4H_{10}$ | Isobutane | L | −158.55 | −21.98 |
| $C_4H_{10}$ | Isobutane | G | −134.61 | −20.89 |
| $C_4H_{10}O$ | *n*-Butanol | L | −326.03 | −161.19 |
| $C_4H_{10}O$ | *n*-Butanol | G | −274.61 | −150.77 |
| $C_5H_{10}$ | 1-Pentene | L | −46.72 | 78.25 |
| $C_5H_{10}$ | 1-Pentene | G | −20.93 | 79.17 |
| $C_5H_{12}$ | *n*-Pentane | L | −173.33 | −9.46 |
| $C_5H_{12}$ | *n*-Pentane | G | −146.54 | −8.37 |
| $C_6H_6$ | Benzene | L | 49.07 | 124.34 |
| $C_6H_6$ | Benzene | G | 82.98 | 129.75 |
| $C_6H_6O$ | Phenol | S | −165.13 | −50.45 |
| $C_6H_6O$ | Phenol | G | −96.42 | −32.91 |
| $C_6H_7N$ | Aniline | L | 31.11 | 149.18 |
| $C_6H_7N$ | Aniline | G | 86.92 | 166.80 |
| $C_6H_{12}$ | Cyclohexane | L | −156.34 | 26.89 |
| $C_6H_{12}$ | Cyclohexane | G | −123.22 | 31.78 |
| $C_6H_{12}$ | 1-Hexene | L | −72.43 | 83.44 |
| $C_6H_{12}$ | 1-Hexene | G | −41.70 | 87.50 |
| $C_6H_{14}$ | *n*-Hexane | L | −198.96 | −4.35 |
| $C_6H_{14}$ | *n*-Hexane | G | −167.30 | −0.25 |
| $C_7H_8$ | Toluene | L | 12.02 | 113.84 |
| $C_7H_8$ | Toluene | G | 50.03 | 122.09 |
| $C_7H_{14}$ | 1-Heptene | L | −98.01 | 88.84 |
| $C_7H_{14}$ | 1-Heptene | G | −62.34 | 95.88 |
| $C_7H_{16}$ | *n*-Heptane | L | −224.54 | 1.00 |

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## 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

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