THERMODYNAMICS

P

 $P_{\rm abs,1}$

PROPERTIES OF SINGLE-COMPONENT SYSTEMS

Nomenclature

- 1. Intensive properties are independent of mass.
- 2. Extensive properties are proportional to mass.
- 3. Specific properties are lowercase (extensive/mass).

State Functions (properties)	
Absolute Pressure, P	(lbf/in ² or Pa)
Absolute Temperature, T	(°R or K)
Volume, V	$(ft^3 \text{ or } m^3)$
Specific Volume, $v = V m/$	$(ft^3/lbm \text{ or } m^3/kg)$
Internal Energy, U	(Btu or kJ)
Specific Internal Energy,	
u = U/m	(Btu/lbm or kJ/kg)
Enthalpy, <i>H</i>	(Btu or kJ)
Specific Enthalpy,	
h = u + Pv = H/m	(Btu/lbm or kJ/kg)
Entropy, S	(Btu/°R or kJ/K)
Specific Entropy, $s = S/m$	[Btu/(lbm-°R) or kJ/(kg•K)]
Gibbs Free Energy, $g = h - Ts$	(Btu/lbm or kJ/kg)
Helmholtz Free Energy,	
a = u - Ts	(Btu/lbm or kJ/kg)

For a single-phase pure component, specification of any two intensive, independent properties is sufficient to fix all the rest.

Heat Capacity at Constant Pressure,

[Btu/(lbm-°R) or kJ/(kg•K)]

Heat Capacity at Constant Volume,

[Btu/(lbm-°R) or kJ/(kg•K)]

The steam tables in this section provide *T*, *P*, *v*, *u*, *h*, and *s* data for saturated and superheated water.

A *P*-*h* diagram for refrigerant HFC-134a providing T, P, v, h, and s data in a graphical format is included in this section.

Thermal and physical property tables for selected gases, liquids, and solids are included in this section.

Properties for Two-Phase (vapor-liquid) Systems

Quality x (for liquid-vapor systems at saturation) is defined as the mass fraction of the vapor phase:



Specific volume of a two-phase system can be written:

- $v = xv_g + (1 x)v_f \text{ or } v = v + xv_f \text{ where}$
- v_f = specific volume of saturated liquid
- v_g = specific volume of saturated vapor
- v_{fg} = specific volume change upon vaporization

- 11. A liquid boils when its vapor pressure is equal to
 - (A) one atmosphere of pressure.
 - (B) the gage pressure.
 - (C) the absolute pressure.
 - (D) the ambient pressure.

22. Which property of state is not an extensive state?

- (A) temperature
- (B) volume
- (C) number of molecules
- (D) mass

 $= v_g - v_f$

Similar expressions exist for *u*, *h*, and *s*:

 $u = xu_g + (1 - x) u_f \text{ or } u = u_f + xu_{fg}$ $h = xh_g + (1 - x) h_f \text{ or } h = h_f + xh_{fg}$ $s = xs_g + (1 - x) s_f \text{ or } s = s_f + xs_{fg}$

PVT BEHAVIOR

Ideal Gas

For an ideal gas, Pv = RT or PV = mRT, and $P_1v_1/T_1 = P_2v_2/T_2$, where

- P = pressure
- v =specific volume
- m = mass of gas
- R = gas constant
- T = absolute temperature
- V = volume

R is *specific to each gas* but can be found from

 \overline{R} = the universal gas constant

$$= 1,545 \text{ ft-lbf/(lbmol-°R)} = 8,314 \text{ J/(kmol•K)}$$

$$= 8.314 \text{ kPa}\cdot\text{m}^{3}/(\text{kmol}\cdot\text{K}) = 0.08206 \text{ L}\cdot\text{atm}/(\text{mole}\cdot\text{K})$$

For *ideal gases*, $c_p - c_v = R$

Ideal gas behavior is characterized by:



The properties of an ideal gas reflect those of a single molecule and are attributable entirely to the structure of the molecule and the system T.

For ideal gases:

$$\left(\frac{\partial h}{\partial P}\right)_T = 0 \qquad \qquad \left(\frac{\partial u}{\partial v}\right)_T = 0$$

For cold air standard, *heat capacities are assumed to be constant* at their room temperature values. In that case, the following are true:

$$\Delta u = c_v \Delta T; \quad \Delta h = c_p \Delta T$$

$$\Delta s = c_p \ln (T_2/T_1) - R \ln (P_2/P_1)$$

$$\Delta s = c_v \ln (T_2/T_1) + R \ln (v_2/v_1)$$

Also, for constant entropy processes:

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k; \qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$
$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{k-1}, \text{ where } k = c_p/c_v$$

Ideal Gas Mixtures

i = 1, 2, ..., n constituents. Each constituent is an ideal gas. Mole Fraction:

$$x_i = N_i/N; N = \Sigma N_i; \Sigma x_i = 1$$

where N_i = number of moles of component i

N =total moles in the mixture

Mass Fraction: $y_i = m_i/m$; $m = \sum m_i$; $\sum y_i = 1$

Molecular Weight: $M = m/N = \sum x_i M_i$

To convert *mole fractions* x_i to *mass fractions* y_i :



where *P*, *V*, *T* = the pressure, volume, and temperature of the mixture and $R_i = R/M_i$

Combining the above generates the following additional expressions for mole fraction.

$$x_i = P_i / P = V_i / V$$

Other Properties: $u = \Sigma (y_i u_i); h = \Sigma (y_i h_i); s = \Sigma (y_i s_i)$ u_i and h_i are evaluated at T s_i is evaluated at T and P_i

Real Gas

Most gases exhibit ideal gas behavior when the system pressure is less than 3 atm since the distance between molecules is large enough to produce negligible molecular interactions. The behavior of a real gas deviates from that of an ideal gas at higher pressures due to molecular interactions.

For a real gas, Pv = ZRT where Z = compressibility factor.

Z = 1 for an ideal gas; $Z \neq 1$ for a real gas

Equations of State (EOS)

EOS are used to quantify *PvT* behavior <u>Ideal Gas EOS</u> (applicable only to ideal gases)

<u>Generalized Compressibility EOS</u> (applicable to all systems as gases, liquids, and/or solids)

Virial EOS (applicable only to gases)

$$P = \left(\frac{RT}{v}\right) \left(1 + \frac{B}{v} + \frac{C}{v^2} + \dots\right) \text{ where } B, C, \dots$$

are virial coefficients obtained from *Pv1* measurements or statistical mechanics.

<u>Cubic EOS</u> (theoretically motivated with intent to predict gas and liquid thermodynamic properties)

$$P = \frac{RT}{v-b} - \frac{a(T)}{(v+c_1b)(v+c_2b)}$$

where a(T), b, and c_1 and c_2 are species specific.

An example of a cubic EOS is the Van der Waals equation with constants based on the critical point:

$$\left(P + \frac{a}{\bar{\sigma}^2}\right) (\bar{v} - b) = \bar{R}T$$

where $a = \left(\frac{27}{64}\right) \left(\frac{\bar{R}^2 T_c^2}{P_c}\right), \quad b = \frac{\bar{R}T_c}{8P_c}$

where P_c and T_c are the pressure and temperature at the critical point, respectively, and *w* is the molar specific volume.

EOS are used to predict:

- *P*, *v*, or *T* when two of the three are specified
- other thermodynamic properties based on analytic manipulation of the EOS
- mixture properties using appropriate mixing rules to create a pseudo-component that mimics the mixture properties

The Theorem of Corresponding States asserts that all normal fluids have the same value of *Z* at the same reduced temperature T_r and pressure P_r .

$$T_r = \frac{T}{T_c} \quad P_r = \frac{P}{P_c}$$

where T_c and P_c are the critical temperature and pressure, respectively, expressed in absolute units. This is captured in the Generalized Compressibility Factor chart.

FIRST LAW OF THERMODYNAMICS

The *First Law of Thermodynamics* is a statement of conservation of energy in a thermodynamic system. The net energy crossing the system boundary is equal to the change in energy inside the system.

Heat Q (q = Q/m) is *energy transferred* due to temperature difference and is considered positive if it is inward or added to the system.

Work W(w = W/m) is considered *positive if it is outward* or *work done* by the system.

Closed Thermodynamic System

No mass crosses system boundary

```
Energy can cross the boundary only in
the form of heat or work. Work
can be boundary work, w_b, or
other work forms (electrical
work, etc.)
```

Reversible boundary work is given by $w_{\rm b} = \int P \, dv$.

Special Cases of Closed Systems (with no change in kinetic or

potential energy)

Constant System Pressure process (*Charles' Law*): $w_b = P\Delta v$ (ideal gas) T/v = constant

Constant Volume process:

 $w_b = 0$ (ideal gas) T/P = constant

Isentropic process (ideal gas):

$$Pv^{k} = \text{constant}$$

w = $(P_{2}v_{2} - P_{1}v_{1})/(1 - k)$
= $R(T_{2} - T_{1})/(1 - k)$

Constant Temperature process (*Boyle's Law*):

(ideal gas) Pv = constant

$$w_{\rm b} = RT \ln (v_2 / v_1) = RT \ln (P_1 / P_2)$$

Polytropic process (ideal gas):

 $Pv^n = \text{constant}$ $w = (P_2v_2 - P_1v_1)/(1 - n), n \neq 1$

Open Thermodynamic System

Mass crosses the system boundary. There is flow work (Pv) done by mass entering the system. The reversible flow work is given by:

First Law applies whether or not processes are reversible.

Open System First Law (energy balance)

 \dot{W}_{net} : rate of net or shaftwork

- \dot{m} mass flow rate (subscripts *i* and *e* refer to inlet and exit states of system)
- g =acceleration of gravity
- Z = elevation
- V =velocity
- $m_s =$ mass of fluid within the system
- u_s = specific internal energy of system
- \dot{Q}_{in} = rate of heat transfer (neglecting kinetic and potential energy of the system)

Special Cases of Open Systems (with no change in kinetic or

potential energy)

Constant Volume process:

 $w_{rev} = -v (P_2 - P_1)$

Constant System Pressure process:

$$w_{rev} = 0$$

Constant Temperature process:

(ideal gas) Pv = constant

$$w_{rev} = RT \ln (v_2/v_1) = RT \ln (P_1/P_2)$$

Isentropic process (ideal gas): $Pv^k = constant$

$$Pv^{k} = \text{constant}$$

$$w_{rev} = k (P_{2}v_{2} - P_{1}v_{1})/(1 - k)$$

$$= k R (T_{2} - T_{1})/(1 - k)$$

$$w_{rev} = \frac{k}{k - 1} R T_{1} \left[1 - \left(\frac{P_{2}}{P_{1}}\right)^{(k - 1)/k} \right]$$

Polytropic process (ideal gas):

$$Pv^{n} = \text{constant}$$

$$w_{rev} = n (P_2v_2 - P_1v_1)/(1-n)$$

Steady-Flow Systems

The system does not change state with time. This assumption is valid for steady operation of turbines, pumps, compressors, throttling valves, nozzles, and heat exchangers, including boilers and condensers.

$$\Sigma \dot{m} (h_i + V_i^2/2 + gZ_i) - \Sigma \dot{m}_e (h_e + V_e^2/2 + gZ_e) + \dot{Q}_{in} - \dot{W}_{out} = 0$$

and

 $\Sigma \dot{m}_i = \Sigma \dot{m}_e$

where

- m = mass flow rate (subscripts i and e refer to inlet and exit states of system)
- g =acceleration of gravity
- Z = elevation
- V =velocity
- \dot{Q} = rate of heat transfer

$$\dot{W}$$
 = rate of work

Special Cases of Steady-Flow Energy Equation

Nozzles, Diffusers: Velocity terms are significant. No elevation change, no heat transfer, and no work. Single mass stream.

Isentropic Efficiency (nozzle) =
$$\frac{V_e^2 - V_i^2}{2(h_i - h_{es})}$$
, where

 h_{es} enthalpy at isentropic exit state.

Turbines, Pumps, Compressors: Often considered adiabatic (no heat transfer). Velocity terms usually can be ignored. There are significant work terms and a single mass stream.

$$h_i = h_e + w$$

Г

Isentropic Efficiency (turbine) = $\frac{h_i - h_e}{h_i - h_{es}}$

Isentropic Efficiency (compressor, pump) = $\frac{h_{es} - h_i}{h_e - h_i}$

For pump only, $h_{es} - h = v (p - p)_{i}$

Throttling Valves and Throttling Processes: No work, no heat transfer, and single-mass stream. Velocity terms are often insignificant.

$$h_i = h_e$$

Boilers, Condensers, Evaporators, One Side in a Heat Exchanger: Heat transfer terms are significant. For a singlemass stream, the following applies:

$$h_i + q = h_e$$

Heat Exchangers: No heat loss to the surroundings or work. Two separate flow rates \dot{m}_1 and \dot{m}_2 :

$$\dot{m}_1(h_{1i} - h_{1e}) = \dot{m}_2(h_{2e} - h_{2i})$$

Mixers, Separators, Open or Closed Feedwater Heaters:

$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e$$
 and
 $\Sigma \dot{m}_i = \Sigma \dot{m}_e$

BASIC CYCLES

Heat engines take in heat Q_H at a high temperature T_H , produce a net amount of work W, and reject heat Q_L at a low temperature T_I . The efficiency η of a heat engine is given by:

$$\eta = W/Q_H = (Q_H - Q_L)/Q_H$$

The most efficient engine possible is the *Carnot Cycle*. Its efficiency is given by:

 $\eta_c = (T_H - T_L)/T_{H'}$, where

 T_H and T_L = absolute temperatures (Kelvin or Rankine).

The following heat-engine cycles are plotted on *P*-*v* and *T*-*s* diagrams in this section:

Carnot, Otto, Rankine

Refrigeration cycles are the reverse of heat-engine cycles. Heat is moved from low to high temperature requiring work, *W*. Cycles can be used either for refrigeration or as heat pumps.

Coefficient of Performance (COP) is defined as:

 $COP = Q_H/W$ for heat pumps, and as $COP = Q_I/W$ for refrigerators and air conditioners.

Upper limit of COP is based on reversed Carnot Cycle:

 $\text{COP}_c = T_H / (T_H - T_L)$ for heat pumps and $\text{COP}_c = T_L / (T_H - T_L)$ for refrigeration.

1 ton refrigeration = 12,000 Btu/hr = 3,516 W

The following refrigeration cycles are plotted on *T-s* diagrams in this section:

reversed rankine, two-stage refrigeration, air refrigeration

PSYCHROMETRICS

Properties of an air-water vapor mixture at a fixed pressure are given in graphical form on a psychrometric chart as provided in this section. When the system pressure is 1 atm, an idealgas mixture is assumed.

The definitions that follow use subscript a for dry air and v for water vapor.

P = pressure of the air-water mixture, normally 1 atm

T =dry-bulb temp (air/water mixture temperature)

 P_a = partial pressure of dry air

 P_v = partial pressure of water vapor

 $P = P_a + P_v$

Specific Humidity (absolute humidity, humidity ratio) @:

 $\omega = m_v/m_a$ where $m_v =$ mass of water vapor $m_a =$ mass of dry air $\omega = 0.622P_v/P_a = 0.622P_v/(P - P_v)$

Relative Humidity (rh) ϕ :

 $\phi = P_v / P_{g'}$ where

 P_g = saturation pressure of water at *T*.

Enthalpy *h*: $h = h_a + \omega h_v$

Dew-Point Temperature T_{dp} : $T_{dp} = T_{sat}$ at $P_g = P_v$

Wet-bulb temperature T_{wb} is the temperature indicated by a thermometer covered by a wick saturated with liquid water and in contact with moving air.

Humid Volume: Volume of moist air/mass of dry air.

SECOND LAW OF THERMODYNAMICS

Thermal Energy Reservoirs

 $\Delta S_{\text{reservoir}} = Q/T_{\text{reservoir}}$, where

Q is measured with respect to the reservoir.

Kelvin-Planck Statement of Second Law

No heat engine can operate in a cycle while transferring heat with a single heat reservoir.

COROLLARY to Kelvin-Planck: No heat engine can have a higher efficiency than a Carnot Cycle operating between the same reservoirs.

Clausius' Statement of Second Law

No refrigeration or heat pump cycle can operate without a net work input.

COROLLARY: No refrigerator or heat pump can have a higher COP than a Carnot Cycle refrigerator or heat pump.

Entropy



Inequality of Clausius

$$\oint (1/T) \delta q_{\text{rev}} \le 0$$

$$\int_1^2 (1/T) \delta q \le s_2 - s_1$$

Isothermal, Reversible Process

$$\Delta s = s_2 - s_1 = q/T$$

Isentropic Process $\Delta s 0; ds 0$

A reversible adiabatic process is

Adiabatic Process $\delta q = 0; \Delta s = 0$

Increase of Entropy Principle

$$\Delta s_{\text{total}} = \Delta s_{\text{system}} + \Delta s_{\text{surroundings}} \ge 0$$

$$\Delta \dot{s}_{\text{total}} = \sum \dot{m}_{\text{out}} s_{\text{out}} - \sum \dot{m}_{\text{in}} s_{\text{in}} - \sum \left(\dot{q}_{\text{external}} / T_{\text{external}} \right) \ge 0$$

Temperature-Entropy (*T*-s) Diagram

$$q_{rev} f_{1}^{= 2T} ds$$

AREA =

Entropy Change for Solids and Liquids

$$ds = c (dT/T)$$

$$s_2 - s_1 = \int c (dT/T) = c_{\text{mean}} \ln (T_2/T_1),$$
where *c* equals the heat capacity of the solid or liquid.

9. A gas sample undergoes the closed cycle shown. The difference in internal energy between state B and state A is 600 J. The heat absorption from state B to state C is -1200 J. What is the heat absorption from state A to state B?



17. 3 kg of steam with quality of 30% has a pressure of 12.056 bar. At that pressure, the specific volume of a saturated fluid is $v_f = 1.5289 \text{ cm}^3/\text{g}$. The specific volume of a saturated vapor is $v_g = 14.1889 \text{ cm}^3/\text{g}$. What is the specific volume of the steam?

(A) $5.25 \text{ cm}^3/\text{g}$ (B) $5.33 \text{ cm}^3/\text{g}$ (C) $5.40 \text{ cm}^3/\text{g}$ (D) $5.48 \text{ cm}^3/\text{g}$ Problems 17–19 refer to the following situation.

A gas goes through the following thermodynamic processes.

A to B:	
B to C:	
C to A:	

The pressure and volume at state C are 1.4 bars and 0.028 m^3 , respectively. The net work during the C-to-A process is 10.5 kJ.



17. What is the volume at state A?

- (A) 0.07 m^3
- (B) 0.10 m^3
- (C) 0.19 m³
- (D) 0.24 m³

18. What work is performed in the A-to-B process?

- (A) -19 kJ
- (B) -13 kJ
- (C) 0 kJ
- (D) 5.3 kJ

19. What net work is derived from one complete A-B-C cycle?

- (A) -21 kJ
- (B) −8.3 kJ
- (C) -6.5 kJ
- (D) 4.8 kJ

Carnot Cycle

The *Carnot cycle* is an ideal power cycle that is impractical to implement. However, its theoretical work output sets the maximum attainable from any heat engine, as evidenced by the isentropic (reversible) processes between states (D and A) and (B and C) in Fig. 28.2. The working fluid in a Carnot cycle is irrelevant.

The processes involved are as follows.

- A to B: isothermal expansion of saturated liquid to saturated vapor
- B to C: isentropic expansion of vapor $(Q = 0, \Delta s = 0)$
- C to D: isothermal compression of vapor
- D to A: isentropic compression $(Q = 0, \Delta s = 0)$







The Carnot refrigeration cycle is a Carnot power cycle running in reverse. Because it is reversible, the Carnot refrigeration cycle has the highest coefficient of performance for any given temperature limits of all the refrigeration cycles. As shown in Fig. 28.7, all processes occur within the vapor dome.

- A to B: isentropic expansion
- B to C: isothermal heating (vaporization)
- C to D: isentropic compression
- D to A: isothermal cooling (condensation)

The coefficients of performance for a Carnot refrigeration cycle establish the upper limit of the COP.

$$(\text{COP})_{\text{Carnot}} = \frac{T_L}{T_H - T_L} \quad \begin{bmatrix} \text{Carnot} \\ \text{refrigerator} \end{bmatrix}$$
 20.0

$$(\text{COP})_{\text{Carnot}} = \frac{T_H}{T_H - T_L} \quad \begin{bmatrix} \text{Carnot} \\ \text{heat pump} \end{bmatrix} \quad 28.9$$







Rankine Cycle

The basic *Rankine cycle* is similar to the Carnot cycle except that the compression process occurs in the liquid region. The Rankine cycle is closely approximated in steam turbine plants. The efficiency of the Rankine cycle is lower than that of a Carnot cycle operating between the same temperature limits because the mean temperature at which heat is added to the system is lower than T_H .

The processes used in the basic Rankine cycle are as follows.

- A to B: vaporization in the boiler
- B to C: isentropic expansion in the turbine
- C to D: condensation
- D to E: isentropic compression to boiler pressure
- E to A: heating liquid to saturation temperature







The thermal efficiency of the entire cycle is

$$\eta_{\rm th} = rac{W_{
m out} - W_{
m in}}{Q_{
m in}} = rac{(h_{
m B} - h_{
m C}) - (h_{
m E} - h_{
m D})}{h_{
m B} - h_{
m E}}$$

Otto Cycle

Combustion power cycles differ from vapor power cycles in that the combustion products cannot be returned to their initial conditions for reuse. Due to the computational difficulties of working with mixtures of fuel vapor and air, combustion power cycles are often analyzed as air-standard cycles.

An *air-standard cycle* is a hypothetical closed system using a fixed amount of ideal air as the working fluid. In contrast to a combustion process, the heat of combustion is included in the calculations without consideration of the heat source or delivery mechanism (i.e., the combustion process is replaced by a process of instantaneous heat transfer from high-temperature surroundings). Similarly, the cycle ends with an instantaneous transfer of waste heat to the surroundings. All processes

are considered to be internally reversible. Because the air is assumed to be ideal, it has a constant specific heat.

Actual engine efficiencies for internal combustion engine cycles may be as much as 50% lower than the efficiencies calculated from air-standard analyses. Empirical corrections must be applied to theoretical calculations based on the characteristics of the engine. However, the large amount of excess air used in turbine combustion cycles results in better agreement (in comparison to reciprocating cycles) between actual and ideal performance.

The *air-standard Otto cycle* consists of the following processes and is illustrated in Fig. 28.6.

- A to B: isentropic compression $(Q = 0, \Delta s = 0)$
- B to C: constant volume heat addition
- C to D: isentropic expansion $(Q = 0, \Delta s = 0)$
- D to A: constant volume heat rejection



υ

The Otto cycle is a four-stroke cycle because four separate piston movements (strokes) are required to accomplish all of the processes: the intake, compression, power, and exhaust strokes. Two complete crank revolutions are required for these four strokes. Therefore, each cylinder contributes one power stroke every other revolution.

The ideal thermal efficiency for the Otto cycle, Eq. 28.4, can be calculated from the *compression ratio*, Eq. 28.5.

$$\eta_{\rm th} = 1 - r_v^{1-k}$$
 28.4

s

$$r_v = \frac{V_{\rm A}}{V_{\rm B}} = \frac{V_{\rm D}}{V_{\rm C}}$$
 28.5

1. A Carnot engine receives 100 kJ of heat from a hot reservoir at 370°C and rejects 37 kJ of heat. Determine the temperature of the cold reservoir.

(A)	−35°C
(B)	$100^{\circ}\mathrm{C}$
(C)	$130^{\circ}\mathrm{C}$

(D) 230°C

What is the maximum efficiency for a cycle between these two temperatures What is the change in entropy?

Problems 23–25 refer to the following situation.

A system operating on the cycle shown uses water as the working fluid. The A-to-B and C-to-D processes are isothermal. The B-to-C and D-to-A processes are isentropic. The pressure of the process at points A and B is 800 kPa, and the pressure at points C and D is 2 kPa. All processes are within the liquid-vapor region for water.



At 800 kPa,

$$h_f = 721.1 \text{ kJ/kg}$$

 $h_g = 2769.1 \text{ kJ/kg}$
 $s_f = 2.0466 \text{ kJ/kg} \cdot \text{K}$
 $s_g = 6.6636 \text{ kJ/kg} \cdot \text{K}$

At 2 kPa,

$$h_f = 73.5 \text{ kJ/kg}$$

 $h_g = 2533.5 \text{ kJ/kg}$
 $s_f = 0.2606 \text{ kJ/kg}$
 $s_g = 8.7245 \text{ kJ/kg}$

23. What is the approximate change in entropy from state A to state B?

- (A) $0 \text{ kJ/kg} \cdot \text{K}$
- (B) 2.1 kJ/kg K
- (C) $4.6 \text{ kJ/kg} \cdot \text{K}$
- (D) $8.5 \text{ kJ/kg} \cdot \text{K}$

Carnot cycle

24. What is the approximate change in entropy from state B to state C?

(A) 0 kJ/kg·K
(B) 2.1 kJ/kg·K
(C) 4.6 kJ/kg·K
(D) 6.7 kJ/kg·K

25. What is the approximate enthalpy at state C?

(A) 74 kJ/kg
(B) 720 kJ/kg
(C) 1800 kJ/kg
(D) 1900 kJ/kg

Exergy (Availability)

Exergy (also known as availability) is the maximum possible work that can be obtained from a cycle of a heat engine. The maximum possible work is obtained in a reversible process.

Closed-System Exergy (Availability)

(no chemical reactions)

$$\phi = (u - u_L) - T_L(s - s_L) + p_L(v - v_L)$$

where the subscript *L* designates environmental conditions and ϕ is availability function.

 $w_{max} = w_{rev} = \phi_i - \phi_2$

Open-System Exergy (Availability)

$$\Psi = (h - h_I) - T_I(s - s_I) + V^2/2 + gZ$$

where *V* is velocity, *g* is acceleration of gravity, *Z* is elevation and Ψ is availability function.

$$w_{max} = w_{rev} = \Psi_i - \Psi_2$$

Gibbs Free Energy, ΔG

Energy released or absorbed in a reaction occurring reversibly at constant pressure and temperature.

Helmholtz Free Energy, ΔA

Energy released or absorbed in a reaction occurring reversibly at constant volume and temperature.

Irreversibility, I

 $I = w_{rev} - w_{actual} = T_L \Delta s_{total}$

HEATS OF REACTION

For a chemical reaction the associated energy can be defined in terms of heats of formation of the individual species $DH_{f}^{\prime\prime}$ at the standard state

$$\left(\Delta H_r^{\circ}\right) = \sum_{\text{products}} \upsilon_i \left(\Delta H_f^{\circ}\right)_i - \sum_{\text{reactants}} \upsilon_i \left(\Delta H_f^{\circ}\right)_i$$

 v_i = stoichiometric coefficient for species "*i*"

The standard state is 25°C and 1 bar.

The heat of formation is defined as the enthalpy change associated with the formation of a compound from its atomic species as they normally occur in nature [i.e., $O_2(g)$, $H_2(g)$, C(solid), etc.]

The heat of reaction varies with the temperature as follows:

$$\Delta H_r^{\circ}(T) = \Delta H_r^{\circ}(T_{\text{ref}}) + \int_{T_{\text{ref}}}^T \Delta c_p dT$$

where T_{ref} is some reference temperature (typically 25°C or 298 K), and:

$$\Delta c_p = \sum_{\text{products}} v_i c_{p,i} - \sum_{\text{reactants}} v_i c_{p,i}$$

and $c_{p,i}$ is the molar heat capacity of component *i*.

The heat of reaction for a combustion process using oxygen is also known as the heat of combustion. The principal products are $CO_2(g)$ and $H_2O(l)$.

Combustion Processes

First, the combustion equation should be written and balanced. For example, for the stoichiometric combustion of methane in oxygen:

$$CH_4 + 2 O_2 \rightarrow CO_2 + 2 H_2O$$

Combustion in Air

For each mole of oxygen, there will be 3.76 moles of nitrogen. For stoichiometric combustion of methane in air:

$$CH_4 + 2 O_2 + 2(3.76) N_2 \rightarrow CO_2 + 2 H_2O + 7.52 N_2$$

Combustion in Excess Air

The excess oxygen appears as oxygen on the right side of the combustion equation.

Incomplete Combustion

Some carbon is burned to create carbon monoxide (CO).

Molar Air-Fuel Ratio, $\overline{A/F} = \frac{\text{No. of moles of air}}{\text{No. of moles of fuel}}$

Air-Fuel Ratio,
$$A/F = \frac{\text{Mass of air}}{\text{Mass of fuel}} = \left(\overline{A/F}\right) \left(\frac{M_{\text{air}}}{M_{\text{fuel}}}\right)$$

Stoichiometric (theoretical) air-fuel ratio is the air-fuel ratio calculated from the stoichiometric combustion equation.

Percent Theoretical Air =
$$\frac{(A/F)_{\text{actual}}}{(A/F)_{\text{stoichiometric}}} \times 100$$

Percent Excess Air = $\frac{(A/F)_{\text{actual}} - (A/F)_{\text{stoichiometric}}}{(A/F)_{\text{stoichiometric}}} \times 100$

VAPOR-LIQUID EQUILIBRIUM (VLE)

Henry's Law at Constant Temperature

At equilibrium, the partial pressure of a gas is proportional to its concentration in a liquid. Henry's Law is valid for low concentrations; i.e., $x \approx 0$.

 $P_i = Py_i = hx_i$ where

h = Henry's Law constant

 P_i = partial pressure of a gas in contact with a liquid

 x_i = mol fraction of the gas in the liquid y_i =

mol fraction of the gas in the vapor P = total pressure

Raoult's Law for Vapor-Liquid Equilibrium

Valid for concentrations near 1; i.e., $x_i \approx 1$ at low pressure (ideal gas behavior)

 $P_i = x_i P_i^*$, where

 P_i = partial pressure of component *i*

- $x_i = \text{mol fraction of component } i$ in the liquid
- $P_i^* =$ vapor pressure of pure component *i* at the temperature of the mixture

Rigorous Vapor-Liquid Equilibrium

For a multicomponent mixture at equilibrium

 $\hat{f}_i^V = \hat{f}_i^L$, where

 \hat{f}_i^V = fugacity of component *i* in the vapor phase

 \hat{f}_i^L = fugacity of component *i* in the liquid phase

Fugacities of component *i* in a mixture are commonly calculated in the following ways:

For a liquid $\hat{f}_i^L = x_i \gamma_i f_i^L$, where $x_i =$ mole fraction of component *i*

 γ_i = activity coefficient of component *i*

 f_i^L = fugacity of pure liquid component *i*

For a vapor, $\hat{f}_i^V = y_i \hat{\Phi}_i P$, where

 y_i = mole fraction of component *i* in the vapor

 $\hat{\bigoplus}_i$ = fugacity coefficient of component *i* in the vapor

P = system pressure

The activity coefficient γ_i is a correction for liquid phase non-ideality. Many models have been proposed for γ_i such as the Van Laar model:

$$\ln\gamma_{1} = A_{12} \left(1 + \frac{A_{12} x_{1}}{A_{21} x_{2}} \right)^{-2}$$
$$\ln\gamma_{2} = A_{21} \left(1 + \frac{A_{21} x_{2}}{A_{12} x_{1}} \right)^{-2}, \text{ where}$$

 γ_1 = activity coefficient of component 1 in a two-component system

 γ_2 = activity coefficient of component 2 in a two-component system

 A_{12}, A_{21} = constants, typically fitted from experimental data The pure component fugacity is calculated as:

$$f_i^L = \Phi_i^{\text{sat}} P_i^{\text{sat}} \exp\left\{v_i^L \left(P - P_i^{\text{sat}}\right) / (RT)\right\}, \text{ where }$$

 Φ_i^{sat} = fugacity coefficient of pure saturated *i*

 $P_i^{\text{sat}} = \text{saturation pressure of pure } i$

 v_i^L = specific volume of pure liquid *i*

R =Ideal Gas Law Constant

T = absolute temperature

Often at system pressures close to atmospheric:

$$f_i^L \cong P_i^{\text{sat}}$$

The fugacity coefficient U_i for component *i* in the vapor is calculated from an equation of state (e.g., Virial). Sometimes it is approximated by a pure component value from a correlation. Often at pressures close to atmospheric, $\hat{\Phi}_i = 1$. The fugacity coefficient is a correction for vapor phase non-ideality. For sparingly soluble gases the liquid phase is sometimes represented as:

$$\hat{f}_i^L = x_i k_i$$

where k_i is a constant set by experiment (Henry's constant). Sometimes other concentration units are used besides mole fraction with a corresponding change in k_i ,

PHASE RELATIONS

Clapeyron Equation for phase transitions:

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{h_{fg}}{Tv_{fg}} = \frac{s_{fg}}{v_{fg}}$$
, where

 h_{fg} = enthalpy change for phase transitions

 v_{fg} = volume change

 s_{fg} = entropy change

T = absolute temperature

 $(dP/dT)_{sat}$ = slope of phase transition (e.g.,vapor-liquid) saturation line

Clausius-Clapeyron Equation

This equation results if it is assumed that (1) the volume change (v_{fg}) can be replaced with the vapor volume (v_{fg}) , (2) the latter can be replaced with $P \not \in \overline{T}$ from the ideal gas law, and (3) h_{fg} is independent of the temperature (*T*).

$$\ln_e\!\left(\frac{P_2}{P_1}\right) = \frac{h_{fg}}{\overline{R}} \cdot \frac{T_2 - T_1}{T_1 T_2}$$

Gibbs Phase Rule (non-reacting systems)

P + F = C + 2, where

 $\mathbf{P} = \mathbf{number}$ of phases making up a system

F = degrees of freedom

C = number of components in asystem

CHEMICAL REACTION EQUILIBRIA

Definitions

Conversion - moles reacted/molesfed

Extent – For each species in a reaction, the mole balance may be written:

 $moles_{i,out} = moles_{i,in} + v_i \xi$ where

 ξ is the extent in moles and v_i is the stoichiometric coefficient of the *i*th species, the sign of which is negative for reactants and positive for products.

Limiting reactant - Reactant that would be consumed first if the reaction proceeded to completion. Other reactants are excess reactants.

Selectivity - Moles of desired product formed/moles of undesired product formed.

Yield - Moles of desired product formed/moles that would have been formed if there were no side reactions and the limiting reactant had reacted completely.

Chemical Reaction Equilibrium

For the reaction

$$aA + bB = cC + dD$$

$$\Delta G^{\circ} = -RT \ln K_{a}$$

$$K_{a} = \frac{\left(\hat{a}_{C}^{c}\right)\left(\hat{a}_{D}^{d}\right)}{\left(\hat{a}_{A}^{a}\right)\left(\hat{a}_{B}^{b}\right)} = \prod_{i} \left(\hat{a}_{i}\right)^{\nu_{i}}, \text{ where }$$

 $\hat{a}_i = \text{activity of component } i = \frac{\hat{f}_i}{\hat{f}_i}$

 f_i^{*} = fugacity of pure *i* in its standard state at the equilibrium reaction temperature, T

= stoichiometric coefficient of component *i* v_i

 ΔG° = standard Gibbs energy change of reaction

 K_a = chemical equilibrium constant

For mixtures of ideal gases:

 f_i° = unit pressure, often 1 bar

$$\hat{f}_i = y_i P = p_i$$

where p_i = partial pressure of component *i*. () ()

Then
$$K_a = K_p = \frac{\left(p_C^c\right)\left(p_D^d\right)}{\left(p_A^a\right)\left(p_B^b\right)} = P^{c+d-a-b}\frac{\left(y_C^c\right)\left(y_D^d\right)}{\left(y_A^a\right)\left(y_B^b\right)}$$

<u>For solids</u> $\hat{a}_i = 1$

<u>For liquids</u> $\hat{a}_i = x_i \gamma_i$

The effect of temperature on the equilibrium constant is

$$\frac{d\ln K}{dT} = \frac{\Delta H^{\circ}}{RT^2}$$

where ΔH° = standard enthalpy change of reaction.

1. What does Dalton's law of partial pressures state about gases?

- (A) The total pressure of a gas mixture is the sum of the individual gases' partial pressures.
- (B) The total volume of a nonreactive gas mixture is the sum of the individual gases' volumes.
- (C) Each gas of a mixture has the same partial pressure as that of the mixture.
- (D) The gas pressure of a mixture is the weighted average of the individual gas pressures.

7. How many phases may exist in equilibrium for a fixed proportion water-alcohol mixture held at constant pressure?

- (A) 0
- (B) 1 (C) 2
- (D) $\frac{2}{3}$

STEAM TABLES Saturated Water - Temperature Table												
Temn	Sat.	Specific V	olume	Internal Energy Enthalpy k.I/kg k.I/kg			Entropy k I/(ka:K					
°C	Press.	III / K	g		KJ/Kg			KJ/Kg)	
T T	kPa	Sat	Sat.	Sat.		Sat.	Sat.		Sat.	Sat.)	Sat.
1	p_{sat}	liquid	vapor	liquid	Evap.	vapor	liquid	Evap.	vapor	liquid	Evap.	vapor
		v_f	v_g	u_f	u_{fg}	\tilde{u}_{g}	\hat{h}_{f}	h_{fg}	\hat{h}_{g}	S_f	S_{fg}	s_g
0.01	0.6113	0.001 000	206.14	0.00	2375.3	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	9.1562
5 10	0.8721	0.001 000	147.12 106.38	20.97 42.00	2361.3 2347.2	2382.3 2389.2	20.98 42.01	2489.6 2477 7	2510.6 2519.8	0.0761	8.9496 8 7498	9.0257 8.9008
10	1.7051	0.001 000	77.93	62.99	2347.2	2396.1	62.99	2465.9	2528.9	0.1310	8.5569	8.7814
20	2.339	0.001 002	57.79	83.95	2319.0	2402.9	83.96	2454.1	2538.1	0.2966	8.3706	8.6672
25 30	3.169	0.001 003	43.36	104.88 125.78	2304.9 2290.8	2409.8 2416.6	104.89 125.79	2442.3 2430.5	2547.2 2556 3	0.3674	8.1905 8.0164	8.5580 8.4533
35	5.628	0.001 004	25.22	125.78	2230.8	2410.0	146.68	2430.5	2565.3	0.4309	7.8478	8.3531
40	7.384	0.001 008	19.52	167.56	2262.6	2430.1	167.57	2406.7	2574.3	0.5725	7.6845	8.2570
45 50	9.593	0.001 010	15.26	188.44	2248.4	2436.8	188.45	2394.8	2583.2	0.6387	7.5261	8.1648
50 55	12.349	0.001 012	9.568	209.32	2234.2	2443.5 2450.1	209.33	2382.7	2592.1	0.7679	7.2234	8.0763 7.9913
60	19.940	0.001 017	7.671	251.11	2205.5	2456.6	251.13	2358.5	2609.6	0.8312	7.0784	7.9096
65	25.03	0.001 020	6.197	272.02	2191.1	2463.1	272.06	2346.2	2618.3	0.8935	6.9375	7.8310
70 75	31.19 38.58	0.001 023	5.042 4.131	292.95 313.90	2176.6 2162.0	2569.6 2475.9	292.98 313.93	2333.8 2321.4	2626.8 2635.3	0.9549 1.0155	6.8004 6.6669	7.7553 7.6824
80	47.39	0.001 020	3.407	334.86	2102.0	2482.2	334.91	2308.8	2643.7	1.0753	6.5369	7.6122
85	57.83	0.001 033	2.828	355.84	2132.6	2488.4	355.90	2296.0	2651.9	1.1343	6.4102	7.5445
90 95	70.14	0.001 036	2.361	376.85 307 88	2117.7	2494.5 2500.6	376.92 307.96	2283.2	2660.1 2668 1	1.1925	6.2866 6 1659	7.4791 7.4150
,5	MPa	0.001 040	1.702	571.00	2102.7	2500.0	571.50	2270.2	2000.1	1.2500	0.1057	7.4137
100	0.101 35	0.001 044	1.6729	418.94	2087.6	2506.5	419.04	2257.0	2676.1	1.3069	6.0480	7.3549
105	0.120 82	0.001 048	1.4194	440.02	2072.3	2512.4	440.15	2243.7	2683.8	1.3630	5.9328	7.2958
110	0.143 27	0.001 052	1.2102	461.14	2057.0	2518.1	461.30	2230.2	2691.5	1.4185	5.8202	7.2387
115 120	0.169.06	0.001 056	1.0366 0.8919	482.30 503.50	2041.4 2025.8	2523.7 2529.3	482.48 503.71	2216.5 2202.6	2699.0 2706.3	1.4734 1.5276	5.7100 5.6020	7.1833 7.1296
125	0.2321	0.001 065	0.7706	524.74	2009.9	2534.6	524.99	2188.5	2713.5	1.5813	5.4962	7.0775
130	0.2701	0.001 070	0.6685	546.02	1993.9	2539.9	546.31	2174.2	2720.5	1.6344	5.3925	7.0269
135 140	0.3130	0.001 075	0.5822	567.35 588.74	1977.7	2545.0 2550.0	567.69 589.13	2159.6	2727.3	1.6870	5.2907 5.1908	6.9777 6.9299
145	0.4154	0.001 085	0.4463	610.18	1944.7	2554.9	610.63	2129.6	2740.3	1.7907	5.0926	6.8833
150	0.4758	0.001 091	0.3928	631.68	1927.9	2559.5	632.20	2114.3	2746.5	1.8418	4.9960	6.8379
155	0.5431	0.001 096	0.3468	653.24 674.87	1910.8	2564.1	653.84 675.55	2098.6	2752.4	1.8925	4.9010	6.7935
165	0.7005	0.001 102	0.2727	696.56	1876.0	2572.5	697.34	2062.0	2763.5	1.9925	4.7153	6.7078
170	0.7917	0.001 114	0.2428	718.33	1858.1	2576.5	719.21	2049.5	2768.7	2.0419	4.6244	6.6663
175	0.8920	0.001 121	0.2168	740.17	1840.0	2580.2	741.17	2032.4	2773.6	2.0909	4.5347	6.6256 6.5857
185	1.1227	0.001 127	0.174 09	784.10	1802.9	2587.0	785.37	1997.1	2782.4	2.1370	4.3586	6.5465
190	1.2544	0.001 141	0.156 54	806.19	1783.8	2590.0	807.62	1978.8	2786.4	2.2359	4.2720	6.5079
195 200	1.3978	0.001 149	0.141 05	828.37 850.65	1764.4	2592.8 2595 3	829.98 852.45	1960.0 1940.7	2790.0 2793.2	2.2835	4.1863 4.1014	6.4698
200	1.7230	0.001 164	0.115 21	873.04	1724.5	2597.5	875.04	1921.0	2796.0	2.3780	4.0172	6.3952
210	1.9062	0.001 173	0.104 41	895.53	1703.9	2599.5	897.76	1900.7	2798.5	2.4248	3.9337	6.3585
215	2.104	0.001 181	0.094 79	918.14 940 87	1682.9	2601.1	920.62 943.62	1879.9 1858 5	2800.5	2.4714	3.8507 3.7683	6.3221 6 2861
225	2.548	0.001 199	0.078 49	963.73	1639.6	2603.3	966.78	1836.5	2802.1	2.5639	3.6863	6.2503
230	2.795	0.001 209	0.071 58	986.74	1617.2	2603.9	990.12	1813.8	2804.0	2.6099	3.6047	6.2146
235 240	3.060	0.001 219	0.065 37	1009.89	1594.2	2604.1	1013.62	1790.5	2804.2	2.6558	3.5233	6.1791
240 245	3.648	0.001 229	0.059 70	1055.21 1056.71	1570.8 1546.7	2603.4	1057.52 1061.23	1700.5 1741.7	2803.8 2803.0	2.7013	3.3612	6.1083
250	3.973	0.001 251	0.050 13	1080.39	1522.0	2602.4	1085.36	1716.2	2801.5	2.7927	3.2802	6.0730
255	4.319	0.001 263	0.045 98	1104.28	1596.7	2600.9	1109.73	1689.8	2799.5	2.8383	3.1992	6.0375
265	5.081	0.001 270	0.038 77	1128.39	1470.0	2596.6	1159.28	1634.4	2790.9	2.8838	3.0368	5.9662
270	5.499	0.001 302	0.035 64	1177.36	1416.3	2593.7	1184.51	1605.2	2789.7	2.9751	2.9551	5.9301
275	5.942	0.001 317	0.032 79	1202.25	1387.9	2590.2	1210.07	1574.9	2785.0	3.0208	2.8730	5.8938
280	6.909	0.001 332	0.030 17	1227.40	1338.7	2580.1	1255.99	1545.0	2773.3	3.1130	2.7903	5.8199
290	7.436	0.001 366	0.025 57	1278.92	1297.1	2576.0	1289.07	1477.1	2766.2	3.1594	2.6227	5.7821
295	7.993	0.001 384	0.023 54	1305.2	1264.7	2569.9	1316.3	1441.8	2758.1	3.2062	2.5375	5.7437
300 305	8.581 9.202	0.001 404	0.021 67	1359.3	1231.0	2563.0 2555.2	1344.0	1404.9	2749.0	5.2534 3,3010	2.4511	5.7045 5.6643
310	9.856	0.001 447	0.018350	1387.1	1159.4	2546.4	1401.3	1326.0	2727.3	3.3493	2.2737	5.6230
315	10.547	0.001 472	0.016867	1415.5	1121.1	2536.6	1431.0	1283.5	2714.5	3.3982	2.1821	5.5804
320 330	11.274 12.845	0.001 499	0.015488	1444.6 1505 3	1080.9 993 7	2525.5 2498 9	1461.5 1525 3	1238.6 1140.6	2700.1 2665.9	3.5507	2.0882 1.8909	5.5362 5.4417
340	14.586	0.001 638	0.010797	1570.3	894.3	2464.6	1594.2	1027.9	2622.0	3.6594	1.6763	5.3357
350	16.513	0.001 740	0.008813	1641.9	776.6	2418.4	1670.6	893.4	2563.9	3.7777	1.4335	5.2112
360 370	18.651 21.03	0.001 893	0.006945	1725.2 1844.0	626.3 384 5	2351.5 2228 5	1760.5 1890.5	720.3 441.6	2481.0 2332.1	3.9147 4,1106	1.1379 0.6865	5.0526 4,7971
374.14	22.09	0.003 155	0.003155	2029.6	0	2029.6	2099.3	0	2099.3	4.4298	0	4.4298

Superheated Water Tables									
T	v	и	h	S	v	и	h	S	
Temp.	m³/kg	kJ/kg	kJ/kg	kJ/(kg·K)	m³/kg	kJ/kg	kJ/kg	kJ/(kg·K)	
•C		$p = 0.01 \mathrm{MI}$	Pa (45.81°C)			$p = 0.05 \text{ MPa} (81.33^{\circ}\text{C})$			
Sat.	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939	
50	14.869	2443.9	2592.6	8.1749 8.4479	3.418	2511.6	2682.5	7.6947	
150	19.512	2587.9	2783.0	8.6882	3.889	2585.6	2780.1	7.9401	
200	21.825	2661.3	2879.5	8.9038	4.356	2659.9	2877.7	8.1580	
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556	
400	20.445	2812.1	3279.6	9.2813	5.284 6.209	2811.5	3278.9	8.3373 8.8642	
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546	
600	40.295	3302.5	3705.4	10.1608	8.057	3302.2	3705.1	9.4178	
700	44.911	3479.6	3928.7	10.4028	8.981	3479.4	3928.5	9.6599	
800	49.526	3663.8	4159.0	10.6281	9.904	3663.6	4158.9	9.8852	
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964	
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4859	
1200	67.987	4467.9	5147.8	11.4091	13.597	4467.8	5147.7	10.6662	
1300	72.602	4683.7	5409.7	11.5811	14.521	4683.6	5409.6	10.8382	
<u> </u>	1 (040	p = 0.10 M	Pa (99.63°C)	7.2504	0.0057	p = 0.20 MP	a (120.23°C)	7 1070	
Sat.	1.6940	2506.1	2675.5	7.3594 7.3614	0.8857	2529.5	2706.7	7.1272	
150	1.9364	2582.8	2776.4	7.6134	0.9596	2576.9	2768.8	7.2795	
200	2.172	2658.1	2875.3	7.8343	1.0803	2654.4	2870.5	7.5066	
250	2.406	2733.7	2974.3	8.0333	1.1988	2731.2	2971.0	7.7086	
300	2.639	2810.4	3074.3	8.2158	1.3162	2808.6	3071.8	7.8926	
500	3 565	3131.6	3488.1	8.8342	1.3493	3130.8	3487.1	8 5133	
600	4.028	3301.9	3704.4	9.0976	2.013	3301.4	3704.0	8.7770	
700	4.490	3479.2	3928.2	9.3398	2.244	3478.8	3927.6	9.0194	
800	4.952	3663.5	4158.6	9.5652	2.475	3663.1	4158.2	9.2449	
900	5.414	3854.8	4396.1	9.7767	2.705	3854.5	4395.8	9.4566	
1100	6 3 3 7	4052.8	4040.3	10 1659	2.957	4032.3	4890 7	9.0303	
1200	6.799	4467.7	5147.6	10.3463	3.399	4467.5	5147.5	10.0262	
1300	7.260	4683.5	5409.5	10.5183	3.630	4683.2	5409.3	10.1982	
		p = 0.40 MF	Pa (143.63°C)			p = 0.60 MP	a (158.85°C)		
Sat.	0.4625	2553.6	2738.6	6.8959	0.3157	2567.4	2756.8	6.7600	
200	0.4708	2564.5	2752.8	6.9299 7.1706	0.3520	2638.9	2850.1	6.9665	
250	0.5951	2726.1	2964.2	7.3789	0.3938	2720.9	2957.2	7.1816	
300	0.6548	2804.8	3066.8	7.5662	0.4344	2801.0	3061.6	7.3724	
350	0.7137	2884.6	3170.1	7.7324	0.4742	2881.2	3165.7	7.5464	
400	0.7726	2964.4	32/3.4	/.8985	0.5137	2962.1	3270.3	7.7079	
600	1.0055	3300.2	3702.4	8.4558	0.6697	3299.1	3700.9	8.2674	
700	1.1215	3477.9	3926.5	8.6987	0.7472	3477.0	3925.3	8.5107	
800	1.2372	3662.4	4157.3	8.9244	0.8245	3661.8	4156.5	8.7367	
900	1.3529	3853.9	4395.1	9.1362	0.9017	3853.4	4394.4	8.9486	
1100	1.4085	4052.0	4039.4	9.5300	1.0559	4051.5	4038.8	9.1485	
1200	1.6996	4467.0	5146.8	9.7060	1.1330	4466.5	5146.3	9.5185	
1300	1.8151	4682.8	5408.8	9.8780	1.2101	4682.3	5408.3	9.6906	
		p = 0.80 MF	Pa (170.43°C)	-		p = 1.00 MP	a (179.91°C)		
Sat.	0.2404	2576.8	2769.1	6.6628	0.194 44	2583.6	2778.1	6.5865	
200	0.2608	2630.6	2839.3	6.8158	0.2060	2621.9	2827.9	6.6940	
300	0.3241	2713.3	3056.5	7.2328	0.2579	2793.2	3051.2	7.1229	
350	0.3544	2878.2	3161.7	7.4089	0.2825	2875.2	3157.7	7.3011	
400	0.3843	2959.7	3267.1	7.5716	0.3066	2957.3	3263.9	7.4651	
500	0.4433	3126.0	3480.6	7.8673	0.3541	3124.4	3478.5	7.7622	
600 700	0.5018	3297.9 3476.2	3699.4 3024 2	8.1333	0.4011	3296.8	3697.9	8.0290 8.2731	
800	0.6181	3661.1	4155.6	8.6033	0.4943	3660.4	4154.7	8.4996	
900	0.6761	3852.8	4393.7	8.8153	0.5407	3852.2	4392.9	8.7118	
1000	0.7340	4051.0	4638.2	9.0153	0.5871	4050.5	4637.6	8.9119	
1100	0.7919	4255.6	4889.1	9.2050	0.6335	4255.1	4888.6	9.1017	
1200	0.8497	4400.1 4681.8	5145.9 5407 9	9.3833 9 5575	0.0798	4403.0 4681 3	5145.4 5407 4	9.2822 9.4543	
1.000	0.2070	1001.0		,	0.7201	1 1001.0		7.4545	

P-h Diagram for Refrigerant HFC-134a





S2IMANYGOMABHT 29

Data provided by DuPont Refrigerants, a division of E.I. duPont de Nemours and Co., Inc.

Thermal and Physical Property Tables

(at room temperature)

GASES										
Substance	Mol wt		c _p		<i>c</i> _v	L	R			
Substance		kJ/(kg·K)	Btu/(lbm-°R)	kJ/(kg·K)	Btu/(lbm-°R)		kJ/(kg·K)			
Gases										
Air	29	1.00	0.240	0.718	0.171	1.40	0.2870			
Argon	40	0.520	0.125	0.312	0.0756	1.67	0.2081			
Butane	58	1.72	0.415	1.57	0.381	1.09	0.1430			
Carbon dioxide	44	0.846	0.203	0.657	0.158	1.29	0.1889			
Carbon monoxide	28	1.04	0.249	0.744	0.178	1.40	0.2968			
Ethane	30	1.77	0.427	1.49	0.361	1.18	0.2765			
Helium	4	5.19	1.25	3.12	0.753	1.67	2.0769			
Hydrogen	2	14.3	3.43	10.2	2.44	1.40	4.1240			
Methane	16	2.25	0.532	1.74	0.403	1.30	0.5182			
Neon	20	1.03	0.246	0.618	0.148	1.67	0.4119			
Nitrogen	28	1.04	0.248	0.743	0.177	1.40	0.2968			
Octane vapor	114	1.71	0.409	1.64	0.392	1.04	0.0729			
Oxygen	32	0.918	0.219	0.658	0.157	1.40	0.2598			
Propane	44	1.68	0.407	1.49	0.362	1.12	0.1885			
Steam	18	1.87	0.445	1.41	0.335	1.33	0.4615			

SELECTED LIQUIDS AND SOLIDS									
		С _р	Density						
Substance	kJ/(kg·K)	Btu/(lbm-°R)	kg/m ³	lbm/ft ³					
Liquids		-							
Ammonia	4.80	1.146	602	38					
Mercury	0.139	0.033	13,560	847					
Water	4.18	1.000	997	62.4					
Solids									
Aluminum	0.900	0.215	2,700	170					
Copper	0.386	0.092	8,900	555					
Ice (0°C; 32°F)	2.11	0.502	917	57.2					
Iron	0.450	0.107	7,840	490					
Lead	0.128	0.030	11,310	705					



de Nevers, Noel, Physical and Chemical Equilibrium for Chemical Engineers, 2nd ed., Wiley, p. 308, © 2012.



REFRIGERATION AND HVAC

Air Refrigeration Cycle

Cycles

Refrigeration and HVAC Two-Stage Cycle



The following equations are valid if the mass flows are the same in each stage.

$$COP_{ref} = \frac{Q_{n}}{WO_{nl} + WO_{n2}} = \frac{h_5 - h_8}{h_2 - h_1 + h_6 - h_5}$$
$$COP_{HP} = \frac{Q_{out}}{WO_{nl} + WO_{n2}} = \frac{h_2 - h_3}{h_2 - h_1 + h_6 - h_5}$$



ASHRAE Psychrometric Chart No. 1

(metric units) © 2013 ASHRAE Psychrometric Chart No. 1



ASHRAE Psychrometric Chart No. 1

