

# THERMODYNAMICS

## 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<sup>2</sup> or Pa)

Absolute Temperature,  $T$  (°R or K)

Volume,  $V$  (ft<sup>3</sup> or m<sup>3</sup>)

Specific Volume,  $v = V/m$  (ft<sup>3</sup>/lbm or m<sup>3</sup>/kg)

Internal Energy,  $U$  (Btu or kJ)

Specific Internal Energy,  $u = U/m$  (usually in Btu/lbm or kJ/kg)

Enthalpy,  $H$  (Btu or kJ)

Specific Enthalpy,  $h = u + Pv = H/m$  (usually in 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,  $g = h - Ts$  (usually in Btu/lbm or kJ/kg)

Helmholz Free Energy,  $a = u - Ts$  (usually in Btu/lbm or kJ/kg)

Heat Capacity at Constant Pressure,  $c_p = \left(\frac{\partial h}{\partial T}\right)_p$

Heat Capacity at Constant Volume,  $c_v = \left(\frac{\partial u}{\partial T}\right)_v$

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

$$x = m_g / (m_g + m_f), \text{ where}$$

$m_g$  = mass of vapor, and

$m_f$  = mass of liquid.

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

$$v = xv_g + (1-x)v_f \text{ or } v = v_f + xv_{fg}, \text{ where}$$

$v_f$  = specific volume of saturated liquid,

$v_g$  = specific volume of saturated vapor, and

$v_{fg}$  = specific volume change upon vaporization.  
 $= v_g - v_f$

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

$$u = xu_g + (1-x)u_f \text{ or } u = u_f + xu_{fg}$$

$$h = xh_g + (1-x)h_f \text{ or } h = h_f + xh_{fg}$$

$$s = xs_g + (1-x)s_f \text{ or } s = s_f + xs_{fg}$$

For a simple substance, specification of any two intensive, independent properties is sufficient to fix all the rest.

For an ideal gas,  $Pv = RT$  or  $PV = mRT$ , and

$$P_1v_1/T_1 = P_2v_2/T_2, \text{ where}$$

$P$  = pressure,

$v$  = specific volume,

$m$  = mass of gas,

$R$  = gas constant, and

$T$  = absolute temperature.

$V$  = volume

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

$$R = \frac{\bar{R}}{(\text{mol. wt})}, \text{ where}$$

$\bar{R}$  = the universal gas constant

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

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

Also, for *ideal gases*:

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

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

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

$$\Delta s = c_p \ln (T_2/T_1) - R \ln (P_2/P_1); \text{ and}$$

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

For heat capacities that are temperature dependent, the value to be used in the above equations for  $\Delta h$  is known as the mean heat capacity ( $\bar{c}_p$ ) and is given by

$$\bar{c}_p = \frac{\int_{T_1}^{T_2} c_p dT}{T_2 - T_1}$$

Also, for *constant entropy* processes:

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k; \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

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

For real gases, several equations of state are available; one such equation is the van der Waals equation with constants based on the critical point:

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

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

where  $P_c$  and  $T_c$  are the pressure and temperature at the critical point, respectively, and  $\bar{v}$  is the molar specific volume.

## 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  $Q$  is energy transferred due to temperature difference and is considered positive if it is inward or added to the system.

### Closed Thermodynamic System

No mass crosses system boundary

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

where

$\Delta KE$  = change in kinetic energy, and

$\Delta PE$  = change in potential energy.

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.)

Work  $W$  ( $w = \frac{W}{m}$ ) is considered positive if it is outward or work done by the system.

Reversible boundary work is given by  $w_b = \int P \, dv$ .

### Special Cases of Closed Systems

Constant Pressure (**Charles' Law**):

$$w_b = P\Delta v$$

(ideal gas)  $T/v = \text{constant}$

Constant Volume:

$$w_b = 0$$

(ideal gas)  $T/P = \text{constant}$

Isentropic (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 (**Boyle's Law**):

(ideal gas)  $Pv = \text{constant}$

$$w_b = RT \ln(v_2/v_1) = RT \ln(P_1/P_2)$$

Polytropic (ideal gas):

$$Pv^n = \text{constant}$$
$$w = (P_2 v_2 - P_1 v_1)/(1 - n)$$

### 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:

$$w_{rev} = - \int v \, dP + \Delta ke + \Delta pe$$

First Law applies whether or not processes are reversible.

**FIRST LAW** (energy balance)

$$\sum \dot{m}_i \left[ h_i + V_i^2/2 + gZ_i \right] - \sum \dot{m}_e \left[ h_e + V_e^2/2 + gZ_e \right] + \dot{Q}_{in} - \dot{W}_{net} = d(m_s u_s)/dt, \text{ where}$$

$\dot{W}_{net}$  = rate of net or shaft work transfer,

$m_s$  = mass of fluid within the system,

$u_s$  = specific internal energy of system, and

$\dot{Q}$  = rate of heat transfer (neglecting kinetic and potential energy of the system).

### Special Cases of Open Systems

Constant Volume:

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

Constant Pressure:

$$w_{rev} = 0$$

Constant Temperature:

(ideal gas)  $Pv = \text{constant}$

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

Isentropic (ideal gas):

$$Pv^k = \text{constant}$$
$$w_{rev} = k(P_2 v_2 - P_1 v_1)/(1 - k)$$
$$= kR(T_2 - T_1)/(1 - k)$$

$$w_{rev} = \frac{k}{k-1} RT_1 \left[ 1 - \left( \frac{P_2}{P_1} \right)^{(k-1)/k} \right]$$

Polytropic:

$$Pv^n = \text{constant}$$
$$w_{rev} = n(P_2 v_2 - P_1 v_1)/(1 - n)$$

### Steady-State 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.

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

and

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

where

$\dot{m}$  = mass flow rate (subscripts  $i$  and  $e$  refer to inlet and exit states of system),

$g$  = acceleration of gravity,

$Z$  = elevation,

$V$  = velocity, and

$\dot{W}$  = 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.

$$h_i + V_i^2/2 = h_e + V_e^2/2$$

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

$h_{es}$  = 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.

$$h_i = h_e + w$$

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

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

**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 single-mass stream, the following applies:

$$h_i + q = h_e$$

**Heat Exchangers:** No heat or work. Two separate flow rates  $\dot{m}_1$  and  $\dot{m}_2$ :

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

See **MECHANICAL ENGINEERING** section.

**Mixers, Separators, Open or Closed Feedwater Heaters:**

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

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

## 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  $T_L$ . The efficiency  $\eta$  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:

$$\eta_c = (T_H - T_L)/T_H \quad \text{where}$$

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

The following heat-engine cycles are plotted on  $P$ - $v$  and  $T$ - $s$  diagrams (see later in this chapter):

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:

$$\text{COP} = Q_H/W \quad \text{for heat pumps, and as}$$

$$\text{COP} = Q_L/W \quad \text{for refrigerators and air conditioners.}$$

Upper limit of COP is based on reversed Carnot Cycle:

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

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

$$1 \text{ ton refrigeration} = 12,000 \text{ Btu/hr} = 3,516 \text{ W}$$

## IDEAL GAS MIXTURES

$i = 1, 2, \dots, n$  constituents. Each constituent is an ideal gas.

**Mole Fraction:**

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

where  $N_i$  = number of moles of component  $i$ .

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

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

**Gas Constant:**  $R = \bar{R}/M$

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

$$y_i = \frac{x_i M_i}{\Sigma (x_i M_i)}$$

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

$$x_i = \frac{y_i/M_i}{\Sigma (y_i/M_i)}$$

**Partial Pressures:**  $P = \Sigma P_i$ ;  $P_i = \frac{m_i R_i T}{V}$

**Partial Volumes:**  $V = \Sigma V_i$ ;  $V_i = \frac{m_i R_i T}{P}$ , where

$P$ ,  $V$ ,  $T$  = the pressure, volume, and temperature of the mixture.

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

**Other Properties:**

$$u = \Sigma (y_i u_i); \quad h = \Sigma (y_i h_i); \quad s = \Sigma (y_i s_i)$$

$u_i$  and  $h_i$  are evaluated at  $T$ , and

$s_i$  is evaluated at  $T$  and  $P_i$ .

## PSYCHROMETRICS

We deal here with a mixture of dry air (subscript  $a$ ) and water vapor (subscript  $v$ ):

$$P = P_a + P_v$$

**Specific Humidity** (absolute humidity, humidity ratio)  $\omega$ :

$$\omega = m_v/m_a \quad \text{where}$$

$m_v$  = mass of water vapor and

$m_a$  = mass of dry air.

$$\omega = 0.622 P_v / P_a = 0.622 P_v / (P - P_v)$$

**Relative Humidity** (rh)  $\phi$ :

$$\phi = P_v / P_g \quad \text{where}$$

$P_g$  = saturation pressure at  $T$ .

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

**Dew-Point Temperature**  $T_{dp}$ :

$$T_{dp} = T_{sat} \text{ at } P_g = P_v$$

*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.

### Psychrometric Chart

A plot of specific humidity as a function of dry-bulb temperature plotted for a value of atmospheric pressure. (See chart at end of section.)

## PHASE RELATIONS

*Clapeyron Equation* for Phase Transitions:

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

$h_{fg}$  = enthalpy change for phase transitions,

$v_{fg}$  = volume change,

$s_{fg}$  = entropy change,

$T$  = absolute temperature, and

$(dP/dT)_{sat}$  = 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 ( $v_g$ ), (2) the latter can be replaced with  $P/RT$  from the ideal gas law, and (3)  $h_{fg}$  is independent of the temperature ( $T$ ).

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

### Gibbs Phase Rule (non-reacting systems)

$P + F = C + 2$ , where

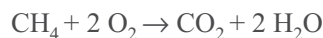
$P$  = number of phases making up a system

$F$  = degrees of freedom, and

$C$  = number of components in a system

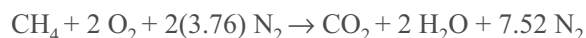
## COMBUSTION PROCESSES

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



### Combustion in Air

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



### 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).

$$\text{Air-Fuel Ratio (A/F): } A/F = \frac{\text{mass of air}}{\text{mass of fuel}}$$

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

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

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

## SECOND LAW OF THERMODYNAMICS

Thermal Energy Reservoirs

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

$Q$  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.

## VAPOR-LIQUID MIXTURES

### 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.,  $x \approx 0$ .

$$P_i = P y_i = h x_i, \text{ where}$$

$h$  = 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, and

$P$  = total pressure.

### Raoult's Law for Vapor-Liquid Equilibrium

Valid for concentrations near 1; i.e.,  $x_i \approx 1$ .

$$P_i = x_i P_i^*, \text{ where}$$

$P_i$  = partial pressure of component  $i$ ,

$x_i$  = mol fraction of component  $i$  in the liquid, and

$P_i^*$  = vapor pressure of pure component  $i$  at the temperature of the mixture.

## ENTROPY

$$ds = (1/T) \delta Q_{\text{rev}}$$

$$s_2 - s_1 = \int_1^2 (1/T) \delta Q_{\text{rev}}$$

### Inequality of Clausius

$$\oint (1/T) \delta Q_{\text{rev}} \leq 0$$

$$\int_1^2 (1/T) \delta Q \leq s_2 - s_1$$

### Isothermal, Reversible Process

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

### Isentropic Process

$$\Delta s = 0; ds = 0$$

A reversible adiabatic process is isentropic.

### Adiabatic Process

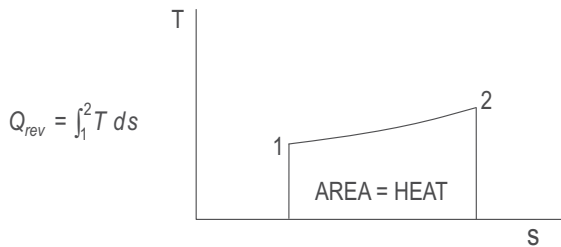
$$\delta Q = 0; \Delta s \geq 0$$

### Increase of Entropy Principle

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

$$\Delta \dot{s}_{\text{total}} = \sum \dot{m}_{\text{out}} s_{\text{out}} - \sum \dot{m}_{\text{in}} s_{\text{in}} - \sum (\dot{Q}_{\text{external}}/T_{\text{external}}) \geq 0$$

### Temperature-Entropy (T-s) Diagram



### 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.

### Irreversibility

$$I = w_{\text{rev}} - w_{\text{actual}}$$

## EXERGY

Exergy is the portion of total energy available to do work.

### Closed-System Exergy (Availability)

(no chemical reactions)

$$\phi = (u - u_o) - T_o (s - s_o) + p_o (v - v_o)$$

where the subscript o designates environmental conditions

$$w_{\text{reversible}} = \phi_1 - \phi_2$$

### Open-System Exergy (Availability)

$$\psi = (h - h_o) - T_o (s - s_o) + V^2/2 + gz$$

$$w_{\text{reversible}} = \psi_1 - \psi_2$$

### Gibbs Free Energy, $\Delta G$

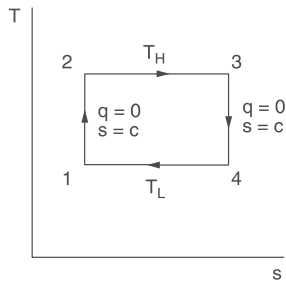
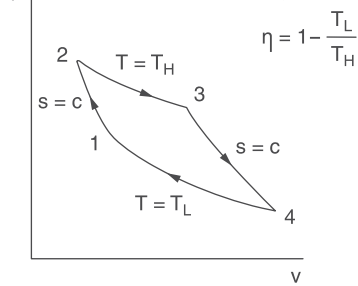
Energy released or absorbed in a reaction occurring reversibly at constant pressure and temperature.

### Helmholtz Free Energy, $\Delta A$

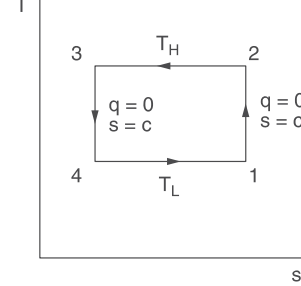
Energy released or absorbed in a reaction occurring reversibly at constant volume and temperature.

## COMMON THERMODYNAMIC CYCLES

### Carnot Cycle



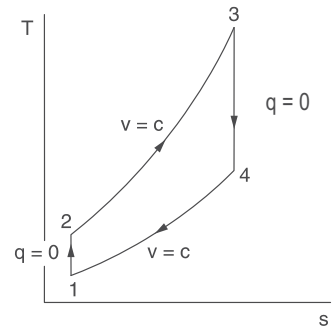
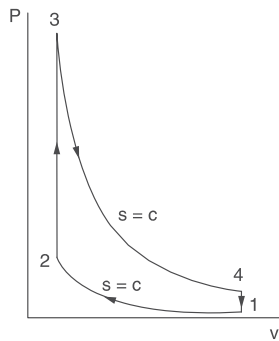
### Reversed Carnot



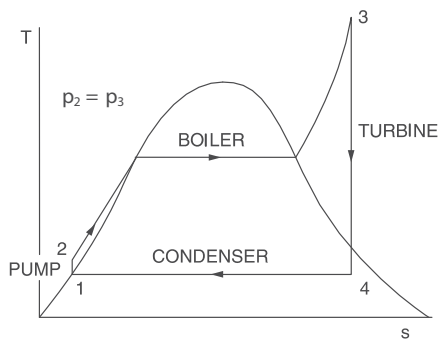
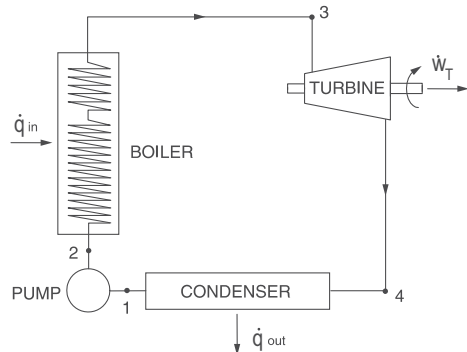
### Otto Cycle (Gasoline Engine)

$$\eta = 1 - r^{1-k}$$

$$r = v_1/v_2$$

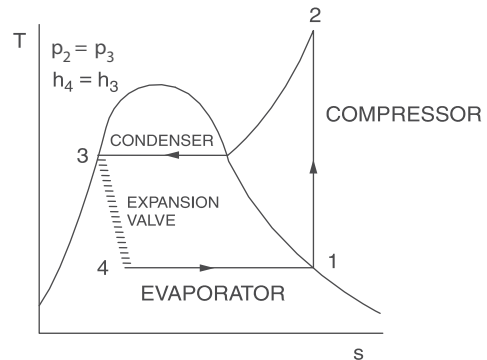
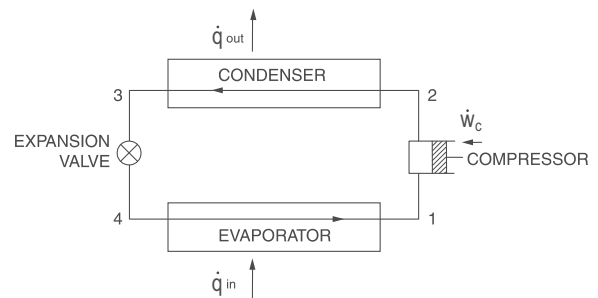


### Rankine Cycle



$$\eta = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

### Refrigeration (Reversed Rankine Cycle)



$$\text{COP}_{\text{ref}} = \frac{h_1 - h_4}{h_2 - h_1}$$

$$\text{COP}_{\text{HP}} = \frac{h_2 - h_3}{h_2 - h_1}$$

<div>STEAM TABLES</div> <div>Saturated Water - Temperature Table</div>												
Temp. °C $T$	Sat. Press. kPa $P_{sat}$	Specific Volume m <sup>3</sup> /kg		Internal Energy kJ/kg			Enthalpy kJ/kg			Entropy kJ/(kg·K)		
		Sat. liquid $v_f$	Sat. vapor $v_g$	Sat. liquid $u_f$	Evap. $u_{fg}$	Sat. vapor $u_g$	Sat. liquid $h_f$	Evap. $h_{fg}$	Sat. vapor $h_g$	Sat. liquid $s_f$	Evap. $s_{fg}$	Sat. vapor $s_g$
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	0.8721	0.001 000	147.12	20.97	2361.3	2382.3	20.98	2489.6	2510.6	0.0761	8.9496	9.0257
10	1.2276	0.001 000	106.38	42.00	2347.2	2389.2	42.01	2477.7	2519.8	0.1510	8.7498	8.9008
15	1.7051	0.001 001	77.93	62.99	2333.1	2396.1	62.99	2465.9	2528.9	0.2245	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	3.169	0.001 003	43.36	104.88	2304.9	2409.8	104.89	2442.3	2547.2	0.3674	8.1905	8.5580
30	4.246	0.001 004	32.89	125.78	2290.8	2416.6	125.79	2430.5	2556.3	0.4369	8.0164	8.4533
35	5.628	0.001 006	25.22	146.67	2276.7	2423.4	146.68	2418.6	2565.3	0.5053	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	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	12.349	0.001 012	12.03	209.32	2234.2	2443.5	209.33	2382.7	2592.1	0.7038	7.3725	8.0763
55	15.758	0.001 015	9.568	230.21	2219.9	2450.1	230.23	2370.7	2600.9	0.7679	7.2234	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	31.19	0.001 023	5.042	292.95	2176.6	2469.6	292.98	2333.8	2626.8	0.9549	6.8004	7.7553
75	38.58	0.001 026	4.131	313.90	2162.0	2475.9	313.93	2321.4	2635.3	1.0155	6.6669	7.6824
80	47.39	0.001 029	3.407	334.86	2147.4	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	70.14	0.001 036	2.361	376.85	2117.7	2494.5	376.92	2283.2	2660.1	1.1925	6.2866	7.4791
95	84.55	0.001 040	1.982	397.88	2102.7	2500.6	397.96	2270.2	2668.1	1.2500	6.1659	7.4159
MPa												
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	0.169 06	0.001 056	1.0366	482.30	2041.4	2523.7	482.48	2216.5	2699.0	1.4734	5.7100	7.1833
120	0.198 53	0.001 060	0.8919	503.50	2025.8	2529.3	503.71	2202.6	2706.3	1.5276	5.6020	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	0.3130	0.001 075	0.5822	567.35	1977.7	2545.0	567.69	2159.6	2727.3	1.6870	5.2907	6.9777
140	0.3613	0.001 080	0.5089	588.74	1961.3	2550.0	589.13	2144.7	2733.9	1.7391	5.1908	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	1910.8	2564.1	653.84	2098.6	2752.4	1.8925	4.9010	6.7935
160	0.6178	0.001 102	0.3071	674.87	1893.5	2568.4	675.55	2082.6	2758.1	1.9427	4.8075	6.7502
165	0.7005	0.001 108	0.2727	696.56	1876.0	2572.5	697.34	2066.2	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
180	1.0021	0.001 127	0.194 05	762.09	1821.6	2583.7	763.22	2015.0	2778.2	2.1396	4.4461	6.5857
185	1.1227	0.001 134	0.174 09	784.10	1802.9	2587.0	785.37	1997.1	2782.4	2.1879	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	1.3978	0.001 149	0.141 05	828.37	1764.4	2592.8	829.98	1960.0	2790.0	2.2835	4.1863	6.4698
200	1.5538	0.001 157	0.127 36	850.65	1744.7	2595.3	852.45	1940.7	2793.2	2.3309	4.1014	6.4323
205	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	1682.9	2601.1	920.62	1879.9	2800.5	2.4714	3.8507	6.3221
220	2.318	0.001 190	0.086 19	940.87	1661.5	2602.4	943.62	1858.5	2802.1	2.5178	3.7683	6.2861
225	2.548	0.001 199	0.078 49	963.73	1639.6	2603.3	966.78	1836.5	2803.3	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	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	3.344	0.001 229	0.059 76	1033.21	1570.8	2604.0	1037.32	1766.5	2803.8	2.7015	3.4422	6.1437
245	3.648	0.001 240	0.054 71	1056.71	1546.7	2603.4	1061.23	1741.7	2803.0	2.7472	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
260	4.688	0.001 276	0.042 21	1128.39	1470.6	2599.0	1134.37	1662.5	2796.9	2.8838	3.1181	6.0019
265	5.081	0.001 289	0.038 77	1152.74	1443.9	2596.6	1159.28	1634.4	2793.6	2.9294	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	6.412	0.001 332	0.030 17	1227.46	1358.7	2586.1	1235.99	1543.6	2779.6	3.0668	2.7903	5.8571
285	6.909	0.001 348	0.027 77	1253.00	1328.4	2581.4	1262.31	1511.0	2773.3	3.1130	2.7070	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	8.581	0.001 404	0.021 67	1332.0	1231.0	2563.0	1344.0	1404.9	2749.0	3.2534	2.4511	5.7045
305	9.202	0.001 425	0.019 948	1359.3	1195.9	2555.2	1372.4	1366.4	2738.7	3.3010	2.3633	5.6643
310	9.856	0.001 447	0.018 350	1387.1	1159.4	2546.4	1401.3	1326.0	2727.3	3.3493	2.2737	5.6230
315	10.547	0.001 472	0.016 867	1415.5	1121.1	2536.6	1431.0	1283.5	2714.5	3.3982	2.1821	5.5804
320	11.274	0.001 499	0.015 488	1444.6	1080.9	2525.5	1461.5	1238.6	2700.1	3.4480	2.0882	5.5362
330	12.845	0.001 561	0.012 996	1505.3	993.7	2498.9	1525.3	1140.6	2665.9	3.5507	1.8909	5.4417
340	14.586	0.001 638	0.010 797	1570.3	894.3	2464.6	1594.2	1027.9	2622.0	3.6594	1.6763	5.3357
350	16.513	0.001 740	0.008 813	1641.9	776.6	2418.4	1670.6	893.4	2563.9	3.7777	1.4335	5.2112
360	18.651	0.001 893	0.006 945	1725.2	626.3	2351.5	1760.5	720.3	2481.0	3.9147	1.1379	5.0526
370	21.03	0.002 213	0.004 925	1844.0	384.5	2228.5	1890.5	441.6	2332.1	4.1106	0.6865	4.7971
374.14	22.09	0.003 155	0.003 155	2029.6	0	2029.6	2099.3	0	2099.3	4.4298	0	4.4298



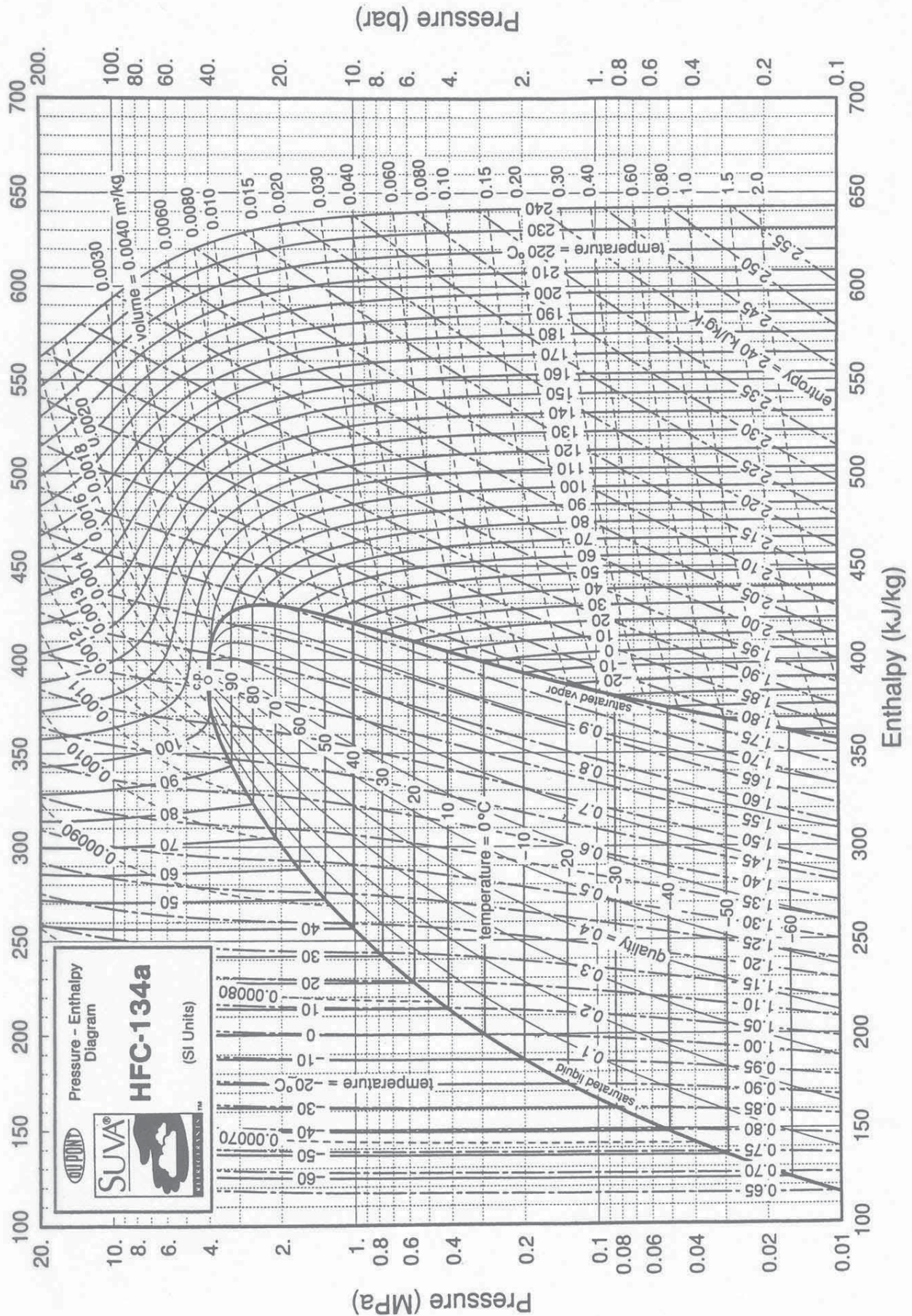
Superheated Water Tables								
$T$ Temp. °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/(kg·K)	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/(kg·K)
$p = 0.01 \text{ MPa (45.81°C)}$					$p = 0.05 \text{ MPa (81.33°C)}$			
Sat.	14.674	2437.9	2584.7	8.1502	3.240	2483.9	2645.9	7.5939
50	14.869	2443.9	2592.6	8.1749				
100	17.196	2515.5	2687.5	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
<b>200</b>	<b>21.825</b>	<b>2661.3</b>	<b>2879.5</b>	<b>8.9038</b>	<b>4.356</b>	<b>2659.9</b>	<b>2877.7</b>	<b>8.1580</b>
250	24.136	2736.0	2977.3	9.1002	4.820	2735.0	2976.0	8.3556
300	26.445	2812.1	3076.5	9.2813	5.284	2811.3	3075.5	8.5373
400	31.063	2968.9	3279.6	9.6077	6.209	2968.5	3278.9	8.8642
500	35.679	3132.3	3489.1	9.8978	7.134	3132.0	3488.7	9.1546
<b>600</b>	<b>40.295</b>	<b>3302.5</b>	<b>3705.4</b>	<b>10.1608</b>	<b>8.057</b>	<b>3302.2</b>	<b>3705.1</b>	<b>9.4178</b>
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
900	54.141	3855.0	4396.4	10.8396	10.828	3854.9	4396.3	10.0967
1000	58.757	4053.0	4640.6	11.0393	11.751	4052.9	4640.5	10.2964
<b>1100</b>	<b>63.372</b>	<b>4257.5</b>	<b>4891.2</b>	<b>11.2287</b>	<b>12.674</b>	<b>4257.4</b>	<b>4891.1</b>	<b>10.4859</b>
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
$p = 0.10 \text{ MPa (99.63°C)}$					$p = 0.20 \text{ MPa (120.23°C)}$			
Sat.	1.6940	2506.1	2675.5	7.3594	0.8857	2529.5	2706.7	7.1272
100	1.6958	2506.7	2676.2	7.3614				
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
<b>250</b>	<b>2.406</b>	<b>2733.7</b>	<b>2974.3</b>	<b>8.0333</b>	<b>1.1988</b>	<b>2731.2</b>	<b>2971.0</b>	<b>7.7086</b>
300	2.639	2810.4	3074.3	8.2158	1.3162	2808.6	3071.8	7.8926
400	3.103	2967.9	3278.2	8.5435	1.5493	2966.7	3276.6	8.2218
500	3.565	3131.6	3488.1	8.8342	1.7814	3130.8	3487.1	8.5133
600	4.028	3301.9	3704.4	9.0976	2.013	3301.4	3704.0	8.7770
<b>700</b>	<b>4.490</b>	<b>3479.2</b>	<b>3928.2</b>	<b>9.3398</b>	<b>2.244</b>	<b>3478.8</b>	<b>3927.6</b>	<b>9.0194</b>
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
1000	5.875	4052.8	4640.3	9.9764	2.937	4052.5	4640.0	9.6563
1100	6.337	4257.3	4891.0	10.1659	3.168	4257.0	4890.7	9.8458
<b>1200</b>	<b>6.799</b>	<b>4467.7</b>	<b>5147.6</b>	<b>10.3463</b>	<b>3.399</b>	<b>4467.5</b>	<b>5147.5</b>	<b>10.0262</b>
1300	7.260	4683.5	5409.5	10.5183	3.630	4683.2	5409.3	10.1982
$p = 0.40 \text{ MPa (143.63°C)}$					$p = 0.60 \text{ MPa (158.85°C)}$			
Sat.	0.4625	2553.6	2738.6	6.8959	0.3157	2567.4	2756.8	6.7600
150	0.4708	2564.5	2752.8	6.9299				
200	0.5342	2646.8	2860.5	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
<b>300</b>	<b>0.6548</b>	<b>2804.8</b>	<b>3066.8</b>	<b>7.5662</b>	<b>0.4344</b>	<b>2801.0</b>	<b>3061.6</b>	<b>7.3724</b>
350	0.7137	2884.6	3170.1	7.7324	0.4742	2881.2	3165.7	7.5464
400	0.7726	2964.4	3273.4	7.8985	0.5137	2962.1	3270.3	7.7079
500	0.8893	3129.2	3484.9	8.1913	0.5920	3127.6	3482.8	8.0021
600	1.0055	3300.2	3702.4	8.4558	0.6697	3299.1	3700.9	8.2674
<b>700</b>	<b>1.1215</b>	<b>3477.9</b>	<b>3926.5</b>	<b>8.6987</b>	<b>0.7472</b>	<b>3477.0</b>	<b>3925.3</b>	<b>8.5107</b>
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
1000	1.4685	4052.0	4639.4	9.3360	0.9788	4051.5	4638.8	9.1485
1100	1.5840	4256.5	4890.2	9.5256	1.0559	4256.1	4889.6	9.3381
<b>1200</b>	<b>1.6996</b>	<b>4467.0</b>	<b>5146.8</b>	<b>9.7060</b>	<b>1.1330</b>	<b>4466.5</b>	<b>5146.3</b>	<b>9.5185</b>
1300	1.8151	4682.8	5408.8	9.8780	1.2101	4682.3	5408.3	9.6906
$p = 0.80 \text{ MPa (170.43°C)}$					$p = 1.00 \text{ MPa (179.91°C)}$			
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
250	0.2931	2715.5	2950.0	7.0384	0.2327	2709.9	2942.6	6.9247
300	0.3241	2797.2	3056.5	7.2328	0.2579	2793.2	3051.2	7.1229
<b>350</b>	<b>0.3544</b>	<b>2878.2</b>	<b>3161.7</b>	<b>7.4089</b>	<b>0.2825</b>	<b>2875.2</b>	<b>3157.7</b>	<b>7.3011</b>
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	0.5018	3297.9	3699.4	8.1333	0.4011	3296.8	3697.9	8.0290
700	0.5601	3476.2	3924.2	8.3770	0.4478	3475.3	3923.1	8.2731
<b>800</b>	<b>0.6181</b>	<b>3661.1</b>	<b>4155.6</b>	<b>8.6033</b>	<b>0.4943</b>	<b>3660.4</b>	<b>4154.7</b>	<b>8.4996</b>
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	4466.1	5145.9	9.3855	0.6798	4465.6	5145.4	9.2822
<b>1300</b>	<b>0.9076</b>	<b>4681.8</b>	<b>5407.9</b>	<b>9.5575</b>	<b>0.7261</b>	<b>4681.3</b>	<b>5407.4</b>	<b>9.4543</b>



# P-h DIAGRAM FOR REFRIGERANT HFC-134a

(metric units)

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# ASHRAE PSYCHROMETRIC CHART NO. 1

(metric units)

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## ASHRAE PSYCHROMETRIC CHART NO. 1

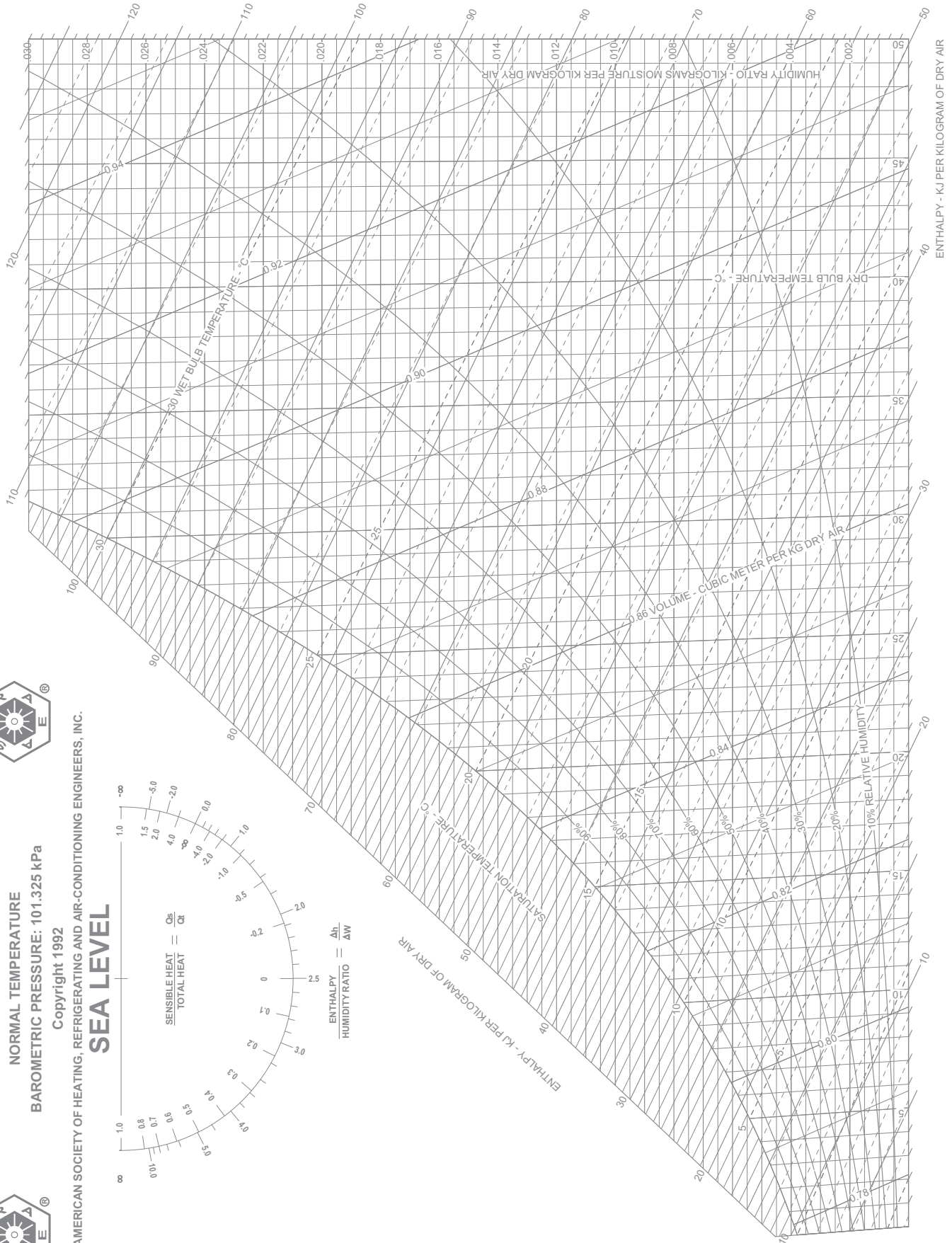
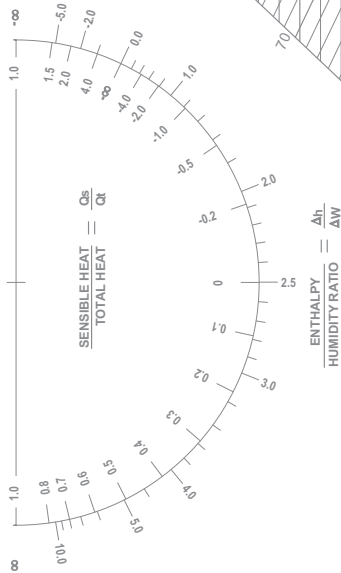
NORMAL TEMPERATURE

BAROMETRIC PRESSURE: 101.325 kPa

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AMERICAN SOCIETY OF HEATING, REFRIGERATING AND AIR-CONDITIONING ENGINEERS, INC.

SEA LEVEL



**THERMAL AND PHYSICAL PROPERTY TABLES**  
(at room temperature)

GASES							
Substance	Mol wt	$c_p$		$c_v$		$k$	R
		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				
Substance	$c_p$		Density	
	kJ/(kg·K)	Btu/(lbm·°R)	kg/m <sup>3</sup>	lbm/ft <sup>3</sup>
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