PROPERTIES OF SINGLE-COMPONENT SYSTEMS

Nomenclature
1. Intensive properties are independent of mass.
2. Extensive properties are proportional to mass.
3. Specific properties are lower case (extensive/mass).

State Functions (properties)
- Absolute Pressure, \( p \) (lbf/in\(^2\) or Pa)
- Absolute Temperature, \( T \) (\(^\circ\)R or K)
- Specific Volume, \( v \) (ft\(^3\)/lbm or m\(^3\)/kg)
- Internal Energy, \( u \) (usually in Btu/lbm or kJ/kg)
- Enthalpy, \( h = u + PV \) (same units as \( u \))
- Entropy, \( s \) [Btu/(lbmol-\(^\circ\)R) or kJ/(kgmol-K)]
- Gibbs Free Energy, \( g = h - TS \) (same units as \( u \))
- Helmholtz Free Energy, \( a = u - TS \) (same units as \( u \))

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:
\[ x = \frac{m_g}{m_g + m_l}, \]
where
\( m_g = \) mass of vapor, and \( m_l = \) mass of liquid.

Specific volume of a two-phase system can be written:
\[ v = xv_g + (1-x)v_f \]
\( v_f = \) specific volume of saturated liquid,
\( v_g = \) specific volume of saturated vapor, and
\( v_{fg} = \) specific volume change upon vaporization.

Similar expressions exist for \( u, h, \) and \( s \):
\[ u = xu_g + (1-x)u_f, \]
\[ h = xh_g + (1-x)h_f, \]
\[ s = xs_g + (1-x)s_f. \]

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
\[ P_1V_1/T_1 = P_2V_2/T_2, \]
where
\( p = \) pressure,
\( v = \) specific volume,
\( m = \) mass of gas,
\( R = \) gas constant, and
\( T = \) absolute temperature.

R is specific to each gas but can be found from
\[ R = \frac{\bar{R}}{(mol. wt.)}, \]
where
\[ \bar{R} = \text{the universal gas constant} = 1.545 \text{ ft-lbf/(lbmol-}^\circ\text{R)} = 8,314 \text{ J/(kmol-K)}. \]

For Ideal Gases, \( c_p - c_v = R \)

Also, for Ideal Gases:
\[ \left( \frac{\partial h}{\partial v} \right)_T = 0 \quad \text{and} \quad \left( \frac{\partial u}{\partial v} \right)_T = 0 \]

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

\[ \Delta u = c_u \Delta T; \]
\[ \Delta h = c_p \Delta T \]
\[ \Delta s = c_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right); \] and
\[ \Delta s = c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right). \]

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
\[ \bar{c}_p = \left[ \frac{\int_{T_1}^{T_2} \frac{c_p}{v} dT}{T_2 - T_1} \right] \]

Also, for constant entropy processes:
\[ P_1V_1^{(k-1)} = T_1V_1^{(k-1)} = T_2V_2^{(k-1)} \]

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 \( W \left( w = \frac{W}{m} \right) \) 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) \( T/v \) = constant

Constant Volume:
\[ w_b = 0 \]
(ideal gas) \( T/P \) = constant

Isentropic (ideal gas),
\[ P_v^{k_n} = \text{constant:} \]
\[ w = (P_2v_2 - P_1v_1)/(1 - k) = R \left( T_2 - T_1 \right)/(1 - k) \]

Constant Temperature (Boyle's Law):
\[ w_b = RT \ln \left( v_2/v_1 \right) = RT \ln \left( P_1/P_2 \right) \]

Polytropic (ideal gas),
\[ P_v^{n} = \text{constant:} \]
\[ w = (P_2v_2 - P_1v_1)/(1 - n) \]

Open Thermodynamic System

Mass to cross 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)
\[ \sum \dot{m} \left[ h_i + V_i^2/2 + gZ_i \right] - \sum \dot{m} \left[ h_e + V_e^2/2 + gZ_e \right] \]
\[ + \dot{Q}_{in} - \dot{W}_{net} = d \left( m_s u_s \right)/dt \]

Where
\[ \dot{W}_{net} = \text{rate of net or shaft work transfer,} \]
\[ m_s = \text{mass of fluid within the system,} \]
\[ u_s = \text{specific internal energy of system,} \]
\[ \dot{Q} = \text{rate of heat transfer (neglecting kinetic and potential energy).} \]

**Special Cases of Open Systems**

Constant Volume:
\[ w_{rev} = -v \left( P_2 - P_1 \right) \]

Constant Pressure:
\[ w_{rev} = 0 \]

Constant Temperature:
\[ w_{rev} = RT \ln \left( v_2/v_1 \right) = RT \ln \left( P_1/P_2 \right) \]

Isentropic (ideal gas):
\[ P_v^{k_n} = \text{constant:} \]
\[ w_{rev} = k \left( P_2v_2 - P_1v_1 \right)/(1 - k) = kR \left( T_2 - T_1 \right)/(1 - k) \]

Polytropic:
\[ P_v^{n} = \text{constant:} \]
\[ w_{rev} = n \left( P_2v_2 - P_1v_1 \right)/(1 - n) \]

**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.

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

\[ \sum \dot{m}_i = \sum \dot{m}_e \]

Where
\[ \dot{m} = \text{mass flow rate (subscripts i and e refer to inlet and exit states of system),} \]
\[ g = \text{acceleration of gravity,} \]
\[ Z = \text{elevation,} \]
\[ V = \text{velocity,} \]
\[ W = \text{rate of work.} \]

**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.
\[ h_i + V_i^2/2 = h_e + gZ_e + V_e^2/2 \]

Efficiency (nozzle) = \[ \frac{h_i - h_e}{2(h_i - h_{es})} \]

**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.
\[ h_i = h_e + w \]

Efficiency (turbine) = \[ \frac{h_i - h_e}{h_i - h_{es}} \]

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.
\[ h_i + q = h_e \]

**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 \( \dot{m}_2 \):
\[ \dot{m}_1 (h_{i1} - h_{i2}) = \dot{m}_2 (h_{e2} - h_{e1}) \]
**Mixers, Separators, Open or Closed Feedwater Heaters:**

\[ \sum m_e h_e = \sum m_i h_i \quad \text{and} \quad \sum m_i = \sum m_e \]

**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:

\[ \eta = \frac{W}{Q_H} = \frac{(Q_H - Q_L)}{Q_H} \]

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

\[ \eta_c = \frac{(T_H - T_L)}{T_H} \]

where \( T_H \) and \( T_L \) are absolute temperatures (Kelvin or Rankine).

The following heat-engine cycles are plotted on \( P-v \) and \( T-s \) diagrams (see page 61):

- 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:

- For heat pumps: \( \text{COP} = \frac{Q_H}{W} \)
- For refrigerators and air conditioners: \( \text{COP} = \frac{Q_L}{W} \)

Upper limit of COP is based on reversed Carnot Cycle:

\[ \text{COP}_c = \frac{1}{\left( \frac{T_H}{T_H - T_L} \right)} \]

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

**IDEAL GAS MIXTURES**

\( i = 1, 2, \ldots, n \) constituents. Each constituent is an ideal gas.

Mole Fraction: \( N_i \) = number of moles of component \( i \)

\[ x_i = \frac{N_i}{N}; N = \sum N_i; \sum x_i = 1 \]

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

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

Gas Constant: \( R = \frac{M}{\text{Molar}} \)

To convert mole fractions \( x_i \) to mass fractions \( y_i \):

\[ y_i = \frac{x_i M_i}{\sum (x_i M_i)} \]

To convert mass fractions to mole fractions:

\[ x_i = \frac{y_i / M_i}{\sum (y_i / M_i)} \]

**Partial Pressures**

\[ p = \sum p_i; p_i = \frac{m_i R T}{V} \]

**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) \( \omega \):

\[ \omega = \frac{m_v}{m_a} \]

\( m_v = \) mass of water vapor and \( m_a = \) mass of dry air.

\[ \omega = 0.622 \frac{p_v}{p_a} = 0.622 \frac{p_v}{(p - p_v)} \]

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

\[ \phi = \frac{m_v}{m_{gs}} = \frac{p_v}{p_{gs}} \]

\( m_{gs} = \) mass of vapor at saturation, and \( p_{gs} = \) 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.

**Humidity 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:

\[ \left( \frac{dp}{dT} \right)_{sat} = \frac{h_{fg}}{V_{fg}} = \frac{5_{fg}}{v_{fg}}, \]

\( h_{fg} = \) enthalpy change for phase transitions,
\( v_{fg} = \) volume change,
\( s_{fg} = \) entropy change,
\( T = \) absolute temperature, and
\( (dP/dT)_{sat} = \) slope of vapor-liquid saturation line.
Gibbs Phase Rule
\[ P + F = C + 2, \]
where
\[ P = \text{number of phases making up a system}, \]
\[ F = \text{degrees of freedom}, \]
\[ C = \text{number of components in a system}. \]

**BINARY PHASE DIAGRAMS**
Allows determination of (1) what phases are present at equilibrium at any temperature and average composition, (2) the compositions of those phases, and (3) the fractions of those phases.

- Eutectic reaction (liquid $\rightarrow$ two solid phases)
- Eutectoid reaction (solid $\rightarrow$ two solid phases)
- Peritectic reaction (liquid + solid $\rightarrow$ solid)
- Pertectoid reaction (two solid phases $\rightarrow$ solid)

**Lever Rule**
The following phase diagram and equations illustrate how the weight of each phase in a two-phase system can be determined:

\[
\text{wt \% } \alpha = \frac{x_{\beta} - x}{x_{\beta} - x_{\alpha}} \times 100
\]
\[
\text{wt \% } \beta = \frac{x - x_{\alpha}}{x_{\beta} - x_{\alpha}} \times 100
\]

(In diagram, L = liquid) If \( x \) = the average composition at temperature \( T \), then

**Iron-Iron Carbide Phase Diagram**

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

\[
\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}
\]

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

\[
\text{CH}_4 + 2 \text{O}_2 + 2(3.76) \text{N}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O} + 7.52 \text{N}_2
\]

**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).

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

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

\[
\text{Percent Theoretical Air} = \left( \frac{A/F}_{\text{actual}} \right) \times 100
\]
\[
\text{Percent Excess Air} = \left( \frac{A/F}_{\text{actual}} - (A/F)_{\text{stoichiometric}} \right) \times 100
\]

SECOND LAW OF THERMODYNAMICS

Thermal Energy Reservoirs
\[ \Delta S_{\text{reservoir}} = \frac{Q}{T_{\text{reservoir}}} \], 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.

\textbf{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.

\textbf{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.

\textbf{ENTROPY}
\[ ds = \frac{1}{T} \delta Q_{\text{rev}} \]
\[ s_2 - s_1 = \int_1^2 \left( \frac{1}{T} \right) \delta Q_{\text{rev}} \]

\textbf{Inequality of Clausius}
\[ \int_1^2 \left( \frac{1}{T} \right) \delta Q \leq s_2 - s_1 \]

\textbf{Isothermal, Reversible Process}
\[ \Delta s = s_2 - s_1 = \frac{Q}{T} \]

Isentropic Process
\( \Delta s = 0; ds = 0 \)
A reversible adiabatic process is isentropic.

Adiabatic Process
\[ \delta Q = 0; \Delta s \geq 0 \]

\textbf{Increase of Entropy Principle}
\[ \Delta s_{\text{total}} = \Delta s_{\text{system}} + \Delta s_{\text{surroundings}} \geq 0 \]
\[ \Delta s_{\text{total}} = \sum m_{\text{out}} s_{\text{out}} - \sum m_{\text{in}} s_{\text{in}} - \sum \left( \frac{Q_{\text{external}}}{T_{\text{external}}} \right) \geq 0 \]

\textbf{Temperature-Entropy (T-s) Diagram}

\[ Q_{\text{rev}} = \int_1^2 T \, ds \]

\textbf{Entropy Change for Solids and Liquids}
\[ ds = c \left( \frac{dT}{T} \right) \]
\[ s_2 - s_1 = \int c \left( \frac{dT}{T} \right) = c_{\text{mean}} \ln \left( \frac{T_2}{T_1} \right) \],
where \( c \) equals the heat capacity of the solid or liquid.

\textbf{Irreversibility}
\[ I = w_{\text{rev}} - w_{\text{actual}} \]

\textbf{EXERGY}
Exergy is the portion of total energy available to do work.

\textbf{Closed-System 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
\( w_{\text{reversible}} = \phi_1 - \phi_2 \)

\textbf{Open-System Availability}
\[ \psi = (h - h_o) - T_o (s - s_o) + V^2/2 + g z \]
\[ w_{\text{reversible}} = \psi_1 - \psi_2 \]

\textbf{Gibbs Free Energy,} \( \Delta G \)
Energy released or absorbed in a reaction occurring reversibly at constant pressure and temperature.

\textbf{Helmholtz Free Energy,} \( \Delta A \)
Energy released or absorbed in a reaction occurring reversibly at constant volume and temperature.
COMMON THERMODYNAMIC CYCLES

**Carnot Cycle**
\[ \eta = 1 - \frac{T_L}{T_H} \]

**Reversed Carnot**
\[ \eta = 1 - r^1 - k \]

**Otto Cycle**
\[ \eta = 1 - r^1 - k \]
\[ r = \frac{v_1}{v_2} \]

**Rankine Cycle**
\[ \eta = \left( \frac{h_3 - h_4}{h_3 - h_2} \right) \]

**Refrigeration**
\[ \text{COP}_{\text{ref}} = \frac{h_1 - h_4}{h_2 - h_1} \]
\[ \text{COP}_{\text{HP}} = \frac{h_2 - h_3}{h_2 - h_1} \]
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<tr>
<th>Temp. °C</th>
<th>Sat. Press. kPa</th>
<th>Specific Volume m³/kg</th>
<th>Internal Energy kJ/kg</th>
<th>Enthalpy kJ/kg</th>
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# Superheated Water Tables

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<th>h kJ/kg</th>
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<th>Temp. °C</th>
<th>v m³/kg</th>
<th>u kJ/kg</th>
<th>h kJ/kg</th>
<th>s kJ/(kg·K)</th>
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<tr>
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<td>14.674</td>
<td>2437.9</td>
<td>2584.7</td>
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<td>500</td>
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<td>3132.3</td>
<td>3489.1</td>
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<td>2592.6</td>
<td>8.1749</td>
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<td>180</td>
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<td>11.5811</td>
<td>1300</td>
<td>72.602</td>
<td>4683.7</td>
<td>5409.7</td>
<td>11.5811</td>
</tr>
</tbody>
</table>

---

**p = 0.01 MPa (45.81°C)**

- v m³/kg: 0.3157
- u kJ/kg: 2567.4
- h kJ/kg: 2756.8
- s kJ/(kg·K): 6.7600

**p = 0.05 MPa (81.33°C)**

- v m³/kg: 0.3157
- u kJ/kg: 2567.4
- h kJ/kg: 2756.8
- s kJ/(kg·K): 7.5939

---

**p = 0.10 MPa (99.63°C)**

- v m³/kg: 0.8857
- u kJ/kg: 2529.5
- h kJ/kg: 2768.8
- s kJ/(kg·K): 7.2795

**p = 0.20 MPa (120.23°C)**

- v m³/kg: 0.8857
- u kJ/kg: 2529.5
- h kJ/kg: 2768.8
- s kJ/(kg·K): 7.1272

---

**p = 0.40 MPa (143.63°C)**

- v m³/kg: 0.3630
- u kJ/kg: 4683.2
- h kJ/kg: 5409.3
- s kJ/(kg·K): 10.1982

**p = 0.60 MPa (158.85°C)**

- v m³/kg: 0.3630
- u kJ/kg: 4683.2
- h kJ/kg: 5409.3
- s kJ/(kg·K): 10.6602

---

**p = 0.80 MPa (170.43°C)**

- v m³/kg: 0.1944
- u kJ/kg: 2583.6
- h kJ/kg: 2778.1
- s kJ/(kg·K): 5.8656

**p = 1.00 MPa (179.91°C)**

- v m³/kg: 0.1944
- u kJ/kg: 2583.6
- h kJ/kg: 2778.1
- s kJ/(kg·K): 5.8656

---

**THERMODYNAMICS (continued)**
P-h DIAGRAM FOR REFRIGERANT HFC-134a

(metric units)

(Reproduced by permission of the DuPont Company)
ASHRAE PSYCHROMETRIC CHART NO. 1
(metric units)
Reproduced by permission of ASHRAE
HEAT CAPACITY TABLES
(at Room Temperature)

<table>
<thead>
<tr>
<th>Substance</th>
<th>Mol wt</th>
<th>( c_p ) (kJ/(kg·K))</th>
<th>( c_v ) (kJ/(kg·K))</th>
<th>( k )</th>
<th>( c_p ) (Btu/(lbm·°R))</th>
<th>( c_v ) (Btu/(lbm·°R))</th>
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<tbody>
<tr>
<td>Gases</td>
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<tr>
<td>Air</td>
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<td>0.718</td>
<td>1.40</td>
<td>0.240</td>
<td>0.171</td>
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<td>Argon</td>
<td>40</td>
<td>0.520</td>
<td>0.312</td>
<td>1.67</td>
<td>0.125</td>
<td>0.0756</td>
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<td>Butane</td>
<td>58</td>
<td>1.72</td>
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<td>1.09</td>
<td>0.415</td>
<td>0.381</td>
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<td>Carbon dioxide</td>
<td>44</td>
<td>0.846</td>
<td>0.657</td>
<td>1.29</td>
<td>0.203</td>
<td>0.158</td>
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<tr>
<td>Carbon monoxide</td>
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<td>1.04</td>
<td>0.744</td>
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<tr>
<td>Ethane</td>
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<td>1.49</td>
<td>1.18</td>
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<td>0.361</td>
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<td>1.67</td>
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<tr>
<td>Hydrogen</td>
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<tr>
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<td>1.67</td>
<td>0.246</td>
<td>0.148</td>
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<tr>
<td>Nitrogen</td>
<td>28</td>
<td>1.04</td>
<td>0.743</td>
<td>1.40</td>
<td>0.248</td>
<td>0.177</td>
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<tr>
<td>Octane vapor</td>
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<td>1.12</td>
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<tr>
<td>Steam</td>
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<td>1.87</td>
<td>1.41</td>
<td>1.33</td>
<td>0.445</td>
<td>0.335</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Substance</th>
<th>( c_p ) (kJ/(kg·K))</th>
<th>( c_v ) (kJ/(kg·K))</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>kg/m³</td>
</tr>
<tr>
<td>Liquids</td>
<td></td>
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</tr>
<tr>
<td>Ammonia</td>
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<td>1.146</td>
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<tr>
<td>Mercury</td>
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<td>0.033</td>
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</tr>
<tr>
<td>Water</td>
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<td>1.000</td>
<td>997</td>
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<td>Solids</td>
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<tr>
<td>Aluminum</td>
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<td>0.215</td>
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</tr>
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<td>Copper</td>
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</tr>
<tr>
<td>Ice (0°C; 32°F)</td>
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</tr>
<tr>
<td>Iron</td>
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</tr>
<tr>
<td>Lead</td>
<td>0.128</td>
<td>0.030</td>
<td>11,310</td>
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</table>