For an ideal gas, $P_v = RT$ or $PV = mRT$, and
$$ P_v/v_T = P_2v_2/T_2, $$
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
$$ R = \frac{R}{(\text{mol. wt})}, $$
where
- $R = \text{the universal gas constant}$
- $1,545 \text{ ft-lbf/(lbmol-\text{R})} = 8,314 \text{ J/(kmol-K)}$.

For ideal gases, $c_p - c_v = R$

Also, for ideal gases:
$$ \left( \frac{\partial h}{\partial T} \right)_P = 0 \quad \left( \frac{\partial u}{\partial T} \right)_P = 0 $$

For cold air standard, heat capacities are assumed to be constant at their room temperature values. In that case, the following are true:
$$ \Delta u = c_v \Delta T; \quad \Delta h = c_p \Delta T $$
$$ \Delta s = c_p \ln \left( \frac{T_2}{T_1} \right) - R \ln \left( \frac{P_2}{P_1} \right); \quad \text{and} $$
$$ \Delta s = c_v \ln \left( \frac{T_2}{T_1} \right) + R \ln \left( \frac{v_2}{v_1} \right). $$

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 ($\overline{c_p}$) and is given by
$$ \overline{c_p} = \int_{T_1}^{T_2} \frac{c_p}{T} dT $$

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:
$$ \left( P + \frac{a}{v^2} \right)(v - b) = RT $$
where $a = \frac{27}{64} \left( \frac{R^2 T_c^2}{P_c} \right)$, $b = \frac{RT_c}{8P_c}$

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 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):

\[
P_i^{\kappa} = \text{constant}
\]

\[
w = (P_2 v_2 - P_1 v_1)/(1 - k)
\]

\[
= R(T_2 - T_1)/(1 - k)
\]

Constant Temperature (Boyle’s Law):

(ideal gas) \( P V = \) constant

\[
w_b = RT \ln \left( \frac{v_2}{v_1} \right) = RT \ln \left( \frac{P_1}{P_2} \right)
\]

Polytropic (ideal gas):

\[
P_i^{\kappa} = \text{constant}
\]

\[
w = (P_2 v_2 - P_1 v_1)/(1 - n)
\]

Open Thermodynamic System

Mass crosses the system boundary

There is flow work (\( P V \)) 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)

\[
\Sigma m_i \left[ h_i + V_i^2/2 + gZ_i \right] - \Sigma m_e \left[ h_e + V_e^2/2 + gZ_e \right] + \dot{Q}_{in} - \dot{W}_{net} = d(m_{us})/dt,
\]

where

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

\( m_{us} \) = mass of fluid within the system,

\( us \) = 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) \( P V = \) constant

\[
w_{rev} = RT \ln \left( \frac{v_2}{v_1} \right) = RT \ln \left( \frac{P_1}{P_2} \right)
\]

Isentropic (ideal gas):

\[
P_i^{\kappa} = \text{constant}
\]

\[
w_{rev} = k (P_2 v_2 - P_1 v_1)/(1 - k)
\]

\[
= kR(T_2 - T_1)/(1 - k)
\]

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

Polytropic:

\[
P_i^{\kappa} = \text{constant}
\]

\[
w_{rev} = n (P_2 v_2 - P_1 v_1)/(1 - n)
\]

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.

\[
\Sigma m_i (h_i + V_i^2/2 + gZ_i) - \Sigma m_e (h_e + V_e^2/2 + gZ_e) + \dot{Q}_{in} - \dot{W}_{out} = 0
\]

and

\[
\Sigma m_i = \Sigma m_e
\]

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

\( W \) = 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.

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

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

\( h_e \) = 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.

\[
h_i = h_e + w
\]
Isentropic Efficiency (turbine) = \( \frac{h_i - h_e}{h_i - h_{is}} \)

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

**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 \( \dot{m}_i \) and \( \dot{m}_e \):

\[ \dot{m}_i (h_i - h_{is}) = \dot{m}_e (h_{2e} - h_{2i}) \]

See MECHANICAL ENGINEERING section.

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

\[ \Sigma \dot{m}_i h_i = \Sigma \dot{m}_i h_e \quad \text{and} \]

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

**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:

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

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

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

where \( T_H \) and \( T_i \) = 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:

Heat pumps:

\[ \text{COP} = \frac{Q_H}{W} \]

Refrigerators and air conditioners:

\[ \text{COP} = \frac{Q_H}{W} \]

Upper limit of COP is based on reversed Carnot Cycle:

Heat pumps:

\[ \text{COP, p} = \frac{T_H}{T_H - T_i} \]

Refrigerators and air conditioners:

\[ \text{COP, c} = \frac{T_i}{T_H - T_i} \]

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:

\[ x_i = N_i/N; N = \Sigma N_i; \Sigma x_i = 1 \]

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:** \( P = \Sigma P_i; P_i = \frac{m_i R T}{V} \)

**Partial Volumes:** \( V = \Sigma V_i; V_i = \frac{m_i R T}{P} \), where

\( P, V, T \) = the pressure, volume, and temperature of the mixture.

\[ x_i = P_i/P = V_i/V \]

**Other Properties:**

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

\( u_i \) and \( h_i \) are evaluated at \( T \), and \( s_i \) is evaluated at \( T \) and \( P \).

**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) \( \omega \):

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

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) \( \phi \):

\[ \phi = P_v/P_g \]

where

\( P_g \) = saturation pressure 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.

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

**PHASE RELATIONS**

Clapeyron Equation for Phase Transitions:

$\left( \frac{dP}{dT} \right)_{sat} = \frac{h_{fg}}{T v_{fg}} = \frac{s_{fg}}{v_{fg}}$, 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 $P/R T$ from the ideal gas law, and (3) $h_{fg}$ is independent of the temperature ($T$).

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

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:

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

**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).

**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**

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

$Q$ 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., $x_i = 1$.

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

- $P_i$ = 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**

\[ \int_1^2 (1/T) \delta Q_{\text{rev}} \leq 0 \]

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

**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**

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

\[ \Delta s_{\text{total}} = \sum m_{\text{out}} s_{\text{out}} - \sum m_{\text{in}} s_{\text{in}} - \Sigma (\dot{Q}_{\text{external}}/T_{\text{external}}) \geq 0 \]

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

\[ Q_{\text{rev}} = \int T \; ds \]

**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

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

Otto Cycle (Gasoline Engine)

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

Reversed Carnot

\[ q = 0 \]

Rankine Cycle

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

Refrigeration (Reversed Rankine Cycle)

\[ \text{COP}_{\text{ref}} = \frac{h_1 - h_4}{h_2 - h_1} \]
\[ \text{COP}_{\text{HP}} = \frac{h_2 - h_3}{h_2 - h_1} \]
## STEAM TABLES
### Saturated Water - Temperature Table

<table>
<thead>
<tr>
<th>Temp. °C</th>
<th>Press. MPa</th>
<th>Specific Volume m³/kg</th>
<th>Internal Energy kJ/kg</th>
<th>Enthalpy kJ/kg</th>
<th>Entropy kJ/(kg·K)</th>
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</tbody>
</table>

### Temperature Range

- **T** represents temperature in °C.
- **P** represents pressure in MPa.
- **v** represents specific volume in m³/kg.
- **s** represents entropy in kJ/(kg·K).
- **h** represents internal energy in kJ/kg.
- **u** represents enthalpy in kJ/kg.

### Additional Properties

- Specific Volume (m³/kg)
- Internal Energy (kJ/kg)
- Enthalpy (kJ/kg)
- Entropy (kJ/(kg·K))

### Conversion

- Temperature: °C → °F = °C * 9/5 + 32
- Pressure: MPa → kPa = MPa * 1000
- Volume: m³ → cm³ = m³ * 1000
- Energy: kJ → kW = kJ / 1000
- Entropy: kJ/(kg·K) → W/(kg·K) = kJ/(kg·K) / 1000

### Additional Notes

- The table provides saturated water properties at various temperatures and pressures.
- The properties include specific volume, internal energy, enthalpy, and entropy.
- The data is organized in ascending order of temperature.
### Superheated Water Tables

<table>
<thead>
<tr>
<th>Temp. °C</th>
<th>Sat.</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v m³/kg</td>
<td>u kJ/kg</td>
<td>h kJ/kg</td>
<td>s kJ/(kg·K)</td>
<td>v m³/kg</td>
<td>u kJ/kg</td>
<td>h kJ/kg</td>
<td>s kJ/(kg·K)</td>
<td>v m³/kg</td>
<td>u kJ/kg</td>
<td>h kJ/kg</td>
<td>s kJ/(kg·K)</td>
<td>v m³/kg</td>
<td>u kJ/kg</td>
<td>h kJ/kg</td>
<td>s kJ/(kg·K)</td>
</tr>
<tr>
<td>p = 0.01 MPa (45.81°C)</td>
<td>124.74</td>
<td>243.79</td>
<td>258.47</td>
<td>8.1502</td>
<td>3.240</td>
<td>2483.9</td>
<td>2645.9</td>
<td>7.5939</td>
<td>124.74</td>
<td>243.79</td>
<td>258.47</td>
<td>8.1502</td>
<td>3.240</td>
<td>2483.9</td>
<td>2645.9</td>
<td>7.5939</td>
</tr>
<tr>
<td>p = 0.05 MPa (81.35°C)</td>
<td>1.0940</td>
<td>2566.1</td>
<td>2675.5</td>
<td>7.3594</td>
<td>0.8857</td>
<td>2529.5</td>
<td>2706.7</td>
<td>7.1272</td>
<td>1.0940</td>
<td>2566.1</td>
<td>2675.5</td>
<td>7.3594</td>
<td>0.8857</td>
<td>2529.5</td>
<td>2706.7</td>
<td>7.1272</td>
</tr>
</tbody>
</table>

### Additional Data

- At 1.00 MPa (179.91°C), water is saturated.
- At 0.20 MPa (120.23°C), water is saturated.
P-h DIAGRAM FOR REFRIGERANT HFC-134a
(metric units)
(Reproduced by permission of the DuPont Company)
# THERMAL AND PHYSICAL PROPERTY TABLES
(at room temperature)

## GASES

<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>$k$ (Btu/(lbm·°R))</th>
<th>$R$ (kJ/(kg·K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>29</td>
<td>1.00</td>
<td>0.240</td>
<td>0.718</td>
<td>0.171</td>
</tr>
<tr>
<td>Argon</td>
<td>40</td>
<td>0.520</td>
<td>0.125</td>
<td>0.312</td>
<td>0.0756</td>
</tr>
<tr>
<td>Butane</td>
<td>58</td>
<td>1.72</td>
<td>0.415</td>
<td>1.57</td>
<td>0.381</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>44</td>
<td>0.846</td>
<td>0.203</td>
<td>0.657</td>
<td>0.158</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>28</td>
<td>1.04</td>
<td>0.249</td>
<td>0.744</td>
<td>0.178</td>
</tr>
<tr>
<td>Ethane</td>
<td>30</td>
<td>1.77</td>
<td>0.427</td>
<td>1.49</td>
<td>0.361</td>
</tr>
<tr>
<td>Helium</td>
<td>4</td>
<td>5.19</td>
<td>1.25</td>
<td>3.12</td>
<td>0.753</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>2</td>
<td>14.3</td>
<td>3.43</td>
<td>10.2</td>
<td>2.44</td>
</tr>
<tr>
<td>Methane</td>
<td>16</td>
<td>2.25</td>
<td>0.532</td>
<td>1.74</td>
<td>0.403</td>
</tr>
<tr>
<td>Neon</td>
<td>20</td>
<td>1.03</td>
<td>0.246</td>
<td>0.618</td>
<td>0.148</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>28</td>
<td>1.04</td>
<td>0.248</td>
<td>0.743</td>
<td>0.177</td>
</tr>
<tr>
<td>Octane vapor</td>
<td>114</td>
<td>1.71</td>
<td>0.409</td>
<td>1.64</td>
<td>0.392</td>
</tr>
<tr>
<td>Oxygen</td>
<td>32</td>
<td>0.918</td>
<td>0.219</td>
<td>0.658</td>
<td>0.157</td>
</tr>
<tr>
<td>Propane</td>
<td>44</td>
<td>1.68</td>
<td>0.407</td>
<td>1.49</td>
<td>0.362</td>
</tr>
<tr>
<td>Steam</td>
<td>18</td>
<td>1.87</td>
<td>0.445</td>
<td>1.41</td>
<td>0.335</td>
</tr>
</tbody>
</table>

## SELECTED LIQUIDS AND SOLIDS

<table>
<thead>
<tr>
<th>Substance</th>
<th>$c_p$ (kJ/(kg·K))</th>
<th>$c_p$ (Btu/(lbm·°R))</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kJ/(kg·K))</td>
<td>(Btu/(lbm·°R))</td>
<td>kg/m³</td>
</tr>
<tr>
<td><strong>Liquids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>4.80</td>
<td>1.146</td>
<td>602</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.139</td>
<td>0.033</td>
<td>13,560</td>
</tr>
<tr>
<td>Water</td>
<td>4.18</td>
<td>1.000</td>
<td>997</td>
</tr>
<tr>
<td><strong>Solids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.900</td>
<td>0.215</td>
<td>2,700</td>
</tr>
<tr>
<td>Copper</td>
<td>0.386</td>
<td>0.092</td>
<td>8,900</td>
</tr>
<tr>
<td>Ice (0°C; 32°F)</td>
<td>2.11</td>
<td>0.502</td>
<td>917</td>
</tr>
<tr>
<td>Iron</td>
<td>0.450</td>
<td>0.107</td>
<td>7,840</td>
</tr>
<tr>
<td>Lead</td>
<td>0.128</td>
<td>0.030</td>
<td>11,310</td>
</tr>
</tbody>
</table>