Properties, Paths, and Processes

When looking at the 1st Law it should be clear that we need to know $h$ (or $u + p/\rho$), $\rho$, $V$ and $z$ at all system inlets and outlets, as well as $\rho$, $V$, $u$, $V$ and $z$ for the mass inside our system when we do our energy accounting. These quantities are examples of properties. Properties are closely tied to Thermodynamic states. It’s time we discuss them.

4.1 What is a property?

A property is:

Property values come from a number of sources. These include analytical expressions for ideal gas or compressed liquid $h$ and $u$, tables of experimentally measured $p$, $T$, $v$, $u$, and $h$ values for liquid-vapor mixtures, $p$, $T$, $v$, $u$, and $h$ values for superheated vapors, plus $T$, $u$ and $h$ values for ideal gases, and graphical interpretations presented as charts. All properties are reported as intensive.

An intensive property can vary with time, can vary with location within a system, and does not depend on system size. Examples of intensive properties include temperature, pressure, and density.

An extensive property can also vary with time and, unlike intensive properties, does depend on system size. Examples of extensive properties include volume, internal energy, kinetic energy, and potential energy.
We can convert an extensive property to an intensive property by dividing the extensive property by the system mass. For example, \textit{specific volume} is an intensive property and is found by:

\begin{equation}
\text{specific volume} = \frac{V}{m}
\end{equation}

Similarly, \textit{specific internal energy} is an intensive property and is found by:

\begin{equation}
\text{specific internal energy} = \frac{U}{m}
\end{equation}

Common thermodynamic properties are tabulated in Table 0-1. Note that neither $W$ nor $Q$ are properties. Energy transfers describe processes, not matter. We’ll discuss processes a bit later.

It’s easy to compute the change in a property. Just subtract the initial value from the final value.

So where do properties come from? Some are easily measured. For example, you can measure temperature with a thermometer, pressure with a pressure gauge, mass with a balance. Other properties must be determined experimentally. We’ll see later that specific volume, specific internal energy, specific enthalpy, and specific entropy have been tabulated as functions of temperature and pressure.
Table 0-1. Thermodynamic properties and their SI units.

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>T</td>
<td>K (or C)</td>
</tr>
<tr>
<td>Pressure</td>
<td>p</td>
<td>N/m² = Pa</td>
</tr>
<tr>
<td>Mass</td>
<td>m</td>
<td>kg</td>
</tr>
<tr>
<td>Volume</td>
<td>V</td>
<td>m³</td>
</tr>
<tr>
<td>Specific volume</td>
<td>v</td>
<td>m³/kg</td>
</tr>
<tr>
<td>Density</td>
<td>ρ</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Energy</td>
<td>E</td>
<td>N-m = J</td>
</tr>
<tr>
<td>Power</td>
<td>P</td>
<td>kJ/sec = kW</td>
</tr>
<tr>
<td>Internal energy</td>
<td>U</td>
<td>kJ</td>
</tr>
<tr>
<td>Specific internal energy</td>
<td>u</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Kinetic energy</td>
<td>KE</td>
<td>kJ</td>
</tr>
<tr>
<td>Specific kinetic energy</td>
<td>ke</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Potential energy</td>
<td>PE</td>
<td>kJ</td>
</tr>
<tr>
<td>Specific potential energy</td>
<td>pe</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>H</td>
<td>kJ</td>
</tr>
<tr>
<td>Specific enthalpy</td>
<td>h</td>
<td>kJ/kg</td>
</tr>
<tr>
<td>Entropy</td>
<td>S</td>
<td>kJ/K</td>
</tr>
<tr>
<td>Specific entropy</td>
<td>s</td>
<td>kJ/kg-K</td>
</tr>
</tbody>
</table>

4.2 Thermodynamic equilibrium and what it implies

In Thermodynamic analyses we can consider mechanical work and heat transfer, plus chemical changes. We have discussed modes of mechanical work and heat transfer and will save chemical changes for future classes such as ME 300 (e.g., combustion reactions where a hydrocarbon and oxygen become carbon dioxide and water).

Equilibrium conditions exist for mechanical work, heat transfer, and chemical changes. You’re familiar with mechanical equilibrium:
Thermal equilibrium exists when:

Chemical equilibrium exists when:

Thermodynamic equilibrium only exists when all three sub-cases are met. In other words, mechanical, thermal and chemical equilibrium must all present. *It is only when thermodynamic equilibrium is taking place that we can accurately specify properties.* How do we rationalize this with mechanical work (requiring an unbalanced force), heat transfer (requiring a temperature gradient), or chemical reactions (related to concentration gradients)? We make use of the model for a quasi-equilibrium situation.

The concept of quasi-equilibrium is a compromise between the desire to allow actual systems to evolve while still allowing properties to be determined any time and any place we need them. The prefix “quasi” means “nearly” so quasi-equilibrium means nearly equilibrium. Mathematically we would term the net force, net temperature difference, and net concentration difference as differential (or infinitesimal) quantities. These differences are most definitely not rapid, finite jumps.

We will always model our systems as obeying the quasi-equilibrium approximation. More about quasi-equilibrium later.
4.3 What is a State and how does it relate to properties?

A state is:

We know that properties are not independent. For example, the ideal gas law describes the relationship between temperature, pressure, and specific volume. So how many independent, intensive properties does it take to fix a state? The answer is found in the Gibb’s Phase Rule:

The number of independent, intensive properties required to fix a state of matter (\( \Pi \)) is two plus the number of chemical species present (\( \Sigma \)) minus the number of phases of mass present (\( \Phi \)).

Let’s consider some examples.

- We have a mixture of gaseous O\(_2\), N\(_2\), CO\(_2\) and Ar (these are the four largest components of atmospheric air).

- A mixture of ice, liquid water and steam (water vapor) coexists.

This scenario represents a special case called the triple point. If we know that the three phases of matter (solid, liquid, and gas) are in equilibrium, then we know the
4. Properties, Paths, and Processes

intensive properties of the system without requiring any additional information about the system.

- A mixture of CO₂ solid (dry ice) and vapor.

- Water vapor exists at some temperature.

It’s important to realize that the definition for a state can be reversed. That means if the state is specified all properties are immediately available. From the third example above, when we specify either the temperature or pressure of our dry ice-CO₂ vapor mixture we immediately know the magnitude of the other. With some additional information about the fraction of substance that is solid or vapor we can determine the magnitudes of $u$, $h$, $s$, $p$ (or $v$), and so on.

4.4 Thermodynamic paths (processes)

The states of our Thermodynamic systems often change. These changes must be “smooth” in the sense that there cannot be big property jumps in short intervals of time or space. The reason is that big jumps in short intervals lead to conditions that are not quasi-equilibrium. No quasi-equilibrium means no accurate properties. No accurate properties mean no analysis.

A Thermodynamic path (or Thermodynamic process) is:
We will almost always model paths as being close to equilibrium, i.e. quasi-equilibrium.

There are an infinite number of Thermodynamic paths. We are only interested in a few (Table 0-2). They are usually processes where one property remains constant. You need to commit these definitions to memory.

Table 0-2. Thermodynamic processes of interest in ME 200.

<table>
<thead>
<tr>
<th>Process</th>
<th>Relation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isenthalpic</td>
<td></td>
</tr>
<tr>
<td>Isobaric</td>
<td></td>
</tr>
<tr>
<td>Isentropic</td>
<td></td>
</tr>
<tr>
<td>Isothermal</td>
<td></td>
</tr>
<tr>
<td>Isometric (or isochoric)</td>
<td></td>
</tr>
<tr>
<td>Polytropic</td>
<td></td>
</tr>
</tbody>
</table>

4.5 Two very common properties \((p \text{ and } T)\)

The two most commonly used properties, in Thermodynamics and in everyday life, are pressure \(p\) and temperature \(T\). There are several versions of each.

Even before you began high school you learned about practical (C) and absolute (K) temperatures. We will use both and you should have committed their relationship to memory.

Pressure also has absolute and practical scales. Absolute pressure has a value of 0 at total vacuum. That means a standard (25 C, sea level) atmosphere has an absolute pressure of 101 kPa.
The practical pressure scale is termed “gage” pressure. Its baseline is one standard atmosphere, so 0 kPa gage is 101 kPa absolute.

There are two types of gage pressures in use, depending on whether the pressure in question is above atmospheric or below it. For cases where the pressure is below atmospheric we report its magnitude below 101 kPa and add the descriptor “vacuum.” When the pressure is above atmospheric we report its magnitude above 101 kPa and just call it “gage” pressure. Unless you are told otherwise, the pressures you will be given in ME 200 are absolute pressures.

4.6 Methods for evaluating properties

How we evaluate properties depends to a large extent on the state of the substance in question. The data we seek come from figures (charts), tables, and/or equations. Not much will be said about equations.

Charts and tables have their own advantages. As you will see, using charts is an excellent means of determining whether a system is liquid, vapor, solid, or a mixture of all three. Using tables leads to much higher accuracy when performing calculations. Our approach to evaluating properties makes use of both.

4.6.1 Thermodynamic Property Charts

Thermodynamic property charts are the easiest property evaluation method to understand. Each substance (water, CO₂, R143a, …) will have its own set of charts. All our charts use the same color scheme.

- All states along the blue curve are pure liquid. This is the “saturated liquid” curve.
- All states along the red curve are pure vapor. This is the “saturated vapor” curve.
• States in the region between the pure liquid and pure vapor curves are mixtures of them. This region has several names, including “wet dome,” “saturated liquid-vapor mixture (slvm),” and “two-phase mixture (2f-mix).”
• The point at the top of the wet dome, where the saturated liquid and saturated vapor curves intersect, is the critical point.
• States to the left of the saturated liquid curve are in the “compressed-liquid” or “sub-cooled liquid” region.
• States to the right of the saturated vapor curve are in the superheated vapor region.
• No solid phase information is shown, as we typically evaluate solid substance physical properties using tables only, or perhaps equations.

Two examples of thermodynamic property diagrams are provided below. Figure 0-1 is the pressure-volume, or $p$-$v$, diagram and Figure 0-2 is the pressure-enthalpy, or $p$-$h$ diagram.

The $p$-$v$ diagram is useful when considering boundary work because the area between a process curve (Thermodynamic path) and the abscissa equals $w_{\text{boundary}}$. (If you can’t immediately recall this, return to Chapter 1 for a refresher.)

The $p$-$h$ diagram is useful when analyzing vapor compression heating and cooling systems. In that case processes for the (assumed) constant pressure heat exchangers and (assumed) constant enthalpy throttling valve appear as straight horizontal or vertical lines.
Figure 0-1. p-v diagram for water.

Figure 0-2. p-h diagram for R-134a.
In addition to the locations of the saturated liquid and saturated vapor curves, pay careful attention to the vertical and horizontal axes - they all have log\textsubscript{10} scales. Also recall that the area computed via integration has a sign associated with it. Processes that tend toward the right (expansion processes) have positive areas while those that head left (compression processes) have negative values. This is consistent with our sign convention for work.

Thermodynamic charts have a number of uses, some qualitative and some quantitative:

- They can be used to quickly determine the physical state of a substance. For instance, at a constant pressure of 10 bar, the water \( p-v \) diagram shows it’s a compressed liquid when \( v \) is 0.001 m\textsuperscript{3}/kg, a 2-\( \phi \) mixture when \( v \) is 0.1 m\textsuperscript{3}/kg, and a superheated vapor when \( v \) is 10 m\textsuperscript{3}/kg. Similarly, the R134a \( p-h \) diagram shows that it’s a compressed liquid at 10 bars when \( h \) is 10 kJ/kg, a 2-\( \phi \) mixture when \( h \) is 100 kJ/kg, and a superheated vapor when \( h \) is 1000 kJ/kg. This insight will be invaluable when you want tabulated data to get more precise values for energy accounting.

- The shapes of process curves on \( p-v \) and \( p-h \) charts immediately tell you something about the thermodynamic path your system of interest is undergoing. Obviously, lines of constant \( p \) (isobars) are horizontal on either a \( p-v \) or \( p-h \) diagram, while vertical lines are constant \( v \) (isochores) in the former and constant \( h \) (isoenthalps) in the latter. Additionally, lines of constant \( T \) (isotherms) can be added to either, lines of constant \( v \) to \( p-h \) and lines of constant \( h \) to \( p-v \). The figures below contain examples.
• The \( p-v \) diagram shows that saturated liquid specific volume is at best a weak function of pressure, as long as the state is far from the critical point. This observation leads to the realization that the density of a liquid doesn’t change significantly with pressure, thereby supporting the engineering model of an incompressible substance.

• Very approximate values for some thermodynamic properties can be extracted from the property charts included in this LectureBook. The specific volume for 10 bar saturated liquid R-134a is approximately \( 8.5 \times 10^{-04} \text{ m}^3/\text{kg} \) while that for 10 bar saturated vapor R-134a is roughly \( 2.2 \times 10^{-02} \text{ m}^3/\text{kg} \).

Furthermore, the critical pressure for water is about 220 bar.

• Slightly more accurate property data can be extracted from online charts; an internet search will lead you to an almost endless number. After some practice you may be able to get property data accurate to three significant figures. But that’s the best you, or anyone else, is going to do!

Since property charts are not good for energy accounting requiring an accuracy of more than two significant figures, we use an alternative approach. That brings us to thermodynamic property tables.

4.6.2 Thermodynamic Property Tables

There are three types of thermodynamic property tables for “real” substances (i.e., not simplified models such as ideal gases and incompressible liquids or solids). The tables are for compressed liquids, for superheated vapors, and for either saturated liquids or saturated vapors and their mixtures. The saturated liquid and saturated vapor property tables come in versions where temperature is the independent variable and where the pressure is the independent variable.
Gibb’s phase rule is very handy when understanding why property tables are organized in this fashion. Since the compressed liquid and superheated vapor cases each consist of only one phase, the phase rule tells us we need two independent intensive variables to specify a fluid’s state. Pressure and temperature were chosen to be those variables, if for no other reason than because they are both easy to measure. An example of each follows.

4.6.2.1 Compressed liquid table

Compressed liquid property data are tabulated as functions of pressure and temperature (Table 0-3). The table is divided into sub-tables, with each sub-table being a matrix having a fixed pressure and several temperatures. Specific properties $v$, $u$, $h$ and $s$ are listed along a single row for each temperature.

Table 0-3. Excerpt from compressed liquid table for NH$_3$.

<table>
<thead>
<tr>
<th>Temp. (C)</th>
<th>Volume (m$^3$/kg)</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p = 20$ bar, $T_{sat} = 49.35^\circ$C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-20</td>
<td>1.5011E-03</td>
<td>87.77</td>
<td>90.77</td>
<td>0.3618</td>
</tr>
<tr>
<td>-10</td>
<td>1.5311E-03</td>
<td>132.99</td>
<td>136.05</td>
<td>0.5372</td>
</tr>
<tr>
<td>0</td>
<td>1.5633E-03</td>
<td>178.72</td>
<td>181.84</td>
<td>0.7080</td>
</tr>
</tbody>
</table>

4.6.2.2 Superheated vapor table

Superheated vapor property data are also tabulated as functions of pressure and temperature, and are also divided into sub-tables (Table 0-4). As for compressed liquids, each sub-table is a matrix having a fixed pressure and several temperatures. Specific properties $v$, $u$, $h$ and $s$ are again listed along a single row for each temperature.
4. Properties, Paths, and Processes

Table 0-4. Excerpt from superheated vapor table for C₃H₈.

<table>
<thead>
<tr>
<th>Temp. (C)</th>
<th>Volume (m³/kg)</th>
<th>Internal Energy (kJ/kg)</th>
<th>Enthalpy (kJ/kg)</th>
<th>Entropy (kJ/kg*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p = 0.5 bar, T_{sat} = -56.97°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sat.</td>
<td>0.797</td>
<td>363.3</td>
<td>403.2</td>
<td>1.872</td>
</tr>
<tr>
<td>-50</td>
<td>0.825</td>
<td>371.5</td>
<td>412.7</td>
<td>1.916</td>
</tr>
<tr>
<td>-40</td>
<td>0.864</td>
<td>383.5</td>
<td>426.7</td>
<td>1.977</td>
</tr>
</tbody>
</table>

4.6.2.3 Saturation tables for pressure and temperature

Saturation tables are more complicated than their compressed liquid or superheated vapor counterparts since they are used to describe a mixture of the liquid and vapor phases. By Gibb’s phase rule this means there is only one independent intensive property. By agreement that is either the pressure or the temperature. This results in a pair of saturation tables, one where pressure is the independent variable and another where the independent variable is temperature. Note that an additional piece of information must be known in order to specify the state—this could be \( v, h, u, x \) or \( s \).

A not so obvious result of Gibb’s phase rule is that choosing either the temperature or pressure of a 2-\( \phi \) mixture automatically specifies the other. You’ll observe this when using either table - the independent variable is in the leftmost green column and has even (often integer) values while its sole counterpart is in the adjacent green column and has non-integer values (Table 0-5 and Table 0-6).

The remaining property data is grouped by color-blue for saturated liquid and red for saturated vapor—with separate \( v, u, h \) and \( s \) columns in each. For cases where we have a single phase we’re set. We get the appropriate property values from either the
blue or red column(s). But life isn’t that simple so we need to introduce mixture properties and a new property called the **quality**.

Table 0-5. Excerpt from saturation table for water. Note that properties are tabulated for integer values of pressure.

<table>
<thead>
<tr>
<th>Pressure (bar)</th>
<th>Temp. (C)</th>
<th>Volume ($v_l$, m$^3$/kg)</th>
<th>Internal Energy ($u_l$, kJ/kg)</th>
<th>Enthalpy ($h_l$, kJ/kg)</th>
<th>Entropy ($s_l$, kJ/kg*K)</th>
<th>Volume ($v_g$, m$^3$/kg)</th>
<th>Internal Energy ($u_g$, kJ/kg)</th>
<th>Enthalpy ($h_g$, kJ/kg)</th>
<th>Entropy ($s_g$, kJ/kg*K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>6.970</td>
<td>0.0010001</td>
<td>29.298</td>
<td>29.299</td>
<td>0.10591</td>
<td>129.18</td>
<td>2384.5</td>
<td>2513.7</td>
<td>8.9749</td>
</tr>
<tr>
<td>0.02</td>
<td>17.50</td>
<td>0.0010014</td>
<td>73.426</td>
<td>73.428</td>
<td>0.26056</td>
<td>66.987</td>
<td>2398.9</td>
<td>2532.9</td>
<td>8.7226</td>
</tr>
<tr>
<td>0.05</td>
<td>32.87</td>
<td>0.0010053</td>
<td>137.74</td>
<td>137.75</td>
<td>0.47620</td>
<td>28.185</td>
<td>2419.8</td>
<td>2560.7</td>
<td>8.3938</td>
</tr>
</tbody>
</table>

Table 0-6. Excerpt from saturation table for water. Note that properties are tabulated for integer values of temperature.

<table>
<thead>
<tr>
<th>Temperature table</th>
<th>Liquid</th>
<th>Vapor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Press. (bar)</strong></td>
<td><strong>Volume ($v_l$, m$^3$/kg)</strong></td>
<td><strong>Internal Energy ($u_l$, kJ/kg)</strong></td>
</tr>
<tr>
<td>0.01</td>
<td>0.0061165</td>
<td>0.0010002</td>
</tr>
<tr>
<td>4</td>
<td>0.0081355</td>
<td>0.0010001</td>
</tr>
<tr>
<td>5</td>
<td>0.0087258</td>
<td>0.0010001</td>
</tr>
</tbody>
</table>

### 4.6.2.4 Quality

Quality is the ratio of the mass of vapor in a mixture to the total mass of the mixture:

Quality only exists in the vapor dome and ranges from 0 to 1. Saturated liquid has quality of 0, which follows from the above equation as $m_{vapor} = 0$ for a saturated liquid. Saturated vapor has quality of 1.
Consider a generic intensive property, \( y \). We can calculate property \( y \) if we know the quality and the values of \( y \) as a saturated liquid (\( y_r \)) and as a saturated vapor (\( y_g \)). We find \( y_r \) and \( y_g \) from the saturation tables.

As an example, you can calculate specific volume as:

Specific internal energy, specific enthalpy, and specific entropy can be similarly calculated.

### 4.6.2.5 Property Changes During Evaporation, Condensation, Boiling, Freezing, and Sublimation

There are significant property differences whenever a phase change occurs. This includes melting and boiling, plus their opposites freezing and condensation. It also includes sublimation and its opposite. The ones we deal with most often are evaporation and condensation.

Many thermodynamic tables include property changes for evaporation (i.e., the property change from saturated liquid to saturated vapor) in a separate column. Since energy addition is required for evaporation, the magnitudes are positive. For a generic property, \( y \), the property change for evaporation is:
4.6.2.6 Property tables for non-condensable ideal gases

Real substances undergoing phase changes are not the only ones of interest. Sometimes we deal with idealizations like the non-condensable ideal gases. The most common are Air, CO\(_2\), He, H\(_2\), H\(_2\)O, N\(_2\) and O\(_2\). They each have their own tables (Table 0-7).

Table 0-7. Excerpt from property table for air.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>200.0</td>
<td>142.5</td>
<td>1.297</td>
<td>600</td>
<td>607.2</td>
<td>434.8</td>
<td>2.410</td>
</tr>
<tr>
<td>210</td>
<td>210.0</td>
<td>149.7</td>
<td>1.345</td>
<td>620</td>
<td>628.3</td>
<td>450.1</td>
<td>2.445</td>
</tr>
<tr>
<td>220</td>
<td>220.0</td>
<td>156.8</td>
<td>1.392</td>
<td>640</td>
<td>649.4</td>
<td>465.5</td>
<td>2.478</td>
</tr>
</tbody>
</table>

4.6.3 Equations for Property Evaluation – the Specific Heats

Some substances have property relationships that are so simple they can be described by a one-term expression. This is mostly true for solids, and can be true for liquids for some of the time. It is true almost always for the noble gases.

The situation with gases is more complicated. For them, the only time a simple property relation is valid is for “small” temperature differences, or for a certain class of molecule. We’re fortunate because the ready availability of ideal gas tables removes the need to use simple expressions and worry about if we have a “small” \(\Delta T\). The only case where we do use the simple relations is for the noble gases.

The simple relationships for solids, liquids and noble gases are all based on the concept of specific heats. They are defined, and examples of their use provided, below.

The specific heats are an indication of how much energy a substance can store in its internal structural modes (typically vibration for solids, vibration and translation for liquids, and vibration, rotation, translation and electronic energy for gases other
than the noble ones). Because they depend on the internal structural modes of a substance, which in turn depend on chemical bond strengths, reduced masses, moments of inertia, masses, and electronic structures, they vary from one chemical specie to another. In this course we wrap up all those molecular level issues into a single continuum concept - the specific heat.

Let’s start with a solid having mass \( m \). The differential form of the 1st Law for this case (no in- or outflow of mass to our solid, the solid is stationary, the process is quasi-equilibrium) where only moving boundary work can take place is

\[
dU = \delta Q - pdV
\]

There are two processes of importance—constant \( V \) and constant \( p \). For the constant \( V \) case the expression becomes

\[
mdu = \delta Q
\]

Or on a specific basis

\[
mc \, dT = \delta Q
\]

Transforming the specific differentials to derivatives with respect to \( T \) gives
\[
\frac{du}{dT} = \frac{\delta q}{dT} \bigg|_{\text{const } \mu} \equiv c_\mu
\]

where \(c_\mu\) is the constant volume specific heat. The constant pressure case is analogous.

\[
\begin{align*}
\mu dp + dU &= \delta Q = \delta H \\
\frac{dh}{dT} &= \frac{\delta q}{dT} \bigg|_{\text{const } p} \equiv c_p
\end{align*}
\]

These two expressions show that the specific heats are the specific energies added to systems per unit increase in system \(T\). Their units are kJ/kg-K.

Perhaps surprisingly, even though \(c_\mu\) and \(c_p\) were derived in terms of the non-property \(q\), \(c_\mu\) and \(c_p\) are properties since they are derivatives of a property (\(u\) or \(h\)) with respect to a property (\(T\)). This is fortuitous because it allows us to compute changes in \(u\) or \(h\) knowing only the material properties \(c_\mu\) or \(c_p\), and the temperature difference \(\Delta T\)

\[
\Delta u = \int c_\mu \, dT
\]

\[
\Delta h = \int c_p \, dT
\]
If we take \( h = u + pv \) for an ideal gas, then differentiate with respect to \( T \), we see that

\[
c_p - c_v = R
\]

Since \( R \) for a solid or liquid is essentially zero, we have only a single specific heat for those two phases. We term this single specific heat \( c \). Specific heats for some common substances are summarized in Table 0-8.

Table 0-8. Specific heats for common substances.

<table>
<thead>
<tr>
<th>Substance</th>
<th>( c ), kJ/kg-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.91</td>
</tr>
<tr>
<td>Cu</td>
<td>0.39</td>
</tr>
<tr>
<td>No. 2 Diesel</td>
<td>1.80</td>
</tr>
<tr>
<td>Gasoline</td>
<td>2.01</td>
</tr>
<tr>
<td>Iron, cast</td>
<td>0.46</td>
</tr>
<tr>
<td>Iron, wrought</td>
<td>0.5</td>
</tr>
<tr>
<td>Methanol</td>
<td>2.39</td>
</tr>
<tr>
<td>Steel, carbon</td>
<td>0.49</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.13</td>
</tr>
<tr>
<td>Water, ice</td>
<td>2.11</td>
</tr>
<tr>
<td>Water, liquid</td>
<td>4.18</td>
</tr>
</tbody>
</table>
4.7 Examples

4.7.1 Air duct

Return to the air duct problem in chapter 2 (Example 2.5.1 on page 2-10). Suppose that outside air enters the duct at 10 °C (50 °F) and leaves at 30 °C (84 °F).

a) What is the increase in specific enthalpy in kJ/kg?
b) What is the increase in specific energy in kJ/kg?
4.7.2 Exhaust Hood Fan

Return to the exhaust hood fan problem in chapter 2
(Example 2.5.5 on page 2-14). Approximate the temperature of air
that leaves the stove top and enters the range hood to be 200 C and
assume all air leaving the stove top enters the range hood.

a) Determine the rate of enthalpy entering the hood in kW.
b) Is it reasonable to assume that all air leaving the stove top
enters the range hood?
4.7.3 Hair Dryer

Return to the hair dryer problem in chapter 1 (Example 1.5.1 on page 1-13). Consumer versions produce maximum outlet temperatures of about 65°C from inlet temperatures of around 22°C.

a) Compute the corresponding change in air specific internal energy and specific enthalpy. Report your answers in kJ/kg.

b) If the dryer consumes 1500 W of electrical power, what is its maximum air flow rate? Report your answer in kg/s.
4.7.4 Turbocharger

The turbocharger from Chapter 3 has air entering the compressor at 1.0 bar and 50 C and exiting at 2.0 bar and 150 C. Exhaust gas (modeled as air) enters the turbine at 1.5 bar and 950 C and exits at 1.05 bar and 870 C.

a) Determine the enthalpies for each of these four states. Report your answer in kJ/kg.
4.7.5 Heating Water

a) To what temperature must water be heated to provide a pressure equal to 5 cm of water above atmospheric? To 20 cm of water above atmospheric? Report your answers in C.
4.7.6 Heat Gun

A heat gun for de-soldering printed circuit boards takes room temperature air (22°C) and raises its temperature to 240°C.

a) What is the increase in specific enthalpy? Report your answer in kJ/kg.

b) If the air pressure change between the gun inlet and outlet is negligible, what can you say about the change in specific internal energy versus the change in specific enthalpy?
4.7.7 Dry Steam

A geothermal well for electric power production uses "dry steam" at a temperature of 150°C.  
[https://en.wikipedia.org/wiki/Geothermal_electricity; 2 Jun 2016]

a) What is the maximum pressure for the steam to remain dry?  
   Report your answer in C.
4.7.8 Geothermal Flash Steam Power Plant

A geothermal flash steam power plant collects high $T$-high $p$ water from a deep well


a) If the fluid temperature is 180 C, what is the minimum pressure required for a 2-$\phi$ mixture to be present? For a pure liquid to be present? Report your answers in MPa.
4.7.9 Lake Michigan

Water temperatures in any large body of water vary between the surface and the deepest depths, as well as with season. For Lake Michigan, in the late summer-early fall, the surface temperature may reach 18°C while the temperature at the deepest point (280 m below the lake surface) can be as cold as 2°C. (http://www.glerl.noaa.gov/pubs/fulltext/2001/20010008.pdf; 2 Jun 2016)

a) Which has a larger impact on the change in water enthalpy between the surface and -280 m? The increase in pressure or the decrease in temperature?
4.7.10 Flash Boil

A high pressure-high temperature liquid can be made to “flash” boil by rapidly lowering its pressure. The pressure drop can be caused by flowing the liquid though a throttling valve, or other restriction.

In the case of a perfect throttling valve, there is no energy lost from the flow during the flashing process.

a) For an input temperature of 200°C and 20 bar, what will be the temperature when the pressure drops to 10 bar? Describe the physical state of the system.
4.7.11 Purdue Power Plant

The boilers at Purdue’s Wade Utility Plant produce steam at 600 psig (~4.2 MPa) and 825 F (~440°C). After partial expansion through the turbine generator, steam at 15 psig (~205 kPa) and 350 F (~175°C) and at 125 psig (~960 kPa) and 530 F (~275°C) is bled off and routed to campus for heating and processing.

[https://stemedhub.org/resources/772/download/What_Would_It_Take_To_Power_Purdue_University.pdf]

a) Identify the physical state for each of these three conditions and determine the corresponding specific enthalpy. Report the latter in kJ.kg.
4.7.12 Hoover Dam

Return to the Hoover Dam problem in chapter 1 (Example 1.5.2 on page 1-14). The water height from the Hoover Dam turbine inlets to the surface of Lake Powell is approximately 180 m. The water enters the turbines at approximately 140 km/hr at a temperature of about 8°C.

a) What is the water enthalpy at the turbine inlet? Report your answer in kJ/kg.

b) If the water temperature rose by 0.1°C during its pass through the turbines, how would that energy change compare to the water kinetic energy at the turbine inlet?
4.7.13 Tea kettle

A 2.0 liter teakettle is filled with 25 C water, then placed on a 1000 W stove element. The water begins to boil within four minutes. The teakettle weighs 0.5 kg and is made of stainless steel.

a) Determine the energy efficiency for this process. Report your answer in %.

b) If you could modify the teakettle and the stove element, what would you do first? Second?

c) If you could put idealizations of your modifications into practice, what is the shortest amount of time required to bring the water to a boil? Report your answer in s.
4.7.14 Coffeemaker efficiency

A typical 12-cup coffeemaker uses between 750 and 1200 W of electrical power when operating.

a) Compute the energy efficiency if the coffeemaker heats 2.8 liters (~12 cups) of room temperature water to 94 C (~200 F) in six minutes. Report your answer in %.
4.7.15 Thermodynamic Property Charts

$p-v$ and $p-h$ charts are provided on the course website for five different substances: water, ammonia, carbon dioxide, propane and refrigerant R-134a. Plot lines (curves) that are isobars, isotherms, and isenthalps on the $p-v$ and $p-h$ diagrams for ammonia, carbon dioxide, propane, and R-134a. In all cases start somewhere in the compressed liquid region and move (if possible) to the superheated vapor region. [That would give six separate curves/lines, three on each chart.] If you can’t connect the compressed liquid and superheated vapor regions with a particular line/curve, sketch it in each of those regions and any region(s) in between.
4.7.16 Application of Gibb’s Phase Rule

How many independent intensive thermodynamic properties are there for:

b) A substance at its triple point?
c) A substance at its critical point?
d) A compressed liquid?
e) A saturated liquid-vapor mixture?
f) An ideal gas?
g) An incompressible substance?
h) A superheated vapor?
4.7.17 Internal Energy

Which of the following substances have internal energies that depend strictly on their temperature?

i) Air if $T > 80$ K.
ii) Ammonia when
iii) Carbon dioxide for
iv) Propane if
v) Refrigerant R-134a for
vi) Water when