Chapter 2

Engineering Basics

The Fundamental Concepts of Engineering Analysis

While this text is built around the Packaging Cycle described in Chapter 1, it is necessary to include a section on the fundamental engineering concepts that lie behind the processes and analyses that this requires. Other chapters will refer back to this section as required, but it can be helpful to go through the concepts and calculations that follow in this chapter in order to understand how and why some of the subsequent processes and components operate and interact.

Many people outside of the field find engineering to be an inscrutable heap of equations that is more concerned with mathematical dexterity than with clarifying the nature of the relationship between abstract mathematical modeling and practical applications in the real world. As a result, students are often either completely discouraged or are left with little to do when it comes to the sorts of real problems they will face in their work environment.

This book approaches the concepts of engineering from a slightly different direction, based on experiences instructing students from non-engineering backgrounds on the underlying ideas of engineering, as well as how to learn and reason as many engineers do. To this end, the text attempts to cover basic engineering concepts in this chapter, with more complex and practical types of applications in food processing and packaging operations throughout the rest of the text.

Basics of Engineering

Engineering, which uses a combination of experiment, experience, mathematics, and science to provide working solutions to practical problems, has many of its roots in the belief that one can reason through the physical nature of the world and reduce it to a series of mathematical and physical models to answer the question "What will happen?" and more importantly "How much of it will happen?" These, then, are usually developed outward to find an appropriate quantitative solution to the situation.

With any system of basic engineering analysis, the underlying quantitative concepts – derived from the conservation of mass and energy – are usually simple, although very complex systems, models, and analyses are sometimes derived from it (Equation 2.1).

$$\text{``Stuff'' In} - \text{``Stuff'' Out} + \text{``Stuff'' Generated} = \text{``Stuff'' Retained} \qquad (2.1)$$

What quickly becomes apparent is that managing this arithmetic model is simply a matter of bookkeeping, and that using the materials, energy, moisture, chemical compound, work, money, or other quantity that goes into a system and that comes out of it at another point, the amount stored, the amount generated or destroyed can all be accounted for or at least estimated. Additionally, the concept of control volumes allows the choice of artificial boundaries within which one can apply this analysis.

Most simple analyses can be done either with empirical research or estimation models, and is often easily handled with a spreadsheet or hand calculator. Additionally, exchanges can be made, such as matter for heat energy and combustion by-products, and chemical admixtures for quantified final reaction products. Without this basic idea, students confronted with a series of simultaneous equations describing engineering equations often get lost in the arithmetic and never see the conceptual idea behind it, and are often hard-pressed to implement the answer.

Variables – Y Bother?

Students who have had "Story Problem" traumas inflicted on them at some point are terrified of the engineer's typical method of describing a physical reality: "We will call the speed of the airplane flying north 'X', and the speed of the car driving south 'Y'..." Although it may seem trivial, most students are usually not allowed the realization that *any* unique, consistent variable for the quantity will do – or none at all. It is perfectly acceptable to write the entire quantity out if it helps with comprehension of the problem (e.g., "The speed of the airplane flying north" and "The speed of the airplane flying south") when doing the final quantitative analysis. After doing one or two practice problems, a sore writing hand will demand the commonsense step of unique single-letter variables of some sort for use in the repetitive steps of writing equation solutions.

This method has been shown to help students who are apprehensive or lacking in recently used mathematics skills to get back up to speed on solution methods. Another helpful step is the practice of explicitly writing down which variables correspond to each quantity. This often helps students sort out relationships and final answers in relation to the real problem at hand once the calculations are completed.

Engineering Analysis

Engineering analysis is often all that people think of when they think of engineering – solving more-or-less abstract problems to try and predict whether a particular design will work or not, sometimes coupled with real-world and prototype testing. As with so many other types of engineering, the underlying idea is often simple, although the analysis and final implementation may be abstract, complex, and difficult.

If there is a canonical method for solving engineering problems, it might look something like this:

(1) Understand What You Are Looking For

Obviously, if one does not know what they are looking for, it will be hard to know when they have finally found it. Students often simply start solving problems and equations at random in a pattern memorized from classroom demonstrations and homework, without considering what the most effective approach will be, or whether they are actually working on the desired part of the problem.

(2) Draw a Diagram

This does not have to be particularly elegant – engineers are notorious for "boxes and arrows" artwork – but providing a visual roadmap for the problem at hand, as well as a place to label and diagram relevant quantities, can simplify large, complex problems and help reduce errors and confusion.

(3) Select and Label Components and Boundaries

By labeling both system boundaries and the components that move across (and within) them, the final analysis will be simpler and more apparent. If engineering is about keeping track of "stuff," a good layout of what is moving and where it is going can help. A bit of practice at this will pay off both in efficient solution of problems and a better intuitive grasp of the solutions' meanings. Using a well-diagramed system, desired quantities may often be found simply by inspecting the diagram rather than complex calculation.

Creating a legend for the map and variables may be helpful. For large processing operations, the variables used may be lost in the complexity of the analysis, and having a "Rosetta Stone" to return to can be very useful.

(4) Set Up the Model That Is Going to Be Used

Although most engineering courses use mathematical models to give quantitative results for the performance of a particular engineering system, and this is often extended to complex, interactive computer models in an era of inexpensive computers, it should be remembered that there are often physical models and simulations that may provide a more efficient means to the same end. Building a simple, physical model and experimenting with it may save months of programming and analysis.

(5) Solve the Equations or Otherwise Utilize the Model

This is where a lot of people want to begin, but it is good practice to go through the other steps first, because real-world engineering situations will expand and become more complex very quickly. The previously mentioned diagrams, referring back to the original conditions as well as providing help in interpreting the results, can help eliminate confusion.

Solution of the problems may be accelerated by the clever use of very simple computational tools. Although most of the examples given in many texts will reduce to a system of one, two, or three equations, real-world problems often become much more complex and require the solution of a large set of simultaneous equations. Hand calculation of a system of five equations can be an experience in patience building and paper consumption.

The "Solver" function available in many spreadsheets and calculators, as well as a host of independently programmable solution methods such as the Gauss-Jordan method, can be applied. There are many good texts on linear algebra, its application to engineering, and its computational solutions that may be consulted for these methods.

The "Law of Computational Correctness" has to be followed if a solution is to be reached. The number of available equations must match the number of unknown quantities, thus creating a well-posed problem in order to provide a solution. An insufficient number of equations (for example, three equations for four unknown quantities) is termed an ill-posed problem in that it has many different solutions (it will provide a two-dimensional line as a partial solution). By

contrast, a well-posed problem, where the number of equations and unknowns are equal (and first defined by Jaques Hadamard in 1902) – has a unique solution that depends on the data used, and provides stable solutions for different data sets [1].

(6) Check the Solution

It is easy to lose sight of the final application when calculating a solution, and produce an answer that makes no common sense (water flowing uphill because of a sign error, or heat being transferred from a cold to a warm region without benefit of a heat pump). Unfortunately, it is also possible to come up with a valid solution that runs contrary to mistaken commonsense. One of the facets of engineering analysis is that one must sometimes trust counterintuitive results – at least to the extent of a careful real-world test. Judicious checking of solutions and testing of final results will help eliminate the incorrect solutions.

Abbreviations and Units

Unfortunately, engineering and all of its subspecialties has dozens, if not hundreds, of quantities that require abbreviation, so that often the abbreviation used is confusing. For example, does **P** stand for power, pressure, probability, Poise (a derived unit), Phosphorus (an element), or something else? Worse, the Roman alphabet only contains 72 upper- and lower-case characters, and the Greek another 48 characters, so every abstract quantity cannot have its own assigned letter, and there is often very little agreement among texts.

One should be careful to keep track of the notation used in analysis so that terms are not inadvertently interposed. Every attempt has been made in this book to list the meanings of variables either with the equation or very close to it. For the student, it can be useful to add a unique subscript or superscript to alleviate the confusion, and again, creating a table or list of variables for large analyses can be an invaluable aide, particularly where a larger group of people are working on the problem.

It is a mistake to neglect units while conducting engineering analysis. There are several fundamental types of units that will be subsequently discussed, but for those starting out with engineering analysis, the principle of Dimensional Correctness must apply.

Dimensional Correctness

Write the units with each quantity at each step of the equation. In an era of inexpensive and capable calculators that have reduced or eliminated arithmetic mistakes, a majority of the calculation errors seen in engineering homework could have been prevented by including the units at every step of the way and recognizing when the units no longer match in the equation. This is an extremely useful flag for analytical errors. As experience is gained, it may be possible to shortcut this from time to time, but in general, it remains good (if tedious) practice.

The operations applied to a quantity must be applied to the units attached to this quantity. Operations with units follow the laws of algebra. A common error is to perform an operation on a quantity – squaring it, for instance, without performing the same operation on the units attached to that quantity.

The distributive law will apply to units (Equation 2.2):

$$22 \, \text{kg} \cdot (12 \text{ m/s}) = \frac{264 \, \text{kg}}{\text{m} \cdot \text{s}} \tag{2.2}$$

Exponents are another source of error (Equation 2.3):

$$\sqrt{296\,\text{m}^2/\text{s}^2} = 14\,\text{m/s},\ \text{not}\ 14\,\text{m}^2/\text{s}^2 \tag{2.3}$$

Additionally, it is not possible to perform addition or subtraction between quantities with different units. Thus, $x = 14\,\text{kg} - 10\,\text{kg·s}^{-2}$ cannot be reduced to a smaller expression.

Types of Units

Fundamental Units

These are the beginning point for larger systems of units. Typically, this will include length (L), mass (m), temperature (T), electrical current in Amperes (A), moles of matter (m), candelas of illumination intensity (cd), and time (often t, τ, or θ to avoid confusion with other uses of T). In English units systems, force (lb_f) is also a fundamental (and confusing) unit.

Derived Units

Derived units are generated from combinations of fundamental units. Simple examples include velocity (L/θ), power in watts ($\text{m}^2\text{·kg·s}^{-3}$), volts of electric potential ($\text{m}^2\text{·kg·s}^{-3}\text{·A}^{-1}$), and so on. In 1995, several *supplementary units* such as the radian were incorporated into the general category of derived units.

Archival Units

Although this is not an official category, the world has long been measuring quantities using what was (often, literally) at hand, and in ways that served well at the time and have simply been carried forward into modern applications. For example, the English system of measurements was partially defined in the Magna Carta in order to eliminate the chronic (and socially incendiary) mismeasurement of grain and wine [2], and continues to this day in many countries. Beyond this, measures evolved such as the inch (the length of three grains of barley laid end to end), the yard (which was created to measure cloth and "corrected" to the length of King Henry I's arm), the pood (a 12th-century Russian grain weight unit), and so on.

Unfortunately, some countries have strongly resisted metrification, particularly the United States and the United Kingdom [3], and the confusion can be both annoying and occasionally disastrous; the loss of the U.S. Mars Climate Orbiter in 1999 was the result of the contracting aerospace company using English units and NASA using metric measurements in linked trajectory correction software, and neither doing the proper conversions [4]. Even the SI units system has its archival problems; the French government's expedition to measure the distance from the North Pole to the equator and calibrate the official length of the meter was rife with fraudulent data, altered to provide a close match to prior expectations, because the actual journey was extremely dangerous and statistical handling of data was not well developed [5].

The food and packaging production industry often lags behind many others in adopting standards such as the SI system, with machinery in a single facility having a mixed set of indicators on equipment of different ages, and so the practitioner is well served to have a good conversion table at hand as working installations may have mixed-unit systems in operation.

Conservative Engineering

This concept does not refer to any particular political preference, but describes the underlying philosophy of most types of engineering. The underpinnings of physics and related fields such as engineering are laws of conservation (thus the "conservative" term).

Conservation of Mass

Mass is neither created nor destroyed within the domain (usually the control volume) of the system. This law, first described by Antoine Lavoisier in 1789 (and matched in similar writings by Mikhail Lomonosov in 1748), simply says that mass may change form (as from a solid to a vapor), but will not be lost.

Conservation of Energy

Energy is neither created nor destroyed within the domain of the system. This law, first postulated in 1842 by Julius Mayer, says essentially the same thing about energy as the previous one says about mass. Energy can change form (from mechanical energy to thermal energy, for instance), but will not be lost.

Conservation of Momentum

Momentum system (defined as Mass times Velocity) will remain constant within the domain of a closed system. This is seldom used in this text, although the concept may be useful in dynamic fluid problems.

   The first two laws of conservation – mass and energy, and the concept of conversion from one form to another – beg the question of what happens when mass is completely converted to energy, as when hydrogen undergoes fusion in the sun to produce helium and heat energy. This was resolved by Einstein's postulation that mass and energy are essentially the same ($E = MC^2$), and thus are conserved. For all practical purposes, the amount of energy that results from a mass-energy conversion is vanishingly small due to the enormously high value of the speed of light ($C \approx 3.0 \times 10^8$ m/s). However, in larger-scale considerations it can become an interesting concept. For example, world energy consumption in 2005 was approximately 15 Terawatts, or 1.5×10^{13} Joules/second [6]. From $E = MC^2$, this has a mass equivalence of (Equation 2.4):

$$M = \frac{E}{C^2} = \frac{(1.5 \times 10^{13} \text{ J/s})}{(3.0 \times 10^8 \text{ m/s})^2} = 1.67 \times 10^{-4} \frac{\left(\frac{\text{J}}{\text{s}}\right)}{\left(\frac{\text{m}^2}{\text{s}^2}\right)} = 1.67 \times 10^{-4} \frac{\left(\frac{\left(\frac{\text{kg} \cdot \text{m}^2}{\text{s}^2}\right)}{\text{s}}\right)}{\left(\frac{\text{m}^2}{\text{s}^2}\right)}$$

$$= 1.67 \times 10^{-4} \text{ kg/s} \tag{2.4}$$

   This emphasizes why the concept of fusion-based energy – providing some means of nearly direct conversion of mass to energy – is so tantalizing considering that direct, efficient conversion of mass to energy could power the world on a microscopic supply of fuel (roughly 14.4 kg of mass per day), though getting rid of the waste heat might pose other problems. The efficient
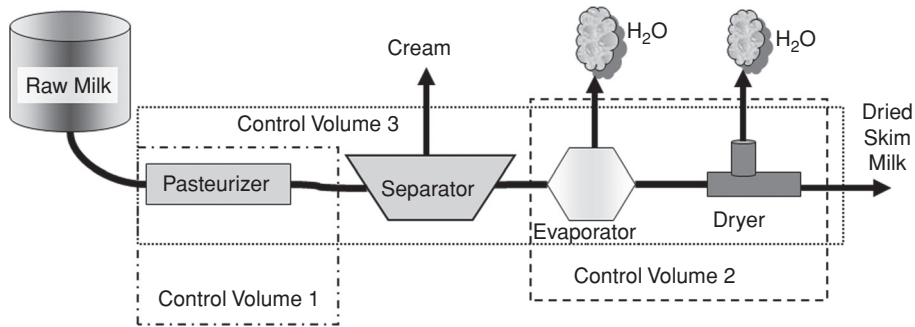
Figure 2.1. Illustration of Control Volumes in Milk Processing

engineering conversion of energy to mass is also conceptually possible, but is confined to high-energy particle accelerator experiments and atomic interactions with gamma rays so far.

Control Volumes

Control volumes are a philosophical convention that has been developed from the process of breaking natural processes down to their most simple parts and studying them in the most isolated manner possible. A control volume (or control area, or control time span) as shown in Figure 2.1 is a convenient set of borders (often completely theoretical) drawn around a particular physical process to facilitate the bookkeeping of which "stuff" is moving in, moving out, or being left behind. More simply, it is a theoretical boundary or system of boundaries that one can use to observe and measure what comes in, what goes out (often into other parts of the process), and what remains. Because overlapping boundaries can be chosen, balances of "stuff" can be done on a particular operation in order to provide more information on other parts where direct information may be lacking. This is the underlying structure of many types of technical analysis from engineering to economics, although it is often difficult to discern from the literature that often omits the diagrams and simply lists equations. Careful choice of control volume(s) can make an enormous difference in the ease of analysis.

System Types

Different types of systems in engineering problems may require different types of systems to be devised, depending on which kinds of "stuff" will cross the boundaries and what sort of theoretical limitations are necessary.

Isolated Systems do not allow the exchange of matter or energy.

Closed Systems, often seen in unit operation problems, do not allow matter to cross the boundary, but heat, mass, work, and volume may all change.

Adiabatic Systems, commonly seen in heat transfer and thermodynamics problems, do not allow heat energy to cross the system boundary.

Open Systems allow heat, work, matter, and other forms of mass and energy to cross the boundary.

Diathermic Systems, which are implicit in many heat-transfer problems, allow *only* heat to cross the boundary of the system.

System States

Steady State

Steady-state operation of a process assumes that the relevant factors are operating at a constant time rate. Thus, a fluid flow system is at steady state if the flow is well established, in its final configuration, and is not increasing or decreasing, and steady-state heat transfer has equilibrated all temperatures and heat flow rates. Nearly all of the examples given in the book are steady-state examples.

Unsteady State

Unsteady-state systems are usually considered to be in transition from one steady state to another, such as in the start-up or shutdown of a particular operation, or a change in its operation rate. The calculation of the relevant factors at any particular time in these unsteady periods can be calculated, although it is usually much more complicated and may require extensive computer approximation of the solution of the relevant differential equations. Approximations of the solution of many unsteady-state problems can be made by "discretizing" the operation – developing a model, usually using a spreadsheet or dedicated program that breaks the unsteady-state operation into very small time steps and aggregates them into an approximate solution of small steady-state parts. This type of stepwise integration, if done carefully, can give a good working solution to a very complex operational problem and is the basis for many computer-based system simulation-and-optimization software packages.

Transient State

Transients are often considered to be momentary perturbations from a steady-state operation, such as a flow surge or voltage spike. The reactions of a system to these short-term dynamic changes can be complex and, although fascinating, are beyond the scope of this text.

Continuous Flow Systems and Batch Systems

The basis for the analysis of a batch system is usually intuitively obvious. Quantities are measured and calculated on a per-batch basis, usually broken down into useful basis units, and the analytical results are returned on a per-batch basis as well. One may reduce this to more fundamental units (kilograms of product, for instance), but the assumption is that the process will start, operate, and then stop, with time-related factors being minimized beyond those reactions occurring within the batch itself.

Continuous flow systems are typically less obvious to work with, but the simple trick of choosing a specific time interval or mass of a particular item (one kilogram of dry solids, for example) to use as a basis will make the solution similar to that of batch processes. Thus, a steady-state process can be analyzed using the chosen time basis, but it must be remembered that the results will be related to the same time basis. It is a common error to forget these units in the final result.

Mass Balances

Beginning with the law of the conservation of mass, mass balances become a fairly simple matter in concept. They can become exceedingly complex when a large number of steps or

a large number of compounds are exchanged or otherwise modified, but the underlying idea remains the same: Within the confines of the control volume, the total mass remains the same. Thus, if sugar, yeast, and water are fermented to form ethanol, yeast, and carbon dioxide, the total mass of these resultant components will be equal to the starting mass. All that remains is accurate accounting of the materials in the control volume.

It is often very useful to track a component that is unchanging in the process (dry air or dry solids, for example) in order to give a constant basis of calculation for those ingredients that are added, subtracted, or changed in some way.

Example: For a product that is only dry solids and moisture, and is composed of 10% dry solids (DS) by weight, what is the final product yield if it is dried to 25% moisture content, and how much moisture is removed in the process (Equation 2.5)?

$$\text{Basis of Analysis: } 1 \text{ kg of raw product}$$

$$1 \text{ kg raw product} \cdot (0.10 \text{ kg DS/kg raw product}) = 0.10 \text{ kg DS},$$

$$\text{Moisture Content} = 1 \text{ kg raw product} - 0.10 \text{ kg DS}$$

$$\therefore 0.90 \text{ kg moisture/kg raw product}$$

$$\downarrow$$

$$\text{Final Moisture Content} = 25\% \text{ moisture/kg final product},$$

$$75\% \text{ dry DS/kg final product}$$

$$\downarrow$$

$$\text{Final Product Yield} = \frac{0.10 \text{ kg DS}}{0.75 \text{ kg DS/kg final product}}$$

$$= 0.133 \text{ kg Final Product/kg raw product}$$

$$\text{Final Product Moisture Content} = 0.133 \text{ kg Final Product} - 0.10 \text{ kg DS}$$

$$= 0.033 \text{ kg Moisture}$$

$$\text{Moisture Removed} = \text{final moisture content} - \text{initial moisture content}$$

$$= \frac{0.033 \text{ kg moisture}}{\text{kg of raw product}} - \frac{0.90 \text{ kg moisture}}{\text{kg of raw product}}$$

$$= \frac{0.867 \text{ kg moisture}}{\text{kg of raw product}} \tag{2.5}$$

A common error in mass balance analysis is to leave out the consideration of particular components in the rush to arrive at a solution. In a fermentation process, for example, a small amount of water is taken up in the hydrolysis of starch, which can lead to calculation errors in the final yield. Another common error results from semantic slips such as the confusion of *dry solids*, which are a theoretical quantity and contain no moisture whatsoever, and *dried product*, which will have lower, but significant, moisture content. Writing these out and assigning them distinctly different variables can reduce the errors considerably.

Tracking and Calculating Component and Total Mass Balances

An advantage to tracking both individual components and the total mass is that it can give an additional source of balance equations for creating a well-posed system of equations for use in determining unknown variables. For instance, the separate components as well as the total mass can be used as separate equations to solve the system of equations. Beyond this, it may be useful to track the solids total and its subcomponents, as well as fluids total and its subcomponents, to generate additional equations for analysis.

Because the analysis resembles a spreadsheet so closely to begin with, adaptation to automatic calculation for process design and process variation analysis is a relatively straightforward matter. Most process-monitoring software, although more internally complicated by its calculations of real time date from production equipment, will display data in a similar fashion.

Blending and Separation Processes

For processes that blend or separate ingredients, it is often most useful to determine the component that will go through the process without being changed (often a solvent or dry solid material) and use that as a mass-based tracking aid in the analysis or basis of calculation. Thus, pure water or dry solids may wind up being useful in the calculation of the amount of a compound carried along with that material during processing. When blending occurs, the volume of the final mix may not be the sum of the initial compounds' volumes (dissolving salt into water will illustrate this), and thus analyses must be done on a mass rather than a volume basis.

Multistage Processes

Multistage processes almost always require multipart analyses and involve multiple and often overlapping systems boundaries. A good diagram, as previously described, can be immensely helpful with this. As systems grow to enormous proportions, it may be nearly impossible to consider the entirety of the operation in a single step, and further subdivisions may have to be made. The analysis of very-large-scale operations is the subject of an entire field of study, and the fortunate beneficiary of the development of relatively simple and intuitive computer simulation models.

Recycle Streams

Recycle streams are a common feature of many processing operations, and represent the return of materials into the process that would otherwise go to waste. It is a commonsense step to reuse reclaimed water or other process materials, but the analysis will then depend on creating proper subsystem boundaries to track the flow of materials back to the start of the process, as well as the forward flow of materials into the final product. Careful labeling or other means of tracking the exact content of both the forward and recycle streams is important because many of these are the output from some type of extraction or reclamation step and will not have the same component balance as the final product.

Energy Balances and Thermodynamics

Energy balances become a bit more complicated, because energy cannot be directly measured, but must be observed indirectly by the effect that it has on a material. The basic concepts involved

in energy balances are usually expressed in the laws of thermodynamics, usually credited to Isaac Newton:

The First Law of Thermodynamics

The total sum of mass and energy in a closed (conservative) system will remain constant. From this, one can say that the sum total of all types of mass and energies will remain constant, although they may change from one form to another (oxidizing mass to create heat energy, for example).

Second Law of Thermodynamics

The quality of energy will degrade, that is, energy will always degenerate into something more random (very often heat), and you cannot return to the same state of energy without loss. Thus, energy will only spontaneously move from a region of high energy to a region of low energy and not the reverse.

Third Law of Thermodynamics

Entropy – the tendency toward disorder in a system – will reach a constant state as temperature decreases.

Process Types

Thermodynamic processes may take one of a number of different paths, depending on which variables are considered to be held constant. It is important to realize that in many instances, the processes that are listed are convenient for the sake of simple mathematical analysis, but are harder to match to real-world phenomena, many of which occur with no constraints on any particular set of variables.

When considering the types of systems, and the processes operating in those systems, it is useful to make a distinction between several types of systems.

Steady State

Steady-state processes occur without a change in the internal energy of the system. These are often used to manage energy transfer between items within the system boundaries.

Adiabatic

Adiabatic processes occur without heat exchange, as previously described, although the temperature or volume may change, as will be illustrated in the section on gas volume and enthalpy.

Isothermal

Isothermal processes operate at a constant temperature, although internal energy may change, as with a phase change in a material such as ice melting to water.

Isobaric

Isobaric processes operate at a constant pressure, though volume or temperature often change.

Isochoric

Isochoric processes operate at a constant volume, though pressure or temperature change.

Isentropic

Isentropic processes operate at a constant entropy value. This will be used in the section on vapor-compression refrigeration.

Isenthalpic

Isenthalpic processes, often confused with isentropic processes, occur at a constant value of enthalpy. A good example of this is the vapor-to-gas expansion through a throttling valve or orifice in vapor-compression refrigeration that occurs at a fixed enthalpy value.

Energy balances finally reduce to the concept that the total energy of a system will change as a function of the net amount of energy entering and leaving a particular system, and the energy may take any number of interconvertable forms giving Equation 2.6:

Net energy change = energy gained across boundaries − energy lost across boundaries

$$(2.6)$$

For any system, then, the energy exchange can be rewritten as Equation 2.7:

Energy into system = Energy out of system + Energy retained by system $\qquad(2.7)$

And as a broad conceptual model, this will explain how most devices operate. For example, an automobile engine's energy balance would be Energy in = Energy Out + Energy Retained, as shown in Table 2.1:

Table 2.1. Types of Energy in Energy Balances

Energy In =	Energy Out +	Energy Retained
Chemical Energy Electrical Current	Mechanical Energy Heat Fluid Flow Sound Light	Electrical Charge in Battery Residual Heat

Energy Terms

Force

Force is defined as an action that will cause a body with mass to accelerate, rotate, or deform a mass. Typically, it is given in Newtons (N) (1 N = 1 m·kg·s^{-2}), or pounds of force (lb$_f$)
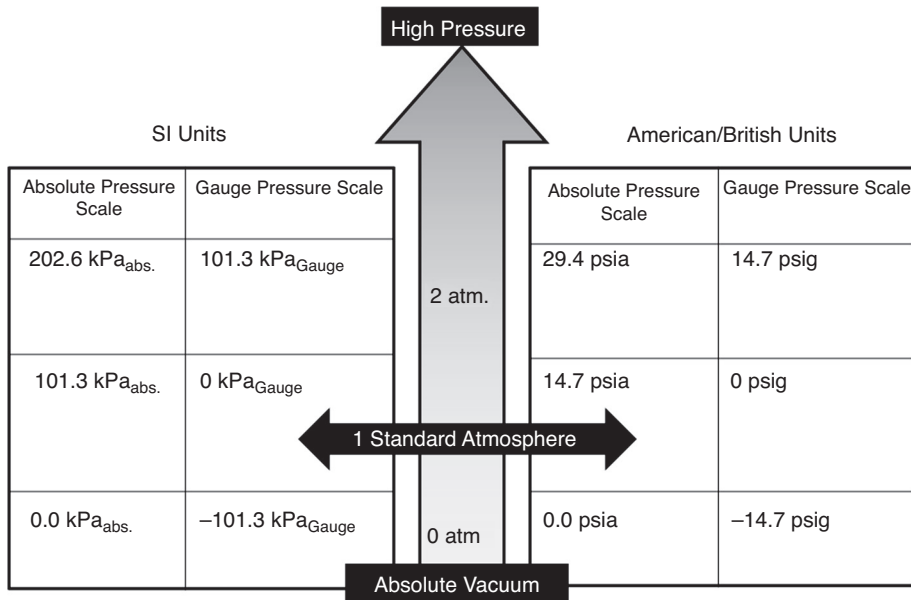
Figure 2.2. Chart of Pressure and Vacuum Terms and Levels

(1 lb$_f$ = 1 lb mass · 1 g, where g is the acceleration of gravity). Note that pounds of force and pounds of mass are properties used in American and English units, and cause a great deal of confusion, particularly when working with fluids problems. SI units systems are generally a great deal more useful, and if it is necessary to analyze a system using the American or English units during operation, it is usually more efficient and less confusing to use SI units to do the analysis and simply convert the final result using a conversion table.

Pressure

Pressure is a term used to describe force distributed over an area, and will be given in Pascal (Newton/meter^2) or pounds of force per square inch (psi). Since Pascals are typically very small amounts of pressure, it is more common to use kPa or MPa when working with everyday pressures in the SI system.

Gauge Pressure

Gauge pressure refers to the relative pressure above 1 atmosphere, as shown in Figure 2.2, and is derived from practical uses utilizing an installed pressure gauge that reads "zero pressure" when the system is in an "unpressurized" state, at ambient pressure.

Absolute Pressure

Absolute pressure refers to pressure above absolute vacuum, and is often used in gas chemistry, thermodynamics of gasses, and low-pressure operations such as flavor extraction and steam operations because the reactions of the substances involved require reference to an absolute

vacuum. Conversion between gauge pressure and absolute pressure is simply accounting for the 1 atmosphere difference:

Gauge Pressure + 1 Standard Atmosphere = Absolute Pressure

Vacuum

For those not used to working with vacuum quantities, the concept of negative pressure is usually confusing at first. Vacuum is usually taken to be the amount of pressure below 1 standard atmosphere, and – confusingly – is reported in positive units:

Absolute Pressure = (1 atmosphere) − (Amount of Vacuum).

Thus, 50 kPa of vacuum (which is actually −50 kPa of gauge pressure) is equivalent to 101.3 kPa − 50 kPa = 51.3 kPa absolute pressure. Visualizing it from an actual measurement device (shown in Figure 2.3) may clarify the concept.

Work

Work is the amount of force (F) applied over a net distance (d); $W = F{\cdot}d$. The "net distance" requirement comes from the integral version of work analysis and can usually be neglected in simple cases. Strictly speaking, if force is applied to an object that then moves but returns to its original starting point having covered no net distance, no work has been done. The units will typically be in $(m{\cdot}kg{\cdot}s^{-2)}{\cdot}m = m^2{\cdot}kg{\cdot}s^{-2}$ or Joules.

Power

Power is the time rate of doing work; $P = W/t$. Thus the units will typically be in $(m^2{\cdot}kg{\cdot}s^{-2})$ $(s^{-1}) = m^2{\cdot}kg{\cdot}s^{-3}$ or Watts (1 Watt = 1 Joule/second). Power is another area where SI and English units may intermix. During the development of steam engines, a measure of the output of a mechanical engine was developed to compare engines to that of the usual motive power used for mine pumps of the time (a draft horse), and engines are still listed in horsepower (hp) in many places (1 hp = 745.7 W), although kilowatts (kW) of mechanical output are beginning to be listed in most manufacturer's data.
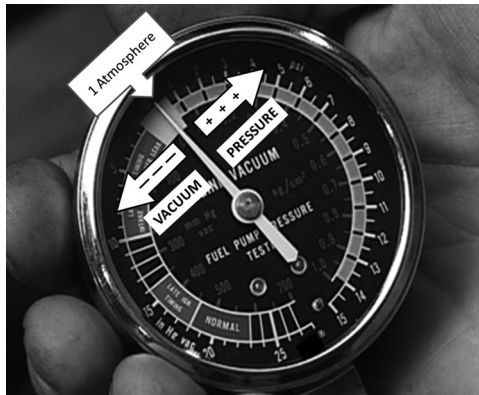
Figure 2.3. A Combination Pressure and Vacuum Gauge

Table 2.2. Heats of Combustion for Selected Common Fuels

Fuel	MJ/kg	BTU/lb
Hydrogen	141.9	61,000
Propane	50.0	21,000
Natural Gas	54.0	23,000
Butane	49.4	21,000
Gasoline	47.0	20,000
Diesel Fuel	45.0	19,500
Ethanol	30.0	12,000
#2 Heating Oil	47.4	20,400
Wood	15.0	6,000
Anthracite Coal	27.0	14,000
Bagasse	17.0	8,800

Thermal Energy

The most common source of thermal energy is the direct combustion of fuels that are nearly always hydrocarbon based. The heat values of these types of fuels are listed in Table 2.2, and most have similar heats of combustion, although ethanol is quite low and hydrogen is quite high.

The forest products and food-processing industries have often used non-traditional sources of fuel for heating where processing by-products can be utilized in biomass furnaces burning processing sawdust, waste, or waste oils. The overall heat production of a particular burner type can be described as Equation 2.8:

Heat Produced = (Heat of Combustion)*(Mass Flow Rate of Fuel)*(Combustion efficiency)

$$kJ/s = (kJ/kg)*(kg/s)*(\varepsilon) \tag{2.8}$$

Burner efficiencies can vary widely, with some types of triple-flue burners exceeding 95% efficiency and mixed-biomass or waste burners, particularly older ones without direct air injection or fluidized bed combustors, being much lower.

Other sources of thermal energy in food processing and packaging include electrical resistance heating, described in the next section, and heat reclaimed from other plant processes, such as the reheating stages in HTST processing, or, on rare occasions, waste heat from nearby industry such as metal foundries. Solar heat, heat pumps, geothermal sources, and other "alternative" energy sources are used when feasible but are often restricted to specific geographic location or environmental conditions.

Energy and Work Sign Conventions

The general adoption of several *sign conventions* – agreed use of mathematical +/− signs to signify the direction of energy, usually heat flow and work – allows the tracking of energy conversion to work, and the reverse.

Table 2.3. Sign Conventions of Heat and Work in Thermodynamics

	Enters System	Leaves System
Heat (q)	+	−
Work (W)	−	+

Using this convention has two distinct benefits. It allows the concept of heat conversion to work to be illustrated – in a steam engine, for example – because heat in and work out are both positive. More usefully, it allows the determination of the net values of a system that may be so complex that the final result is not intuitively clear.

Mechanical, Electrical, and Other Types of Non-thermal Energy

Many sources for food processing operations concern themselves with thermal processes, but it is important to remember, particularly in a machinery-intensive operation such as food processing and packaging, that there are many other types of energy use that must be accounted for. Although the early industrial age saw a great deal of use of water or wind power to directly operate milling and pumping operations, these sources of power are now almost exclusively run through electrical generators first, and then reutilized via electric motors in order to increase distribution and incorporate versatility by interfacing with electrical power grids. Mechanical energy that was once generated in a central steam engine and transmitted via a central driveshaft to belts and pulleys throughout a factory is now generated by much smaller electrical motors on an as-needed basis, although live steam is still supplied from boilers for thermal processes and compressed air may be used for actuators and conveyors. Motors of all types range widely in size, from very small electro-servomotors and actuators to megawatt hydraulic units used for large industrial machinery and diesel-electric propulsion drives in ships and trains.

Fluid Power

Compressed air, vacuum, and hydraulics are other sources of mechanical energy utilization, although these usually originate in large electric or diesel-powered pumps and compressors. Compressed air and hydraulics offer the ability to operate in wet or hazardous conditions, with compressed air providing simple and inexpensive machine actuators and hydraulics providing the potential for enormous power transmission due to the relatively incompressible nature of the operating fluid. Because of energy losses in distributing the respective fluids, these methods may be less energy-efficient than other means, but compensate by offering durability and simplicity of installation in complex devices.

The basic types of piston linear actuators used in pneumatic and hydraulic systems produce a force that is proportional to the surface area of the piston face and the applied pressure (Equation 2.9):

$$F = P_{\text{fluid}} \cdot A_{\text{piston}} \qquad\qquad (2.9)$$

F : Force, N
P : Fluid Pressure, Pa, (N/m^2)
A : Area of piston face that fluid exerts pressure on, m^2

Pneumatic and hydraulic motors convert fluid flow into rotary mechanical motion using turbines, vanes, gears, or pistons. Although somewhat inefficient, *Swash Plate* hydraulic motors that utilize variable-displacement linear pistons against an osculating disc can provide enormous

starting torque and variable speed use for employment in heavy construction and fabrication machinery.

Electrical Energy

Electrical energy is a primary source of mechanical power in many processing and packaging operations. It is used to generate mechanical power, light, heat, and is widely – indeed, almost uniquely – used to transmit information because it moves almost instantaneously over large distances. It is used as a very efficient means of centralizing power generation because the high-voltage electrical distribution networks typically lose very little energy, and electricity can be easily converted into other types of energy such as light or mechanical power.

Simple electrical circuits such as resistance heaters and filament lights can be analyzed by using Ohm's Law (Equation 2.10):

$$P = IE = \frac{E^2}{R}$$

$$I = \frac{E}{R}$$

$$E = IR$$

$$P = I^2R \tag{2.10}$$

P: Power, Watts, W
I: Current, Amperes, A
E: Potential, Volts, V

From the first equation, one can see why fuses and circuit breakers exist. If a short circuit occurs at a constant voltage, lowering the resistance to nearly zero, the current will increase to nearly infinity, causing fires or other damage to the other wiring in the circuit.

It should be stated that for more complex inductive circuits such as many types of motor-starting circuits and nearly all electronic devices, the generalized Ohm's Law must include impedance (Z) terms as well as complex (frequency-specific) terms that will not be considered in this text.

Because electrical energy can be switched on and off instantaneously, and can be used to generate heat in highly localized areas, the packaging industry uses electrical resistance heating to operate heat sealers to fuse plastic surfaces together. Electrical resistance heating can be used to power large-scale industrial processes – arc furnaces depend on it – but in a broader context, it is not the most efficient means of generating heat in many cases because the original source of the electrical energy is fuel combustion, and a substantial inefficiency is inherent in the generation, transmission, and subsequent reconversion of electricity into heat.

Forms of Mechanical Energy

Mechanical energy can take an enormous variety of forms, as previously described, ranging from fluid motion to acoustic energy as well as friction and deformation of materials. A complete analysis of the source or disposition of mechanical energy typically will not account for many of these terms, and this text will only examine a few that are immediately relevant.

Potential Energy (PE)

Potential energy is usually defined as the energy that is stored, usually by raising a mass above a datum level by a particular amount (Equation 2.11):

$$PE = m \cdot g \cdot h \tag{2.11}$$

PE: Potential Energy, $\dfrac{kg \cdot m^2}{s^2}$

m: mass, kg

g: acceleration of gravity, m/s^2

h: height above datum, m

Potential energy may also include energy stored in an extended elastic spring, an electric battery or other chemical or nuclear reaction, or in a compressed gas, which will facilitate the consideration of the trade-offs between potential energies and the kinetic energy that may be producing them. For example, the kinetic energy expended by a mechanical device to operate a compressor provides potential energy in the form of compressed air that can be used at a later date.

Kinetic Energy (KE)

Kinetic energy is the energy of movement, which, in addition to the obvious movement of mass discussed here, can include thermal energy – considered in the heat transfer section of this chapter – acoustic energy, and electrical energy in an active circuit.

A simple, steady-state system may be written as Equation 2.12:

$$KE = 1/2 \, mV^2$$

KE = Kinetic Energy, $\dfrac{kg \cdot m^2}{s^2}$

m = mass, kg

V = velocity, m^2/s^2

$$\tag{2.12}$$

From the first law of the conservation of energy, then, it is possible to see how, in a closed system, one may track the changes between mechanical energy, velocity, pressure, and many other energy forms.

A classic example of the trade-off between kinetic and potential energy is an amusement park roller coaster (Figure 2.4). Cars are mechanically hauled to the top of a tall ramp, where the potential energy is at its maximum while kinetic energy is nearly zero from the slow movement of the cars. As the car accelerates down the ramp, potential energy (height) is exchanged for kinetic energy (velocity) until at the very bottom of the ramp, the cars are moving at their maximum velocity at minimum height. The inertia of the system again carries the cars to their highest available point, trading kinetic for potential energy and back again, until wind resistance and rolling friction cause the ever-decreasing system of exchanges to come to ground level.

Thermal Energy and Temperature

The fundamental units of thermal energy often relate to temperature, and these are often indexed to either an absolute temperature (Kelvin [°K] and Rankine [°R]) or their respective relative measurements (Celsius [°C] and Fahrenheit [°F]). Absolute temperature is often used in the
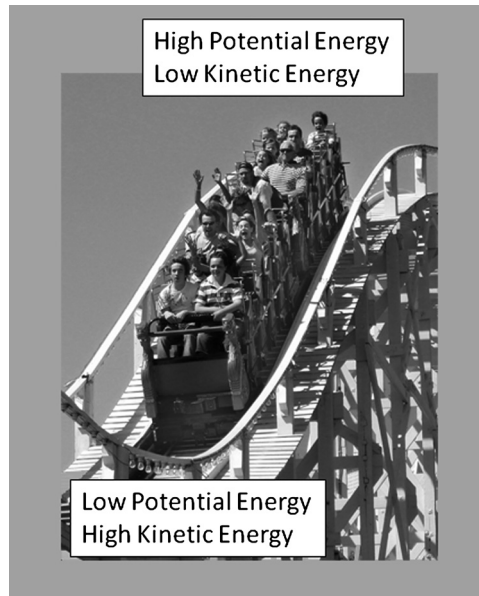
Figure 2.4. Roller Coaster Illustration of Potential and Kinetic Energy
Source: Wikimedia Commons. Source: Stevage. Used under Creative Commons License

understanding of basic chemical and thermodynamics, whereas the relative measurements are often used for more practical purposes. Both of these are simple conversions (Equation 2.13):

$$°F = °R + 460$$
$$°C = °K + 272$$
(2.13)

For temperature *change* problems, such as those in heat transfer, it is useful to remember that the chosen units (within a specific units system) do not matter (Equation 2.14):

$$\Delta T°K = \Delta T°C$$

since

$$
\begin{aligned}
T_2°C - T_1°C &= T_2(°K + 272) - T_1(°K + 272) \\
&= T_2°K(+272) - (T_1(°K + 272)) \\
&= T_2°K - T_1°K + (+272 + {}^-272) \\
&= T_2°K - T_1°K
\end{aligned}
$$

similarly,

$$\Delta T°R = \Delta T°F$$

but, of course,

$$\Delta T°R \neq \Delta T°C$$
$$\Delta T°K \neq \Delta T°F$$
(2.14)

Heat energy is particularly difficult to deal with because it may affect a material in two different ways. The obvious way that increasing or decreasing the heat energy of a material
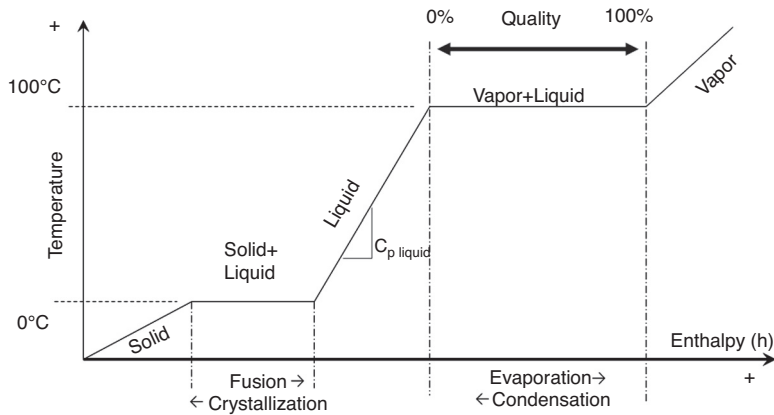
Figure 2.5. Relationship of Phase, Temperature, Enthalpy, and Specific Heat Content for Water at Sea Level

will change it is in a change of temperature, but there is also the matter of phase changes – the freezing, thawing, boiling, and condensing that most materials will exhibit. To account for the overall thermal energy contained in matter, a general term, enthalpy, is used. The best example of how enthalpy may be used is to observe it correlated to temperature in water, where the concept was originally considered (Figure 2.5).

Note that there are two distinct changes that occur as a result of the changing internal energy in a system: the change of phase and the change of temperature. These were first described by Dr. Joseph Black, a professor of medicine at the University of Glasgow, Scotland, after 1756, as he was attempting to determine the most efficient way to distill scotch whiskey that had become enormously popular in the booming British international trade economy. Dr. Black noticed that a mass of water would absorb heat but not change temperature when it was changing phase from ice to water, and that the absorption of the same amount of heat in a single-phase system (water only) would cause a change in temperature. He referred to the change of temperature as *sensible heat* because one could measure (sense) it as a change in temperature, and to the change of phase as *latent heat* because no temperature change could be measured and thus the heat was going to some other result – that of the phase change.

This was the beginning of the quantitative understanding of the intrinsic energy contained in matter, and had enormous future implications. One of Black's colleagues, James Watt, an instrument maker who was hired by the University of Glasgow in the 1750s to repair astronomical instruments, adapted several of the principles to improving the existing Newcomen steam engines that were used to pump water from mines, and produced one of the first relatively compact and efficient sources of steam power – the Watt steam engine – providing an engine to drive the nascent Industrial Revolution. Black and Watt collaborated further to gain an important understanding of the nature of heats of evaporation and condensation of water, and, by extension, those properties in other compounds. The final result was a general consideration of energy in a system, termed enthalpy, and generally defined as (Equation 2.15):
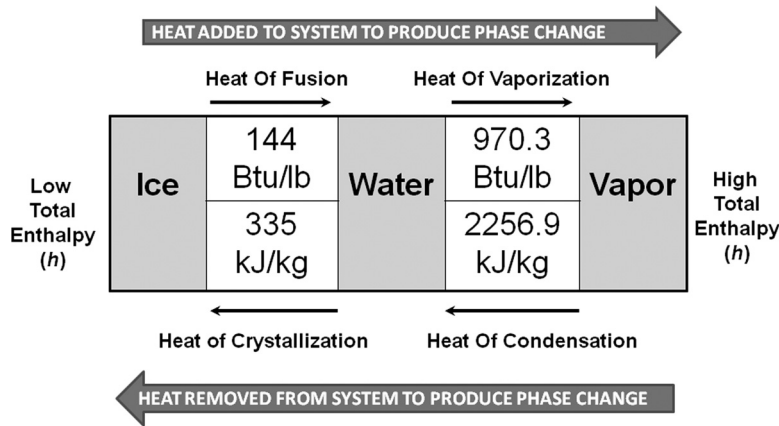
$$h = U + pV \tag{2.15}$$

h: Enthalpy, joules, J
U: Internal Energy, J
p: pressure, Pa
V: volume, m^3

Figure 2.6. Latent Heats of Phase Changes In Water

From this relationship, it can be readily demonstrated that enthalpy can vary as a function of variations in pressure, volume, or internal energy. For many of the discussions in this text, pressure and volume will be considered to be constant while the internal energy term, U, will change. Enthalpy is usually measured relative to temperature and pressure absolutes for use in chemistry and physics, but a large amount of the data is referenced to more useful measures such as the freezing point of water.

The change of enthalpy content of the water in any form can be observed as either a change of phase or a change of temperature, and one can calculate the amount of energy that goes into or out of the material to change it as required. Although most people are comfortable with the notion that adding heat will cause the changes that one observes when moving to an increased state of enthalpy, since this is what boiling water or thawing ice entails, what is not intuitively obvious in this is that when moving to a state of lower enthalpy, heat is removed from the system, either by spontaneous rejection of heat or by extracting it with a cooling device such as a refrigerator. The practical implications demand that, when doing process designs, many freezing processes in the food industry have to consider the heats of crystallization and the effect of materials in the path of that heat as it leaves the product, as shown in Figure 2.6.

The phenomenon of heat being released on crystallization is occasionally utilized in orchards to prevent fruit from freezing by spraying it with water during cold snaps, and by liquid chemical heat packs that evolve heat by crystallizing saturated solutions, particularly sodium acetate.

Pressure, Phase, and Criticality

The phase that a particular compound exhibits under specified circumstances is dependent on the surrounding pressure, temperature, and the vapor pressure of the material itself. Although the relationship between phase, pressures, and temperature is well handled by the Clausius-Clapeyron equations, a good rule of thumb for practical applications is shown in Table 2.4.

This is useful when determining the phase of liquid-vapor changes both in steam utilization and refrigeration, although the latter is well handled by refrigeration charts. An additional use for this principle is when gasses are compressed above their thermodynamic critical point until they become a *supercritical fluid*, whereupon they have the ability to both diffuse through solids and to act as a solvent. This allows processes such as the removal of caffeine from coffee to be conducted

Table 2.4. The Relationship of Phase and Pressure

Vapor Pressure of Material & Surrounding Pressure	Material State
Vapor Pressure $\geq$ Surrounding Pressure	Material in vapor state
Vapor Pressure $<$ Surrounding Pressure	Material in liquid or solid state

without toxic organic solvents. Although this process requires substantial pressure vessels to operate, the lack of residual solvents in the final product makes it appealing for more and more types of solvent operations in foods, pharmaceutical, and some types of industrial operations.

Specific Heat

The ratio of temperature change to heat input (enthalpy change) per unit mass is called specific heat capacity, which is usually shortened to specific heat. Heat capacity, which is a mass-independent term, is occasionally (and incorrectly) used as well. Specific heat values may be determined at either a constant pressure (C_p) or constant volume (C_v). Because the two are very similar for solids and liquids at the relatively low pressures and temperatures used in food processing operations, C_p is most often used and the difference between the two is seldom considered in food and other relatively low-energy systems. In calculations that are beyond the scope of this text, involving the large flows of superheated vapors or gasses such as turbine design and large-scale chemical refining, these differences become quite significant, but for most food-processing operations, the difference is negligible and C_p will be used.

Specific Heats of Complex Food Compounds

Although this text begins its discussion of specific heat values with simple compounds such as water, most food-processing operations involve compounds that have a complex and sometimes nonlinear specific heat range that is most often experimentally determined through calorimetry or some other method. Nonlinearities in heterogeneous foods may be the result of phase changes within the compounds – the crystallization or fusion of lipids, desorption of water, or some other chemical reactions. If specific data are not available for the estimation of specific heat capacities of particular food materials – these are often tabulated in published literature and handbooks and a few of these are provided in the chapter appendix – then estimation equations are available that will give a reasonable approximation of the heat needed to affect a particular temperature change [7].

The Siebel equations [8] gave a very simple first estimate of specific heat based on moisture content (Equation 2.16):

$$C_p = .04F + .02S + M \tag{2.16}$$

C_p: specific heat, $\dfrac{\text{Btu}}{\text{lb}_m \cdot {}^\circ\text{F}}$

M: water mass fraction
S: solids (non $-$ fat) fraction
F: fat fraction

However, they only give good correlation for high-moisture, low-fat foods.

Subsequent approximations such as those by Heldman and Singh (Equation 2.17) account for a larger number of components in order to provide a more accurate estimation [9]:

$$C_{\mathrm{p}} = 1.424w_{\mathrm{c}} + 1.549w_{\mathrm{p}} + 1.675w_{\mathrm{f}} + 0.837w_a + 4.187w_{\mathrm{m}} \qquad (2.17)$$

C_{p}: specific heat, $\dfrac{\mathrm{kJ}}{\mathrm{kg} \cdot {}^{\circ}\mathrm{C}}$

w_{c}: mass fraction of carbohydrates

w_{p}: the mass fraction of proteins

w_{f}: is the mass fraction of fats

w_a: is the mass fraction of ash

w_{m}: is the mass fraction of moisture

These allow a larger number of variables to accommodate more diverse materials more accurately. These approximations are usually based on the fundamental composition of the food materials (fat, protein, carbohydrates, moisture, ash, etc.) and are the result of analyzing a good deal of published data and generating a statistical approximation for the specific heat values within the relevant ranges of temperature and composition. There have been a large number of subsequent studies published regarding these types of estimations, many of which are difficult to use without a spreadsheet, but that will give a good, close correlation depending on the accuracy of formulation or material component analysis [10].

Heat Flow and Specific Heat

Heat added or rejected in temperature changes can be calculated as a factor of the temperature change, mass of compound, and specific heat (Equation 2.18):

$$q = M \cdot C_{\mathrm{p}} \cdot \Delta T \qquad (2.18)$$

q: heat necessary for temperature change, J

M: mass of component, kg

C_{p}: specific heat of compound, $\dfrac{\mathrm{J}}{\mathrm{kg} \cdot {}^{\circ}\mathrm{K}}$

ΔT: process temperature change, ${}^{\circ}\mathrm{K}$ or ${}^{\circ}\mathrm{C}$ usually $(T_{\mathrm{final}} - T_{\mathrm{initial}})$

Note that this only accounts for the materials changing temperature; if the material changes phase, the relevant energy associated with that phase change must be accounted for. For mass-flow systems, where there is a time rate of mass exchange, the heat flow can be calculated on the same time basis.

Specific heat is determined by rewriting the equation as (Equation 2.19):

$$C_{\mathrm{p}} = \frac{q}{M \cdot \Delta T} \qquad (2.19)$$

Here, the amount of heat energy required to affect a given temperature change can be experimentally determined.

Latent Heat

Latent heats are often called heats of fusion, crystallization, vaporization, and condensation as shown in Figure 2.6, depending on the process that is actually being described and its direction. These quantities are fixed for standard pressure conditions, and for most applications may be treated as constants. Changes in surrounding pressure will affect the heats of vaporization and condensation of liquids and of fusion and crystallization of solids, and should be considered in applications involving high- or low-pressure operations. The values for latent heats of compounds are usually available in engineering handbooks or in published literature. Note that the value for latent heat will only account for the heat flow to change the phase of the material – any temperature changes must be accounted for using specific heats or an equivalent method.

Heat Flow

The overall heat flow is given as (Equation 2.20):

$$q = \Sigma \left\{ MC_p \Delta T \right\} + \Sigma \left\{ \Delta \text{ latent heat} \right\} \tag{2.20}$$

So, for a simple water system, the amount of heat required to change ice at $-10°C$ to water vapor at $+120°C$ is (Equation 2.21):

Sensible heat energy to raise temperature of ice from $-10°C$ to $0°C$)
$+$ (Latent heat energy [heat of fusion] to change ice to water at $0°C$)
$+$ (Sensible heat energy to raise the temperature of the liquid water from $0°C$ to $100°C$)
$+$ (Latent heat energy $-$ heat of vaporization $-$ to change liquid water to vapor
  at $100°C$)
$+$ (Sensible heat energy to superheat vapor from $100°C$ to $120°C$)
  _____
            Total Heat Energy Required

$$\tag{2.21}$$

The amount of energy given off when the process is reversed is the same. Because of the conventions used in thermodynamics, the sign will indicate whether heat is absorbed $(+)$ or given off $(-)$. Of course, this kind of calculation can be both tedious and error-prone, particularly when working under non-standard conditions, so tabulated values of the relevant heat energies and other coefficients have been devised to ease the use of this information.

Liquid/Vapor Tables (Steam Tables)

Because it may be most efficient to burn fuels directly on-site to produce heat, and because steam transmission is a robust means of thermal energy transfer, a great deal of the energy for processing in the food industry is taken from steam supplies. Thus, a working knowledge of the energy available from steam is necessary. Steam tables, as well as thermodynamic tables for many types of refrigerants and gasses, are supplied in many engineering handbooks and are available online as well as in program form for use in many types of computing devices. Typically, these will contain heat energy values for specific states of matter, with temperature and pressure being the most common. For the purposes of this book, we can assume that the energy changes in the process are path-independent, and thus all that is necessary is to know the state of the system at the beginning and at the end of the process. An abbreviated steam table is in the chapter appendix, though it should be mentioned that for actual engineering applications, a more detailed table should be consulted.

Because of the conservation of energy in the system being considered, the usual method of use is to determine the total energy content of the material at the end of the process and the total at its beginning, and then determine the difference (Equation 2.22):

Energy Requirement = (Final Enthalpy Value) − (Initial Enthalpy Value)

$$= h_{\text{final}} - h_{\text{initial}} \tag{2.22}$$

h: enthalpy, J/kg

This is quite simple so long as the materials remain in a single phase, but it is often difficult to determine the phase of the material unless one knows the environmental conditions in which the materials exist.

Vaporization and Condensation

To account for the heat movement in liquids vaporizing or condensing, remember that a liquid vaporizes only when the vapor pressure of the liquid equals or exceeds that of the surrounding pressure. For example:

> The absolute vapor pressure of water at 100°C is approximately 14.696 PSI or 101.3 kPa, or 1 atmosphere. At sea level, then, water will make the transition to vapor when it reaches 100°C. At 20,000 feet, the surrounding pressure of the air is approximately 46% of that at sea level, equivalent to 46.52 kPa, indicating that water will boil – the vapor pressure of the liquid exceeding the surrounding pressure – at approximately 79°C, absorbing heat as it does so.

Thus, by reducing the surrounding pressure, a liquid may be made to boil at very low temperatures, and conversely by increasing the pressure, vapor may be converted to liquid even though their measured temperature is much higher than the liquid's "normal" boiling point – the basis of refrigeration processes described later in this chapter.

This has practical applications in many areas, including low-temperature evaporation in the food industry as well as the use of pressurized radiators in automobiles that allow the coolant to run at elevated temperatures without boiling. This principle is also used in "puffing" cereals where grain kernels (typically, rice or wheat) are saturated with superheated water in a closed chamber, then the pressure chamber is opened, the endosperm of the grain expands with the steam, and the moisture is usually carried away as vapor, as well as in extrusion processes where superheated water expands as the extrudate exits the pressurized extrusion barrel via the extrusion die to make a puffed product. The same principle highlights the hazard associated with removing a radiator cap from an overheated car, or removing the cap from a glass jar of food that has been heated above the boiling point in a microwave oven. In these cases, releasing the sealed cap will allow the pressure surrounding the liquids to drop to atmospheric pressure all at once, at which point the liquids boil explosively, often causing severe burns.

Quality of Steam

Because there is a large span of energy values that are available as water (or other materials) makes the transition from pure saturated liquid to pure saturated vapor, it is necessary to calculate the *quality* or useable energy content in the liquid-vapor mix. Conceptually, this means that a mass of steam that is primarily composed of saturated liquid droplets is likely to produce less energy of condensation than the same mass of steam that is completely saturated vapor and

therefore has a higher enthalpy value. This is not an intuitively obvious quantity, but can be measured using steam calorimeters that are specialized devices used to measure the energy contained in a mass of steam. Large steam operations may utilize *wet steam separators* to remove water droplets via centrifugation or other means to increase the energy content of the plant steam (Equation 2.23):

$$\text{Steam Quality} = (1 - x)(h_{sl}) + (x)(h_{sv}) \tag{2.23}$$

x: steam quality, the ratio of saturated vapor to saturated liquid, kg/kg or %
h_{sl}: enthalpy of saturated liquid, J/kg
h_{sv}: enthalpy of saturated vapor, J/kg

Based on the same analysis, the thermal quality of other mixtures, such as ice and water, can be done using a simple mass balance, but it is seldom used.

Other Liquid-Vapor Systems

While this book relies primarily on water-steam systems for illustration, there are similar systems for any number of other compounds ranging from simple gasses such as helium or carbon dioxide and liquids such as ethanol to elements that one does not commonly associate with vapor state, such as aluminum, which boils at 2,467°C and is used to coat plastic films.

Properties of Ideal Gasses and Vapors

Most simple gasses that do not change phase can be described by the ideal gas equation (Equation 2.24):

$$PV = nRT \tag{2.24}$$

P: absolute pressure, N/m^3
V: volume, m^3
n: number of moles of gas
R: gas constant, $R = 8.314 \dfrac{J}{°K \times mol}$ although many other systems of units may be used.
T: absolute temperature, °K

This can be used to describe the change in volume, temperature, pressure, or number of moles of gas involved in a particular process. One of the more useful tools that can be applied to problems involving the ideal gas law is a table of values for R, provided in the chapter appendix, the ideal gas constant that incorporates as many of the units that one is using at the time. When gas mixtures are used, the ideal gas law can be modified to accommodate Dalton's law of partial pressures (Equation 2.25):

$$P_x V = n_x RT$$

and by extension,

$$PV_x = n_x RT \tag{2.25}$$

x: fraction of particular gas species
P_x: partial pressure of gas species
V_x: volume fraction of gas species

Another useful modification of the ideal gas law for calculations where many of the constants (volume, pressure, or temperature) are held constant is (Equation 2.26):

$$PV = nRT$$

Holding $n,\ V,\ R$ constant:

$$\frac{P_{\text{final}}}{P_{\text{initial}}} = \frac{T_{\text{final}}}{T_{\text{inital}}}$$

Holding n, P, R constant:

$$\frac{V_{\text{final}}}{V_{\text{inital}}} = \frac{T_{\text{final}}}{T_{\text{inital}}}$$

Holding n, R, T constant:

$$\frac{P_{\text{final}}}{P_{\text{inital}}} = \frac{V_{\text{inital}}}{V_{\text{final}}} \tag{2.26}$$

Mechanics of Materials

All materials have similar characteristics that may be described in simple situations by a number of relatively simple descriptive equations.

Solid Mechanics

Although the nature of solid mechanics – important to basic human endeavors such as building construction since prehistoric times – has been investigated for millennia, the first mathematical underpinnings were provided by Robert Hooke in 1678, who proposed the simple elastic equation (Equation 2.27):

$$\sigma = E\varepsilon \tag{2.27}$$

σ : stress, (force per unit area), Pa, psi, Lb_f/ft^2
E : elastic modulus ("Young's Modulus"), Pa, Lb_f/ft^2
ε : strain, dimensionless; (length/length or %)

Stress

Stress in its most simple terms is the amount of force that an object is subjected to divided by the area over which it is applied. Thus, a strip of material with a sectional area of 1 cm^2 or 1.0×10^{-4} m^2 that is subjected to a force of 1 N will have a stress of 1 N/$(1.0 \times 10^{-4}$ m$^2) =$ 10,000 Pa $= 10$ kPa.

Strain

Strain is the distance that a material deforms, usually as a result of applied stress. It is most often expressed as a percentage, calculated as the final length divided by the original length. Thus, if the material was originally 10 cm long, and after the application of stress was 12 cm long, the strain would be 12/10 or 120%.

Elastic Modulus

Sometimes called Young's Modulus, after Thomas Young who established it in the early 1800s, the elastic modulus is the numerical relationship between stress and strain. It is convenient to think of this in terms of a spring or rubber band that will stretch some known distance upon the application of a force. The elastic modulus is simply calculated as stress divided by strain (Equation 2.28):

$$E = \frac{\sigma}{\varepsilon} \tag{2.28}$$

Note that for the viscoelastic materials described in this chapter, this number will usually decrease over time – a property called *creep* or *cold flow*, as the material deforms farther and farther under applied stress, and which requires time-based terms to describe.

Deformation of Solids

One of the simpler ways of describing the behavior of solid materials under stress is to place them under tension and describe their changing modes of deformation and failure as more stress applied. Because the linear-elastic behavior of solids (Figure 2.7) has already been described, subsequent additional stress and strain will often include one or more of the following features.
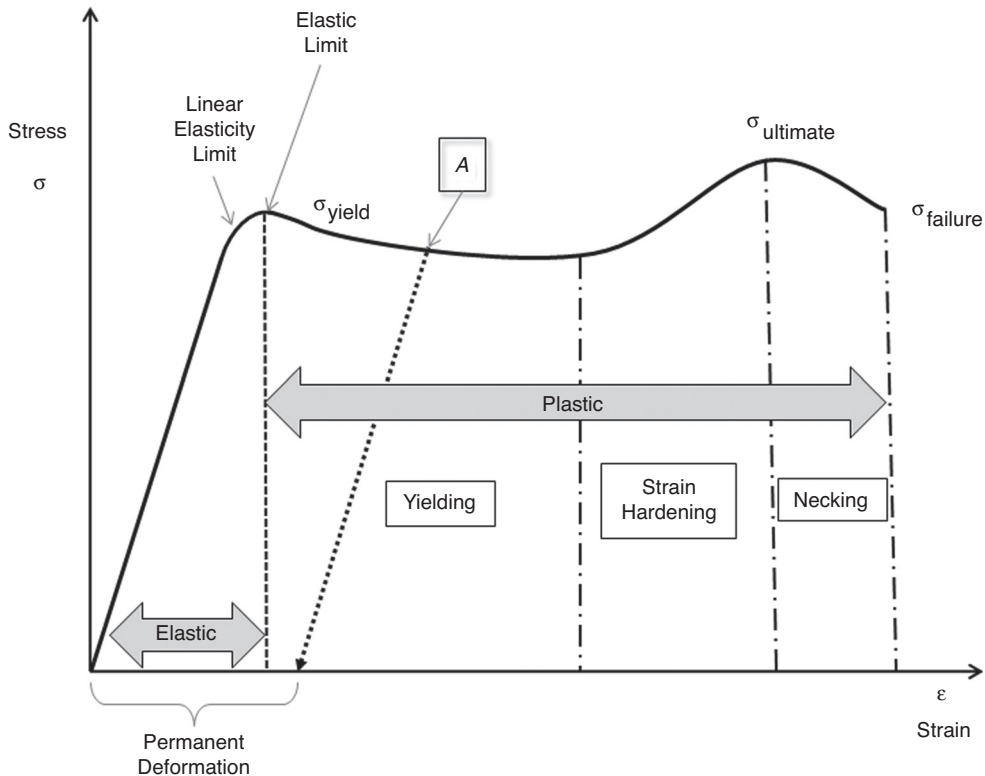
Figure 2.7. Stress-Strain Diagram for Material Under Tensile Load

Limit of Linear Elasticity

Just beyond the limit of linear elasticity, the material still behaves in a completely elastic manner, returning to original shape after the force is removed, but the linear relationship between stress and strain no longer holds. Most often, it becomes a curvelinear relationship that indicates that the material's molecular structure is distorting in unusual ways and is approaching the point at which elastic recovery is not possible.

Elastic Limit/Yield Point

The elastic limit, often different from the limit of linear elasticity, is the point at which the material will no longer behave in a strictly elastic manner, returning completely to its original dimensions. In a brittle material, this is often the failure point as well, but in a ductile material, the material may continue to deform before failing, but part of the deformation will be permanent.

Plastic Deformation

A material that exceeds the elastic limit without breaking will begin to exhibit plastic deformation that then continues until the material fails. For an extremely ductile material, there may be several hundred percent strain in the plastic deformation portion of the stress-strain curve, whereas for brittle materials such as glass and hardened steel, there may be little or none. Plastic deformation has a large number of immediate applications in metalworking and paper, as well as in what we commonly term plastics, because the mechanism of forming the material, either folding it or molding it into the useable shape of a bottle cap or an automobile fender, depends on plastic deformation of the material. Materials that are plastically deformed will store elastic energy as well, and will "spring back" slightly on release of applied force, but also exhibit useable permanent deformation as shown at point **A** on the stress-strain diagram (Figure 2.7).

Failure Point

Also called the *rupture point* or *breaking point*, this is where the materials fail completely by breaking or tearing. The failure stress is taken to be the stress that is applied when this occurs. Note that the failure stress may not be the same as the ultimate stress, and may occur after substantial deformation.

Ultimate Stress

This is the maximum stress that a material exhibits at any point under load. This may occur in any one of several points in the stress-strain curve, depending on the material. In a very brittle material such as glass, the ultimate stress, yield point, and failure stress may be very closely associated (Figure 2.8). In a highly ductile material, the ultimate stress may occur near the yield point or it may occur during plastic deformation. Some materials that exhibit cold-drawing behavior will show an extremely high ultimate stress at the failure point due to the material's molecular structure undergoing reorientation.
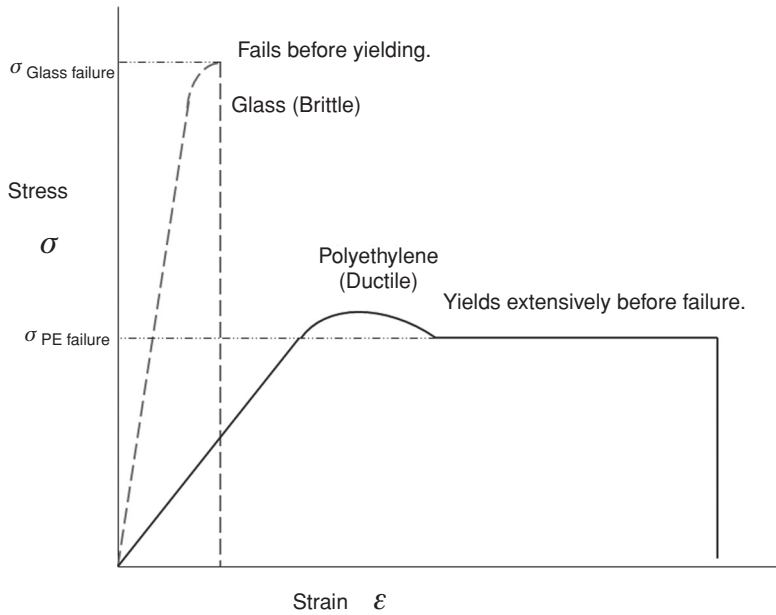
Figure 2.8. Stress-Strain Diagram Comparison of Brittle and Ductile Materials

Stress Concentration and Failure in Brittle Materials

Stress concentration and brittle fracture in elastic materials may be estimated using the Griffith Equation (Equation 2.29) (Figure 2.9) [11]:

$$\sigma_{\text{elliptical crack tip}} = \sigma_{\text{applied}} \left(1 + 2\sqrt{\frac{l/2}{\rho}} \right) \tag{2.29}$$

l: crack length, m
ρ: crack tip radius, m
σ_{applied}: applied stress, Pa

Note that the Griffith Equation shows the substantial effect of either a deep crack or a very small crack tip can have in concentrating stress past the failure point in a brittle material. Thus, small scratches or defects can have a great effect on brittle materials such as glass and tempered steel.

Although a thorough treatment of failure mechanics is beyond the scope of this book, a simple version may be given for brittle materials that promote or inhibit crack propagation as follows:

Initiation

Failure begins at some small weakness or stress concentration point in the material. A small flaw, scratch, or dent may cause this.
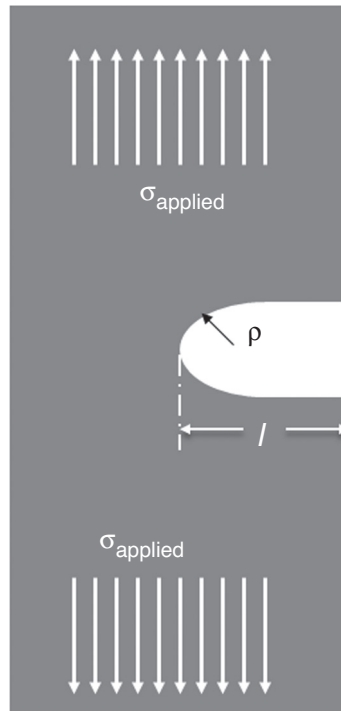
Figure 2.9. Diagram of Griffiths Brittle Failure Model

Propagation

Failure of the material will continue because the stress is still being concentrated along the progressing tip of the failure zone.

*Termination*

The failure zone continues to propagate until it is stopped. Typically, this occurs when the original stress is relieved, when the failure zone runs out of material to travel through and the piece breaks, or when it encounters an obstruction as shown in Figure 2.10a.

A crack in a piece of brittle material such as the aluminum skin of an airplane can be stopped by drilling a hole at the tip of the crack. This distributes the stress over a wide area, causing the crack growth to stop as shown in Figure 2.10b. The last means of termination results in several interesting phenomena in nature where this principle is used to add strength to materials that might be considered quite fragile otherwise. Materials can be fabricated that have *failure interrupters* in them that will exhibit strength characteristics that are quite different than the base materials from which they are fabricated. Mollusk shells are made of material that is essentially soft chalk, but is produced in such a way that it is made of microscopic overlapping plates. This structure stops any crack that may have started from progressing through the material, rendering the material very strong. In man-made structures, the interruption of failure points is often used to advantage. One of the positive features of engineered composite materials is that fractures seldom have an uninterrupted path to travel, inevitably encountering a discontinuity at a fiber
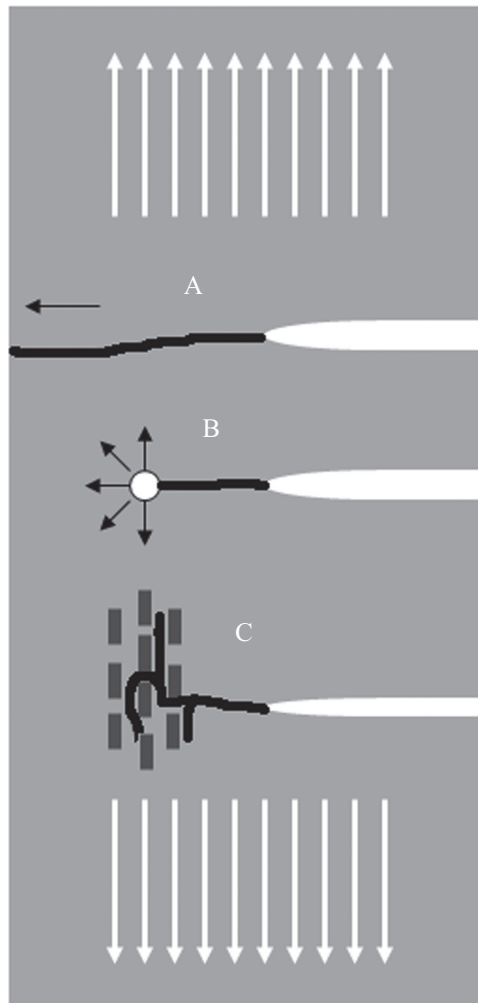
Figure 2.10. Diagram of Failure and Crack Interruptors

bond or other surface and not allowing the crack to progress easily, thereby making the material tougher, as shown in Figure 2.10c.

Failure in Ductile Materials

Ductile materials fail in more complex ways, but in general it is the result of tearing or dis-association of the structure along the boundaries of some micro- or macromolecular boundary or defect, and is accompanied by the large-scale deformation that its name would imply. In general, the material will exhibit necking, then void formation, then convergence into a final large-scale crack, and finally failure. During this process, a great deal of energy is absorbed in the microfracturing, tearing, and deformation of the material, so ductile materials are often used for their toughness – their ability to absorb a great deal of energy while deforming – rather than

their high failure strength. Automobile bumpers, sporting goods, and the like are usually made of high-impact polymers that will absorb a tremendous amount of energy before breaking.

Types of Materials

Elastic

Elastic materials store deformation energy as dimensional deflection. An elastic material will deform upon the application of stress and then return to its original dimensions when the stress is removed. Rubber bands and many harder metals such as steel are good examples of elastic materials, as is glass.

Viscous

Viscous materials dissipate deformation energy as flow. A viscous material will flow when stress is applied, and when the stress is removed, flow stops and the material will not return to its original dimensions; thus it does not store energy in the same manner as an elastic solid. Most fluids are viscous materials, as well as some biological and engineering materials.

Viscoelastic

Viscoelastic materials exhibit properties of both viscous and elastic materials, with the elastic properties predominating. Many biological and plastic materials are viscoelastic to some degree. Plastic materials and particularly those plastic materials used in the packaging industry often are viscoelastic. Viscoelastic materials are time-dependent, in that they will change over time after load application. Most often, viscoelastic materials will exhibit a property termed creep or cold flow, distorting under sustained load and dissipating load energy slowly over time as the structure becomes more and more distorted. Since these are no longer linear elastic materials, a time-dependent constitutive equation is necessary to describe them, the simplest being that in Equation 2.30:

$$\tau = E(t)\varepsilon \tag{2.30}$$

τ: stress, (force per unit area), Pa, psi, $\mathrm{Lb_f/ft^2}$
$E(t)$: time-dependent modulus, Pa, $\mathrm{Lb_f/ft^2}$
t: time, s
ε: strain, dimensionless; (length/length or %)

where E(t) is considered to decrease over time as a function of the particular material involved to account for the continued deformation of the material under a constant load, or to account for the decreasing force contained in the material under a constant deformation. More complex models exist, and time-dependent materials are an entire branch of theoretical mechanics and materials science, but this will illustrate the basic concept.

Elastoviscous

Similarly, these exhibit properties of both viscous and elastic materials, where the viscous properties dominate the system's behavior. These are similar to viscoelastic materials, but most often used for gels and biological fluids.

Anelastic

This is a broader term for the previous two terms that simply defines the relationship between stress and strain as being a complicated, time-dependent function. Because research into elasto-viscous, viscoelastic, and other time-dependent materials leads to a plethora of similar terms for similar materials exhibiting similar phenomena, this is an attempt to simplify the terminology. This should not be confused with *inelastic*, meaning "having no elastic properties" – something that rarely, if ever, occurs in real materials.

Rate-Dependent

This is a type of material that has an elastic modulus or other characteristic that is dependent on the rate of load application. A true elastic material will be rate-independent, exhibiting the same elastic modulus regardless of the rate of load application. Rate-dependent materials, on the other hand, will exhibit a differing elastic modulus depending on the rate at which the load is applied. Additionally, materials may exhibit failure points, plasticity, and load characteristics dependent on the load application rate. Some very good examples of this are time-dependent materials such as plastics, as well as rubber compounds and the natural cellulosic polymers that make up paper.

Fluid Flow Systems

For fluid systems, it is first necessary to develop an understanding of the nature of fluid systems as used by engineers. Fluids, which include both liquids and gasses, may be thought of as either *compressible* or *incompressible*, depending on whether they change density with pressure. Although it is commonly thought that liquids are incompressible while gasses may be readily compressed, this is not absolutely true. Sound waves are readily propagated through water or other fluids by compression and rarefaction – a truly incompressible fluid would not transmit sound at all. However, in useful analyses, the assumptions that liquids are generally incompressible and gasses are compressible are used. There are some significant deviations from this, particularly in the food industry that routinely handles materials that are foamed or otherwise have gasses trapped in a liquid matrix. Hydraulics systems engineers also must contend with the fact that hydraulic fluid in heavy machinery will entrain a good deal of air when being used and will become "spongy", able to compress somewhat, reducing the effectiveness of many hydraulically driven implements.

For fluid flow to occur, there must be the application of force (usually in the form of a pressure differential), and unlike solids, which will deform under the application of force, this will result in a time rate of flow.

Thus, much as stress produces strain in a solid and vice versa, shear force produces shear flow in fluids and vice versa. Additionally, a differential in flow velocities will create shear force, with viscosity, the corresponding resistance to shearing (and therefore flow), corresponding to a solid material's resistance to deformation. A rough correspondence between solid mechanics and fluid mechanics is shown in Equation 2.31:
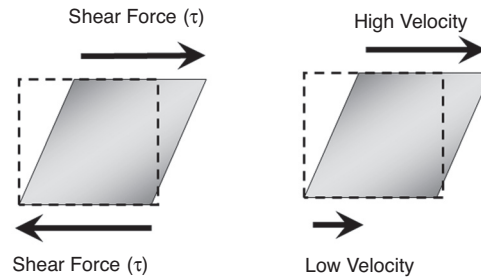
Solids   (2.31)

$$\sigma = E\varepsilon$$

σ : stress, (force per unit area)
E : elastic modulus ("Young's Modulus")
ε : strain

Figure 2.11. Diagram of Shear Deformation in Fluids

Fluids

$$\tau = \mu\dot{\gamma} = \mu\frac{dV}{dx}$$

 τ: shear stress, Pa

 μ: viscosity, Poise, 1 Poise $= 1\,\text{Pa}\cdot\text{s} = 1\,\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$

 $\dot{\gamma}$: velocity gradient, $\dfrac{dV}{dx}$, s^{-1}

Flow will continue so long as the force is applied and, unlike elastic solids, will not return energy once the force is removed. Fluid flow energy is usually dissipated as turbulence, friction, and eventually heat energy.

Flow Regimes

Fully developed flow may be thought of as either *laminar* or *turbulent*. Laminar flow indicates that the flow of the material does not change lateral position as it progresses along a reference axis, and thus a particle of material that is at a certain position in the cross section of the fluid flow will not change that position as the fluid makes its way down the flow channel or pipe. Because of this, laminar flow does not exhibit the same heat and mass transfer capacity as turbulent flow. The flow profile of a laminar flow regime is usually parabolic, with the maximum velocity in the center of the pipe being approximately twice that of the average velocity, although this will change with viscosity. Turbulent flow, on the other hand, indicates a great deal of mixing, and any material will change position in all three axes as it is transported. Because of this, the peak velocity at any point is statistically uncertain but can be approximated as 1.2 times the average flow velocity of the fluid for Newtonian fluids.

Reynolds Number

The Reynolds number is a dimensionless number that is used to determine the fluid flow regime as shown in Equation 2.32:

$$\text{Re} = \frac{\rho V x}{\mu} \tag{2.32}$$

 ρ: fluid density, kg/m^3

 V: fluid velocity, m/s

x: characteristic length dimension usually pipe diameter (D) or
   distance from leading edge in fluid flow, m
μ: viscosity, Poise, 1 Poise $= 1\,\text{Pa}\cdot\text{s} = 1\,\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$

For flow in pipes with diameter D,

$$\text{Re} = \frac{\rho V D}{\mu}$$

Re $< 2{,}100$,	laminar flow – poor mixing, parabolic flow profile
$2{,}100 < $ Re $< 4{,}000$	transitional flow – not used in this text
$4{,}000 < $ Re	turbulent flow – good mixing, flow profile variable

Developed Flow in Pipes, Tubes, and Ducts

As fluids enter a piping or channel system, they will exhibit momentary turbulence and insta-bility as the fluid inertia continues to disrupt the fluid flow regime for some time, resulting in *undeveloped flow*. For developed flow to occur, the fluid must travel a distance approximated by the Entrance Length Number (*El*) (Equation 2.33) [12]:

$$L_{\text{fd}} = \text{El}^* D \qquad\qquad (2.33)$$

L_{fd} : length of flow to fully developed velocity profile, m
D : pipe diameter, m
El : entrance length number, dimensionless
$\text{El}_{\text{turbulent}} = 4.4\,(\text{Re})^{.167}$
$\text{El}_{\text{laminar}} = 0.06\,(\text{Re})$

Energy Equation

For the handling of fluid products, the energy requirements of a fluid flow system may be expressed as (Equation 2.34):

$$W_{\text{s}} = \Delta\text{KE} + \Delta\text{PE} + \Delta P/\rho + E_{\text{f}} \qquad\qquad (2.34)$$

W_{s} is the energy required to drive the process, in m^2/s^2. This value is positive if energy is put into the system (such as with a pump) and negative if energy is being extracted (as with a hydro-electric turbine). The power (in Watts) required to drive the process may be obtained by mul-tiplying W_{s} in m^2/s^2 by the mass flow rate in kg/s; ($\text{m}^2/\text{s}^2{}^*\text{kg/s} = \text{kg}^*\text{m}^2/\text{s}^3 = (\text{kg}^*\text{m}^2/\text{s}^2)/\text{s} - \text{J/s} = \text{Watts}$)

ΔKE is the change in kinetic energy in the system, also in m^2/s^2, $\Delta\text{KE} = \frac{1}{2}\,m(V_{\text{final}} - V_{\text{initial}})^2$.

ΔPE is the change in potential energy in m^2/s^2, usually related to a change in height (h) of the fluid. This is most often calculated as $mg(h_{\text{final}} - h_{\text{initial}})$.

$\Delta P/\rho$ is the change in system energy due to pressure changes in m^2/s^2. $\Delta P/\rho = (V_{\text{final}} - V_{\text{initial}})/\rho$. The quantity ΔP is divided by density, ρ, to create dimensional consistency with the other terms.

E_f is energy losses due to friction in the system in m²/s². Most often this is calculated using the Fanning Friction Equation and estimations given in Equation 2.35 [13]. There is also a similar Darcy-Weisbach friction factor that is often used by civil and mechanical engineers, and whose value is four times that of the Fanning Friction Factor – the two should not be confused.

$$E_f = \frac{2fV^2L_{total}}{D} \tag{2.35}$$

f: Fanning friction factor, Dimensionless
V: Average fluid velocity, m/s
L_{total}: Total pipe length, including sum of equivalent pipe lengths, m
D: Actual pipe inside diameter, m (may be different than published pipe size designation)

Estimation Equations for the Fanning friction factor (f):

For Laminar Flow:		
Re < 2300	Moody:	$f = 16/\text{Re}$
For Turbulent Flow:		
$10^4 < \text{Re} < 10^7$	Filonenko:	$f = (1.58 \ln(\text{Re}) - 3.28)^{-2.0}$
$3000 < \text{Re} < 10^5$	Blasius:	$f = 0.079\,\text{Re}^{-2.5}$
$6000 < \text{Re} < 2.0 \times 10^5$	McAdams:	$f = 0.046\,\text{Re}^{-0.2}$
$2000 < \text{Re} < 10^5$	Koo:	$f = 0.0014 + 0.125\,\text{Re}^{-0.32}$

Source for Estimation Equations: "Charmeau, A. et al. (2009) "Ultrahigh Specific Impulse Nuclear Thermal Propulsion", DOE Award Number DE-FG07-05ID14699, Final Report. p.166.
Available from: DOE Office of Scientific and Technical Information: http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=718A80A47AACC05C5D7C0C8A4B9E3C90?purl=/950459-XggUh7/

Note that fluid viscosity plays a role in both the Reynolds number and the Fanning friction equation, making it the dominant factor in many food-related fluids with high viscosities, and thus most of the power that is often needed in a pumping system is used to overcome fluid friction (Figure 2.12) rather than any great distance, height, or pressure:

Pipe Equivalent Lengths

Equivalent lengths (L_{eq}) is a method used to simplify the accounting for friction and pressure loss through piping systems that have fittings, valves, diameter changes, and other deviations from flow in simple, straight pipes. Using the equivalent length formula shown in Equation 2.36:

$$L_{eq} = L'/D \tag{2.36}$$

L_{eq}: equivalent length of pipe used in friction calculation, m
D: actual inside diameter of pipe, m
L': length equivalence factor specific to the particular fitting or bend, dimensionless
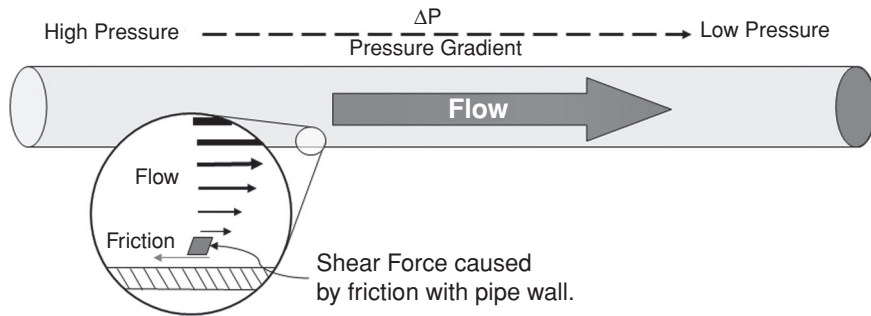
Figure 2.12. Diagram of Fluid Shear in Pipe Flow

in the friction equation, the equivalent straight-pipe lengths may be found and added to the overall length of straight pipes in the friction equation. Some simple L' values are shown in Table 2.5, but in practical use, these are tabulated in engineering handbooks or may be supplied by the fitting or equipment manufacturer.

Pump Efficiencies

Like most mechanical devices, fluid pumps are subject to inefficiencies due to impeller design, leakage, turbulence, and other design factors. When using the energy equation for any practical purpose, one must realize that the energy equation will only give the theoretical value for power in the fluid. This will not be the amount of power that must be applied to an inefficient pump or being produced by an inefficient fluid-flow turbine, so inefficiencies must be considered. Most pumps or turbines have an efficiency rating, either supplied by the manufacturer or that can be generalized from handbooks that may be used to calculate the actual power involved (Equation 2.37):

Pumped system (W_s negative): Actual power required $= W_s/\varepsilon$

Turbine system (W_s positive): Actual power produced $= W_s{}^*\varepsilon$

(2.37)

Table 2.5. L'/D Values for Common Fittings and Bends

Item	Description	L'/D
Globe Valve	Fully Open	340
Ball Check Valve	Fully Open	150
90° Standard Angle		30
45° Standard Angle		16
Tee Fitting	Flow through "run"	20
Tee Fitting	Flow through "branch"	60
Return Bend ("U") Fitting		50

Source: Department of Defense (2004), "United Facilities Criteria (UFC);
Exterior Mechanical Utility Distribution." UFC 3-430-09N.
http://www.wbdg.org/ccb/DOD/UFC/ufc_3_430_09.pdf

While students usually try to memorize this (and then often misapply it), it is more useful to remember that any power-handling device will lose energy in the exchange, so whether it is the fluid flow providing power to a turbine or a pump providing power to move the fluid, the energy transmitted through the device will always be less than that supplied to it.

Pressure and Safety in Fluid Systems

The energy equation may be used to determine the pressure at any point in a piping network, but particular care must be taken with high-pressure systems where rupture of pipes, seals, or equipment housings may create a safety hazard. Additionally, if the pressure of a fluid drops below its vapor pressure, the phenomenon of *cavitation* will occur – low-pressure bubbles of vapor rapidly forming and collapsing, usually on a localized basis. This can impede pump efficiency and, if the collapse of the bubbles is energetic enough, will create acoustic shock waves that will chip material from the pump impellers and housings. This will shorten the life of the equipment and cause problems with stray metal in the product.

Misuse of Energy Equation Fluid Flow Models

It is tempting to use the energy equation models to attempt to calculate the flow requirements for all types of situations, but it should be remembered that the application of equations to estimate the operation of a system based on relatively low viscosity Newtonian fluids will probably not work well when applied to very thick, viscous fluids often used in the food industry. Many of these materials are gels and viscous solids and barely flow under high pressure in a regime termed *plug flow*, where slugs of material are pushed intact through the system with very little deformation. Rheological determination of the flow properties can assist in determining the proper type of modeling equation, or whether the flow can be modeled on a fluids basis. There have been instances of process engineers attempting to use the energy equation to calculate flow parameters with obviously inappropriate materials, with catastrophic equipment failure such as pump seal and explosive pipe rupture as a result.

Rheology

Rheology is the study of the flow and deformation of matter. Very often this is utilized in the study of the nature of flow of fluids and fluid-like materials. Although water, hydrogen gas, and corn syrup may not appear to have many features in common, the basic concepts of rheology apply to all of them. Because many food products are made up of complex fluid mixtures, often with unusual characteristics, rheology becomes an important consideration in food engineering.

Viscosity

Viscosity is a measure of a fluid materials resistance to flow, and for many common systems is related back to the flow behavior of water under standard conditions. There are several common types of fluids, all of which are distinguished by viscosity characteristics.

Newtonian fluids have constant viscosity that will only vary with temperature, and are described by the simple, linear relationship between shear force and shear rate, as shown in
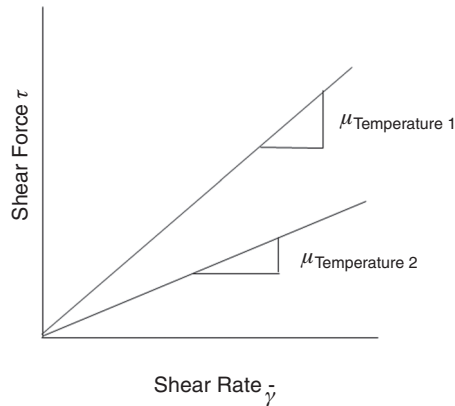
Figure 2.13. Relationship of Shear Force and shear Rate in Newtonian Fluids

Figure 2.13 and described by Equation 2.38:

$$\tau = \mu \, \dot{\gamma} \tag{2.38}$$

τ : shear stress in the fluid, Pa
$\dot{\gamma}$: shear rate of fluid flow, s^{-1}
μ : viscosity, Pa $\cdot$ s

Power Law fluids are related by a similar equation that accommodates the non-linearity in the stress-shear rate relationships (Equation 2.39):

$$\tau = k\dot{\gamma}^n \tag{2.39}$$

k : consistency index, dimensionless
n : flow behavior index, dimensionless

The experimentally determined *consistency index* and *flow behavior index* replace the viscosity term and will give an indication of the non-linear response to changing shear stress in the fluid. The simplest case is where the flow behavior is completely linear – a Newtonian fluid – and thus $k = \mu$ and $n = 1$.

Adding an initial stress that must be overcome to start the fluid flow, which is a common feature in rheologic fluids – most annoyingly, ketchup and salad dressing in glass bottles – and these fluid types become *Bingham fluids*, thus Equation 2.40 gives:

$$\tau = \tau_0 + k\dot{\gamma}^n \tag{2.40}$$

τ_0 : inital shear stress to initiate flow, Pa

For practical purposes, there are several equations that allow flow analysis to be done using the equations available for generalized Newtonian fluid flow, but with the appropriate calculation adjustments for the Reynolds number and other factors. In effect, this will allow the analysis of a simple flow system that is under steady-state conditions given the appropriate fluid parameters.
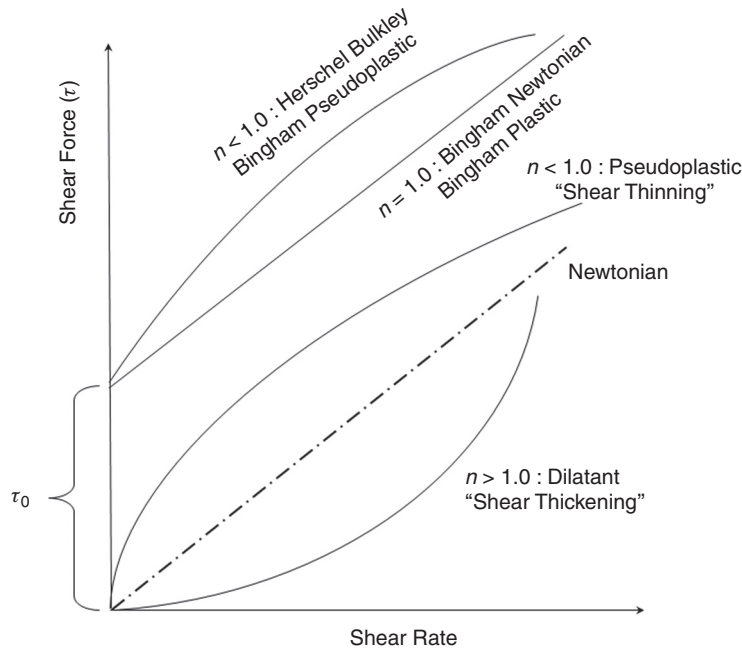
Figure 2.14. Relationship of Shear Force and Shear Rate in Power Law Fluids

Viscoelastic Materials

Viscoelastic (and elastoviscous) materials both store energy as an elastic solid and dissipate energy over time as a fluid; their describing equations are more complex and must manage to describe the stress-strain relationship as a function that includes time as well.

In practical use, several other models beyond the simple time-dependent one given in Equation 2.41 have been proposed to describe simple viscoelastic types of materials. These are usually modeled by engineers after two simple devices: a spring and a dashpot. A spring is simply a piece of material that can store and instantly return elastic energy, and a dashpot is a simple piston-and-orifice device that dissipates force through viscous fluid flow over time.

A practical combination of spring and dashpot can be found in screen door closers that force the door closed slowly by combining spring force and fluid flow to provide slow, steady closing force, or in automobile suspensions that combine a shock absorber (dashpot) and spring to provide isolation from shock and vibration caused by driving over rough surfaces. This latter principle becomes important in shock and vibration isolation for packaged products, and will be discussed in Chapter 9.

"Static" Properties of Viscoelastic Materials

Combining the spring and dashpot components in different sequences gives a means of visualizing and quantifying the relationship between force and response in the materials. In essence, they are very similar in the sense that they will show a short-term response that mimics a simple elastic solid, and over a longer period of time will exhibit continued deformation over time that either will reach an extreme value and stop or will continue until the material fails.

Maxwell Model

Kelvin–Voigt Model

Standard Linear Solid Model
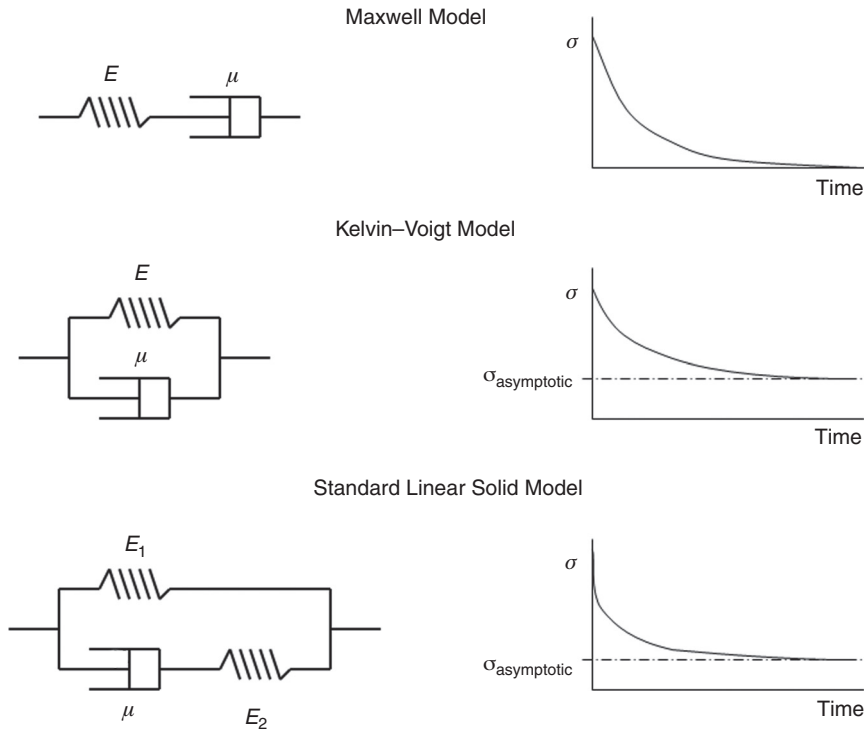
Figure 2.15. Viscelastic Models and Their Behavior Under Sustained Stress

The three most common viscoelastic models are the Maxwell, Kelvin-Voigt, and the standard linear solid model, which are shown, along with their time response to a constant stress loading, in Figure 2.15; their respective constitutive equations are shown in Equation 2.41.

Maxwell Model:

$$\frac{d\varepsilon}{dt} = \frac{\sigma}{\mu} + \frac{1}{E}\left(\frac{d\sigma}{dt}\right)$$

Kelvin-Voigt Model:

$$\sigma(t) = E\varepsilon(t) + \mu\left(\frac{d\varepsilon(t)}{dt}\right)$$

Standard Linear Solid Model:

$$\frac{d\varepsilon}{dt} = \frac{\dfrac{E_2}{\mu}\left(\dfrac{\mu}{E_2}\dfrac{d\sigma}{dt} + \sigma - E_1\varepsilon\right)}{E_1 + E_2} \tag{2.41}$$

E_n: elastic modulus of spring element n
μ: viscosity coefficient for dashpot

The Maxwell model is the only model that allows stress to be completely dissipated and the material to extend indefinitely mimicking a viscoelastic fluid or very soft polymer, whereas

in the Kelvin-Voigt model, the stress will reach an asymptotic value ($\sigma_{asymtotic}$) and stop. The standard linear solid model adds initial, instantaneous elastic stress removal to the Kelvin-Voigt model, which is a moderately good representation of many polyolefins and packaging plastics. Further, the constitutive equations allow further analysis of material response to vibration and unusual loading schemes.

The practical implications of this are extremely important in the design of packaging structures because they are often required to sustain loads for periods ranging from weeks to years. A hanging pouch of viscoelastic material that exhibits a large and continuing degree of deformation over time will sag and perhaps fall from a display, and a pressurized soft drink bottle would expand into a nearly cylindrical balloon, making them both unstable and unappealing, whereas polymers that have predictable degrees of initial deformation may be properly engineered to fit specific applications.

Dynamic Properties of Viscoelastic Materials

Viscoelastic materials' combination of solid and fluid properties makes them unique in their response to cyclical input. Simple undamped springs will exhibit either an amplifying or damping effect depending on the relationship of the natural frequency of the system to its forcing frequency. Fluid response is somewhat more complex because it responds to the velocity of fluid flow rather than a simple measure of force. Because of this, fluid systems tend to provide a phase shift in their response, considering that the peak velocity often occurs at minimal deflections in the fluid system – the midpoints between extremes.

The combination of viscous and elastic properties may be utilized to "tune out" specific frequencies, reducing the amount of vibration transmitted. This concept is often used in a general form in the design of many package cushions, but is often carefully implemented into specially engineered couplings designed to reduce vibration from motorcycle and automobile engines, and in delicate aerospace installations. This will be discussed further in Chapter 9, in the section dealing with transportation damage and cushioning.

Heat Transfer

Heat transfer is critically important in many types of processing operations that depend on thermal processes for sterilization or pasteurization, as well as in many types of packaging-manufacturing systems. As with the other conservative engineering models, the underlying assumption is that there is a control volume, and that the energy entering, leaving, or remaining within the volume must be accounted for. Although there are many types of energy transfer, as previously described, heat transfer is typically broken into three main modes of energy transfer: radiation, conduction and convection. All of these rely on a variation of the generalized heat transfer equation (Equation 2.42):

$$q = UA(\Delta T_{ht}) \tag{2.42}$$

q : amount of heat transferred, W, $\dfrac{\text{kg} \cdot \text{m}^2}{\text{s}^3}$

ΔT_{ht} : heat transfer temperature difference $^\circ$K

A : heat transfer area, m^2

U : heat transfer coefficient, $\dfrac{\text{W}}{\text{m}^{2\circ}\text{K}}$

Radiation Heat Transfer

Radiation heat transfer is the only one of the three main modes that does not require an intermediate material such as a solid or liquid through which the heat is transferred. Instead, it relies on electromagnetic energy transfer, usually in wavelengths near the infrared spectra. Other types of radiation, using higher frequencies, rely on the receiving materials or structures to convert the energy such as light or microwave energy to lower-frequency forms such as heat.

Radiative heat transfer is dependent on several factors, including the differences in energy of the surfaces emitting and absorbing the energy (quantified as similar *emissivity* and *absorption* coefficients, respectively), the absolute temperatures of the surfaces, and a constant known as the Stefan-Boltzmann constant. Thus, the radiation heat transfer value can be quantified for a surface radiating heat to a very large area as (Equation 2.43):

$$q = \sigma A_1 \varepsilon_1 \left(T_1^4 - T_2^4\right) \tag{2.43}$$

q: the overall heat transfer from emitter, W
$\sigma = (5.6703 \; 10^{-8} \; \text{W/m}^2\text{K}^4)$; the Stefan-Boltzmann Constant
A is the area of the emitting surface, m^3
ε_1 is the emissivity of the emitting surface, dimensionless
T_1 is the absolute temperature of the emitting surface,°K
T_2 is the absolute temperature of the cooler surroundings,°K

A partial table of emissivity reveals why radiative and absorbing surfaces are often painted black when a great deal of heat exchange is desired, and why touching a dark surface such as the hood of a black car on a sunny day can be a painful experience. The emissivity values (ε) of several example surfaces are given in Table 2.6.

Conduction Heat Transfer

Unlike radiation, conduction requires an intermediate material to transfer the heat into or out of a material. It is distinguished from convective heat transfer because the conducting materials usually do not move. Heat conduction depends on several factors: the temperature difference across a particular material, the nature of the material's ability to convey heat, and the surface area involved. Fourier's Law, named after Joseph Fourier, the French mathematician and physicist who first postulated it, can be used to describe the one-dimensional (linear) heat flow through a solid body as (Equation 2.44):

$$q = -k\mathbf{A}\frac{\partial \mathbf{T}}{\partial \mathbf{x}} \approx -k\mathbf{A}\frac{\Delta \mathbf{T}}{\Delta \mathbf{x}} \tag{2.44}$$

q: overall heat transfer, W
A: heat transfer area, m^2
k: thermal conductivity, $\dfrac{\text{W}}{°\text{C} \cdot \text{m}}, \dfrac{\text{W}}{°\text{K} \cdot \text{m}}$
$\dfrac{\partial \mathbf{T}}{\partial \mathbf{x}}$: generalized temperature differential, °C/m, °K/m
$\dfrac{\Delta \mathbf{T}}{\Delta \mathbf{x}}$: steady-state temperature difference $\Delta \mathbf{T}$ through distance $\Delta \mathbf{x}$, °C/m, °K/m

(Note that the negative term ensures that the heat flow will move from hot to cold region)

Table 2.6. Table of Selected Emissivity (ε) Values

Material	ε
Carbon Black	0.95-0.99
Steel, Polished	0.7
Ice & Snow	0.94-0.99
Black Paint	0.96
Bread (average)	0.9
Wood	0.85
Soil	0.38
Aluminum Paint	0.30
Aluminum Foil	0.06-0.09
Silver, Polished	.01

Sources: S. Grabowski, M. Trigui, M. Marcotte, and F. Castaigne (2006). "Heat Transfer Coefficients on Cakes Baked in a Tunnel Type Industrial Oven," *Journal of Food Science* 64(4), 688–94.
N. Hamdami, J.-Y. Monteau, and Alain Le Bailb (2004). "Heat and Mass Transfer in Par-Baked Bread during Freezing," *Food Research International* 37(5), 477–88.
MODIS UCSB Emissivity Library. http://g.icess.ucsb.edu/modis/EMIS/html/em.html
N. P. Zogzas, M. K. Krokida, P. A. Michailidis, and Z. B. Maroulis (2002). "Literature Data of Heat Transfer Coefficients in Food Processing," *International Journal of Food Properties* 5(2), 391–417.

For a composite surface such as that shown in Figure 2.16, which is a common feature in insulated structures ranging from food packages to picnic coolers to house walls, the overall equation becomes (Equation 2.45) based on the assumption of constant heat flow through the composite section of material:

for *n* layers with individual thicknesses: $\Delta X_{1,2,3\ldots n}$ and thermal conductivities: $k_{1,2,3\ldots n}$

$$q = -A \left[\frac{\Delta T_{\text{overall}}}{\left(\frac{\Delta X_1}{k_1}\right) + \left(\frac{\Delta X_2}{k_2}\right) + \cdots + \left(\frac{\Delta X_n}{k_n}\right)} \right] \tag{2.45}$$

A: heat transfer area, m^2

$\Delta T_{\text{overall}}$: temperature difference throughout entire composite structure, $^\circ$C, $^\circ$K

Calculation of steady-state heat conduction is a fairly straightforward exercise once the material thicknesses and thermal conductivities are known. Thermal conductivities of some materials are given in Table 2.7.

Convection Heat Transfer

The third major means of heat transfer, convective heat transfer is the most commonly experienced in everyday life. Heat is convected into or out of our body continuously to maintain body temperature and to remove heat generated by our body's metabolic processes. For convection to occur, it is necessary to have a moving fluid to exchange heat. Convective heat transfer therefore becomes the most complex to calculate because it requires an understanding of fluid flow and
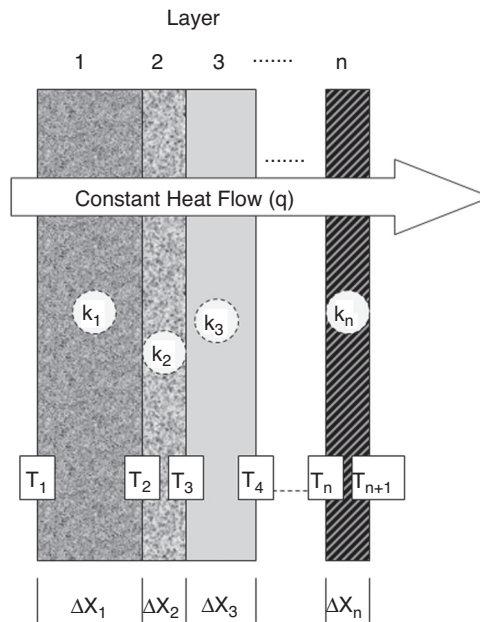
Figure 2.16. Composite Heat Conduction Diagram

the bulk properties of materials to arrive at a quantitative estimation of how much heat will be exchanged under a given set of conditions. In addition to this, for many of the estimation systems, knowledge of whether the system is a *forced* or *natural* convection system is necessary, because the amount of heat exchanged is often different by several orders of magnitude.

Considering that we have already defined fluids in terms of compressible and incompressible rather than liquid or gas, we have a set of equations that will predict fluid flow for both liquids

Table 2.7. Thermal Conductivities of Common Materials

Thermal Conductivities (W/(m°K))	
Aluminum	205–250
Steel	36–54
Stainless Steel	16.3
Glass	0.8–1.4
Packaging Plastics	0.04–0.52
Foods	0.6–0.7
Water	0.5–0.6
Ice	1.6–2.2
Snow	0.05–0.25
EPS Foam	0.03
Urethane Foam	0.021
Fiberglass	0.04
Silica Aerogel	0.003–0.03

Source: "Thermal Conductivity of Some Common Materials."
http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html

and gasses. For convective heat transfer, we also have to have an understanding of what is causing the fluid movement – convection – to understand the amount of heat energy that will be transferred.

Natural convection, sometimes called free convection, is driven by the change in bulk density of the fluid. As the fluid is heated, it will expand, and will decrease in density, causing it to rise to a region of similar density. As it cools, its density will increase and it will sink. In many heating systems, as well as in nature, these two events will be coupled, causing a repeating cycle of heating and cooling of the same material, often forming *convection cells*, regions where the hot material flows upward in a column then settles in a region outside of the upwelling fluid. Clouds are the most common example of this, although it can be observed on the surface of a pot of boiling water. Natural convection is often exploited to manufacture relatively inexpensive heat exchangers with few or no moving parts that are used in solar collectors, hot water heaters, and geothermal heating systems. Because fluid velocity is determined solely by bulk density changes, it is not immediately apparent what the Reynolds number is, and so it is often hard to discriminate between the laminar or turbulent flows. This is usually determined as a result of other empirical formulas.

Forced convection, on the other hand, relies on an external source of power for the fluid movement and is usually orders of magnitude more effective in transferring heat than natural convection. Although natural convection effects still exist in a forced-convection system, they are usually overwhelmed by the action of the pump or fan, and are most often neglected in simple calculations. In a forced-convection system, fluid velocity can be measured or calculated and a Reynolds number determined.

The overall heat transfer in a convective system is given by (Equation 2.46):

$$q = hA(T_f - T_s) \tag{2.46}$$

q: overall convective heat transfer, W/m^2

h: convective heat transfer coefficient, $\dfrac{W}{m^2 \cdot {}^\circ C}$, $\dfrac{W}{m^2 \cdot {}^\circ K}$

A: heat transfer area, m^2

T_f: fluid temperature, $^\circ$C, $^\circ$K

T_s: surface temperature, $^\circ$C, $^\circ$K

Determination of the Convective Heat Transfer Coefficient

Determination of the convective heat transfer coefficient is the most arduous part of calculating a value for convective heat transfer. Although tabulated estimations exist, the determination of this value may require any number of different types of analyses. Because of the complexity of these calculations, a series of simple empirical equations based on the type of flow and other parameters have been designed to calculate the Nusselt number (Equation 2.47):

$$\mathrm{Nu} = \frac{h \cdot L}{k} \tag{2.47}$$

h: the convective heat transfer coefficient, $\dfrac{W}{m^2 \cdot {}^\circ C}$, $\dfrac{W}{m^2 \cdot {}^\circ K}$

L: characteristic length of system, m

k: Fluid thermal conductivity, $\dfrac{W}{m \cdot {}^\circ C}$, $\dfrac{W}{m \cdot {}^\circ K}$

For pipes, $L = D$

$$\text{Nu} = \frac{h \cdot D}{k}$$

By rearranging terms:

$$h = \frac{\text{Nu} \cdot k}{d}$$

Determining the Nusselt number in practical applications requires that the nature of the flow regime, fluid type, and type of convection be known, as well as perhaps several other factors to determine which equation to apply. These have been derived by dimensional analysis and empirical studies, and are therefore useful only within the limited conditions set forth in the equation set. However, once the estimation of the Nusselt number is made, Equation 2.47 may be combined with the known values for diameter and fluid thermal conductivity to give an immediate estimate of the value of the heat transfer coefficient (h).

Estimation of The Nusselt Number

Estimation of the Nusselt number is a large part of heat transfer analysis, and there are a number of empirical formulas available for different materials and flow regimes. A very limited list of generally applicable models will help understand the method of analysis, but specific applications may require consulting a more specialized heat transfer reference.

Nusselt Number for Turbulent Flow

The simplest estimation calculation for fully developed turbulent flow in smooth tubes that considers the effects of temperature on the fluid viscosity was proposed by Sieder and Tate (Equation 2.48) [14]:

$$\text{Nu} = 0.027 \text{Re}^{0.8} \, \text{Pr}^{0.33} \left(\frac{\mu_{\text{bulk}}}{\mu_{\text{wall}}} \right)^{0.14} \tag{2.48}$$

Pr: Prandtl Number, dimensionless

$$\text{Pr} = \frac{C_{\text{p}} \cdot \mu_{\text{bulk}}}{k}$$

μ_{bulk}: bulk viscosity of fluid, Pa $\cdot$ s

μ_{wall}: viscosity of fluid at heated or cooled surface, Pa $\cdot$ s

C_{p}: specific heat of fluid, J/(kg K)

k: thermal conductivity of fluid, W/(m K) and is valid for

$0.7 \leq \text{Pr} \leq 16{,}700$

$\text{Re} \geq 10{,}000$

$\dfrac{L}{D} > 10$

For laminar heat transfer in tubes, another estimation equation is available (Equation 2.49):

$$\text{Nu} = 1.86(\text{Re} \cdot \text{Pr})^{0.33} \left(\frac{D}{L}\right)^{0.33} \left(\frac{\mu_{\text{bulk}}}{\mu_{\text{wall}}}\right)^{0.14} \tag{2.49}$$

$\quad D$: tube diameter, m

$\quad L$: tube length, m and is valid for

$\quad \text{Re} \cdot \text{Pr} \cdot \dfrac{D}{L} > 10$

Formation of Laminar Sublayers

Because of the three-dimensional nature of real-world applications, Reynolds numbers description of fluid flow applies in all directions of fluid flow. For a flat heat exchanger plate or the surface of a tubular heat exchanger, a region just near the surface may develop laminar flow, even in flow regimes that are generally turbulent. This will interfere with heat transfer, because the laminar fluid flow will transfer heat only by conduction due to the lack of mixing. If this phenomenon is obstructive enough, the flow or heat exchanger will have to be modified to correct the problem, and the application may require scraped-surface heat exchangers or unusual surface profiles to overcome this limitation. These are a common feature in food processing applications with high viscosity fluids.

Heat Exchangers

Heat exchangers are a means of transferring heat from one medium to another, and typically involve at least one fluid component. These exchangers may take many diverse forms in nature and engineering from jackrabbits' ears that have evolved to help lose body heat in the desert to the extraordinary energy transfer systems that are designed into nuclear power plants. In food processing, heat exchangers run the gamut from a simple cooking pot to complex, multistage systems for aseptic processing.

Direct-contact heat exchangers will mix the heating medium (typically, hot water or "culinary steam" that does not add taste to the product) with the product, and the more common, indirect heat exchangers will separate the heating or cooling medium from a product by means of a series of tubes, plates, or other surfaces that are typically made of a thermally conductive material such as stainless steel.

Because of the diverse nature of food products, the heat exchangers that have been developed to process them are similarly diverse, but they all share the requirements of being thermally efficient, cost-effective, durable, and sanitary. Low-viscosity fluids that easily develop turbulent flow can be processed in single or multipass tubular or plate heat exchangers, whereas more viscous products may have to have shaped tubes or even mechanically driven scraped-surface heat exchangers to achieve proper mixing.

Shell and Tube Heat Exchangers

As their name implies, the simplest of shell and tube heat exchangers may be a simple pipe that is jacketed with heating or cooling media. In practice, these will usually involve many parallel tubes, perhaps folded or otherwise arranged to increase efficiency. Energy balances between product and media may be calculated using an energy balance with the addition of the use of

the log mean temperature differential, considering that no distinct temperature difference exists to work with. Additionally, the direction of flow of product relative to heating or cooling media is important because the maintenance of high temperature differences with countercurrent flow exchangers will provide a more efficient heat-transfer system than a concurrent one.

Heat Exchanger Calculations

The rate of heat transfer through a heat exchanger is similar to the one previously given by the general conduction equation (Equation 2.50):

$$q = UA(\Delta T_{ht}) \tag{2.50}$$

q: Heat Transferred, kJ

U: Heat Transfer Coefficient, $\dfrac{\text{kJ}}{\text{m}^2 \cdot {}^{\circ}\text{C}}$

A: heat transfer area, m^2

ΔT_{ht}: heat transfer temperature gradient, ${}^{\circ}\text{C}$

From this, it is obvious that higher rates of temperature differential will allow the use of a smaller (and thus less expensive) heat exchanger for a given value of U and a fixed need for q. To this end, several different strategies have been adopted, either by using a counterflow heat exchanger (Figure 2.18) that maintains a higher temperature differential between the inlets and outlets of both product and heating or cooling media, as well as the construction of heat exchangers that utilize multiple surfaces (so called *multitube* or *multipass* heat exchangers) to improve the value of U. Automobile radiators that must remove the waste heat from internal combustion engines are typically single-pass, multitube heat exchangers that rely on thin, flat tubes with attached thin fins of copper or aluminum to help transfer heat from the engine coolant into the airstream caused by vehicle movement and fan operation. As more and more tubes and passes accumulate, the overall effectiveness of the heat exchanger is hampered by the changing temperature of the heating or cooling media as it passes through the exchanger's many stages. This is accommodated by incorporating a correction factor F into the overall heat transfer equation (Equation 2.51) that is either taken from a standard heat exchanger configuration or is supplied by the manufacturer based on experimental evaluation.

$$q = F(UA\Delta T) \tag{2.51}$$

F: Correction factor, dimensionless

where F may range from 0.6 to 1.0 in typical applications and can be found either in manufacturer's test results or in standard handbooks.

Log Mean Temperature Differential

For many types of heat conduction, it is not intuitively obvious what the temperature differential should be. In this case, the log mean temperature difference provides a slightly more accurate estimation of heat exchanger performance (Equation 2.52):

$$\Delta T_{ht\ log\ mean} = \left(\frac{(T_{h_2} - T_{c_2}) - (T_{h_1} - T_{c_1})}{\ln \left[\dfrac{(T_{h_2} - T_{c_2})}{(T_{h_1} - T_{c_1})} \right]} \right) \tag{2.52}$$

Figure 2.17. Concurrent Flow Shell and Tube Heat Exchanger
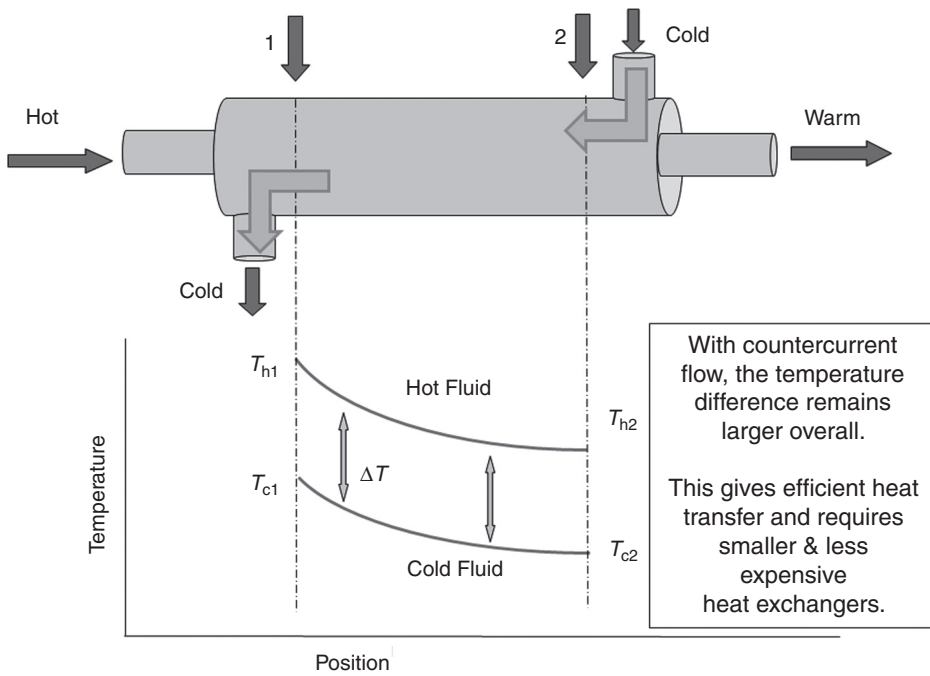
Note that ΔT, the temperature difference, converges.

This causes a reduction of heat transfer and requires larger heat exchanger areas.

Figure 2.18. Concurrent Flow Shell and Tube Heat Exchanger

With countercurrent flow, the temperature difference remains larger overall.

This gives efficient heat transfer and requires smaller & less expensive heat exchangers.

where ΔT_1 and ΔT_2 are taken at inlet and outlet points of many heat exchangers as shown in Figures 2.16 and 2.17, and thus the overall heat transfer can be expressed as (Equation 2.53):

$$q = U \cdot A \cdot \left(\frac{(T_{h_2} - T_{c_2}) - (T_{h_1} - T_{c_1})}{\ln \left[\frac{(T_{h_2} - T_{c_2})}{(T_{h_1} - T_{c_1})} \right]} \right) = U \cdot A \cdot \Delta T_{\text{ht log mean}} \tag{2.53}$$
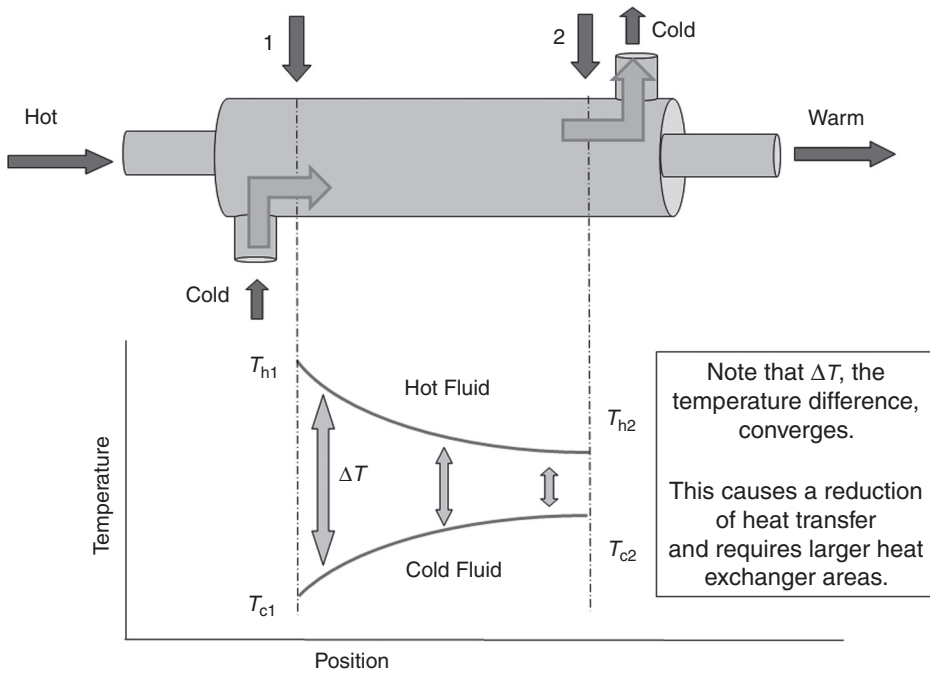
Other Types of Heat Exchangers

Jacketed kettles are often used for batch processing in small to medium-sized operations and rely on having large kettles with the inner surface mated to coils or a hollow jacket to transfer heat into or out of the product. Similar methods are used in the brewing industry to remove the heats of fermentation, although these may be as simple as a closed fermenter with a film of water flowing over its outer surface. Immersion coil heat exchangers work in similar fashion except that they rely on a simple coil of tubing that is immersed in the product to transfer heat. These have the advantage of being extremely simple, but may be hard to clean properly with certain types of products, or if product has been cooked onto the surface. Scraped-surface heat exchangers are used for very viscous liquids and rely on mechanical scrapers to remove the film of heated or cooled product from the outer heat transfer surface. Ice cream freezers are a common example of this type of heat transfer device, with the added feature that the scraping assembly (called a *dasher*) is used to incorporate necessary air (called *over run* because it expands the total product volume) into the ingredient mix as it freezes.

Plate-type heat exchangers utilize large hollow plates with product and heat-transfer fluid in alternate chambers to provide a very large surface area and efficient heat transfer. Most plate systems are constructed with gasketed subassemblies held together in a large press structure so that they can be completely disassembled to clean the product surfaces after operation. These are particularly common in dairy operations.

Alternative Food Processing Technologies

The preceding sections described some of the classic modes of conducting thermal heat into or out of a product, and while these predominate in industry because of the ease of use and relatively low cost and high reliability of installed equipment, there are other processing methods that are being used on either an experimental or limited basis that provide thermal processing without using the three basic methods previously described.

Ohmic Heating

Ohmic heating has been a viable processing method for many years – the first implementations were conducted during the nineteenth century – and although the process parameters are now well described, the basic concept remains the same: a current applied to a resistive material will generate internal heat in a material according to Ohm's law. The advantage to this type of processing is that the heat is generated within the product itself and is therefore not subject to the problems with time lag inherent in conductive heating of thick sections of material.

Although this seems like an appealingly simple and effective means of processing materials, it depends on a moderate balance of conductivity and resistance. If the material has too little

resistance, the heat generation will be very low, and if the material has too much resistance, it will require enormous current flow to operate properly. Further, the current flow in a product will be along a path of least resistance, so for heterogeneous materials, the heating may occur in a single phase or ingredient while the rest of the material remains underheated. A good example of this might be a meat-containing stew where the conductive saline broth would provide a good current path (and therefore poor heat generation) whereas the resistive meat and vegetable solids would only be heated indirectly, leaving them underprocessed. Finally, using electricity directly, with the previously described thermodynamic losses, is often more expensive than generating heat directly from some other fuel source. So, for these types of products to be processed by Ohmic heating, the factors of economics, effectiveness, and efficiency have to converge. A homogenous, somewhat resistive moist product that resists efficient processing by other means, often as a result of poor thermal conductivity, is an ideal target product for this type of processing operation, and because of its ability to process product in a continuous fashion, it may be ideal for certain types of in-line pasteurization and sterilization processes, and particularly those coupled to aseptic packaging lines. The pet food industry has been successfully experimenting with Ohmic heating for some time for use with its moist and semimoist products.

High-Pressure Processing

High-pressure processing, which relies on extremely high pressures, often combined with a time or flow protocol, has also been around since the nineteenth century, and substantial commercial sterility for processed fruits was reported as early as 1914 [15]. The phenomenon has remained a curiosity for some time because of the difficulty of producing a cost-effective means of treating products at the extremely high pressures necessary. Recent interest has been the result of the availability of high-pressure technologies that were produced for other processes such as continuous-flow devices for the high-pressure stripping of paint from ships, or batch systems originally produced as hot and cold autoclaves for the densifying, compacting, and curing of composite and ceramic material structures, such as powder-casting.

One of the attractions of high-pressure processing is that it is a *cold* process; although some heat is generated as compression occurs, this is relatively small when compared to typical thermal processing techniques and can aid in the preservation of flavors and colors in delicate products. As one might expect, there are *textural changes* that may occur as a result of the enormous distortion of the materials in the press-cell wall, and fiber rupture may cause an undesired homogenization process or lead to undesired organoleptic changes.

Complete microbial inactivation in high-pressure processes may be problematic as well; most current applications are used to extend the shelf life of refrigerated foods rather than provide shelf stability. This is due to the highly variable pressure sensitivity of different organisms, and the durability of bacterial spores. Spore-forming bacteria such as *C. botulinum* and *Bacillus cereus* have demonstrated tremendous resistance to pressure, and several types of non-sporeforming bacteria that have been studied are highly resistant to high pressure processing – for example, *E. coli* O157:H7 required 700 MPa, and *S. aureus* 700 MPa to achieve a 5 log-cycle reduction in population [16]. The final result of this is that other co-factors such as pH, salinity, or partial thermal processing may be included in the final processing regime to achieve the desired result. High-pressure processing is currently best utilized as a pasteurization device for liquid products and some meats and fruit or vegetable purees. Slow throughput times and incomplete inactivation of some organisms has continued to be a problem in the manufacture of shelf-stable foods using high pressure as the sole means of commercial sterilization.

An additional hurdle to the use of high-pressure processing is the high cost of installed equipment and the comparatively slow cycle rate for batch processes, although it is interesting to note that on at least one occasion, companies that have installed processing equipment for their own use have found that there is sufficient demand to warrant the installation of additional equipment for use in contract packaging operations.

## Microwave Heating and Processing Principles

Microwave ovens and thermal processing, invented as a result of the intensive development of accurate microwave aerial radar during World War II, have revolutionized the way that food is prepared in most of the developed world, with sales in developing countries with workable electric power distribution systems soaring as well. Microwave heating was discovered by Percy Spencer, who developed magnetron manufacturing methods for Raytheon during World War II, and who reportedly noticed that a candy bar in his pocket melted as he stood in front of an operating magnetron system, though he must be considered lucky given the cataract hazards from microwave energy [17]. To understand the mechanisms that packages and food use to convert microwave energy into heat in the oven cavity, it is first necessary to have a description of the general mode of operation of ovens' conversion of electric power into a useful electromagnetic field (EMF) within the oven cavity.

The internal circuitry of a household microwave oven takes household current (typically, 100–240 VAC at 50–60 Hz, depending on location), amplifies the voltage, and passes it through a cavity magnetron. The flow of electrons causes the cavity to emit a high-power electromagnetic field (EMF) at one of two approved frequencies (usually 2,450 MHz, although 915 MHz systems exist for commercial processing). The physics of this are somewhat complex, but the process of creating a powerful, single-frequency EMF from electric current is roughly analogous to the way a whistle creates a loud, single-frequency tone from a turbulent stream of air. Energy conversion efficiency is good, in the range of 60–70%, and frequency control is sufficient so this remains the universal method of microwave generation for home ovens.

From the magnetron, the EMF is channeled through a waveguide duct to the oven cavity, often passing through a *stirrer*, a rotating, multifaceted reflector that alters the beam dispersion into the oven cavity so that standing nodes and antinodes – which can cause hot and cold spots in the cooking foods – are avoided. Nodes are regions where overlapping waves reinforce, causing high-energy areas, and antinodes are regions where overlapping waves cancel one another out, causing low-energy areas. Most new ovens have rotating platforms built in to further distribute energy application to the food product to avoid hot and cold regions in the product. It is also possible to use a microwave EMF field to generate high-temperature plasma fields, but there is currently no commercial implementation of this for home food preparation.

Heating Mechanisms

There are two major heating mechanisms that are possible in a microwave oven: dipole rotation and ionic polarization. In dipole rotation, the polar molecules will try to "follow" the oscillating electric field, generating heat. Water, fats, and other very polar substances tend to heat more quickly than dry, non-polar ones. Given the broad range of polar compounds in foods, this is the predominant heating mechanism. Ionic polarization is most often a secondary effect and generates heat as shifting electric field accelerates ions, which generates heat when collisions occur on molecular level, as shown in Figure 2.19.
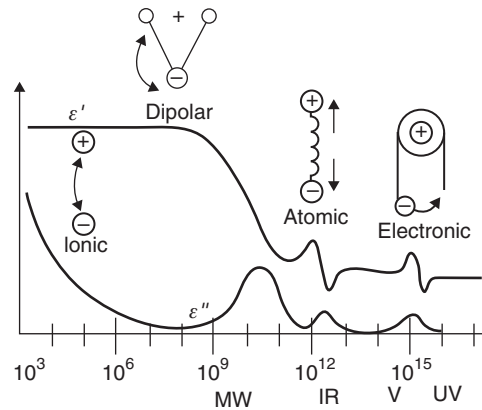
Figure 2.19. Dielectric Response of Materials
Source: Dr. Kenneth A. Mauritz, Used with Permission

Power Density, Heat, and the Dielectric Properties of Materials

Power density per unit volume can be given by Equation 2.54:

$$p = \omega \cdot \varepsilon'' \cdot \varepsilon_0 \cdot E^2 \tag{2.54}$$

$\omega = (2\pi f)$: the angular frequency, rad/s

f: frequency, Hz

ε'': the imaginary component of the complex permittivity equation: $\varepsilon = \varepsilon'\omega + i\varepsilon''\omega$

ε': the real component of the complex permittivity equation (not used in power calculation)

ε_0: the free space permittivity

E: electric field strength

Generally, permittivity or the dielectric constant (ε'), is a measure of how a particular material will allow an electric field to penetrate, with low-dielectric materials typically being considered conductors (neglecting frequency effects) and high-dielectric materials being considered insulators. Copper wire has a very low dielectric constant, and is therefore a good conductor, whereas the polymer insulation on wire has a high constant and is used as an insulating cover. The complex permittivity component is generally termed the dielectric loss factor (ε'') and is generally used as a measure of a material's ability to dissipate electrical energy as heat. Materials that have a high loss factor are termed *lossy* materials and are the basis for microwave susceptors to convert microwave energy into heat in food packaging, as well as many other applications including stealth antiradar coatings.

The loss tangent – the ratio of resistance to reactance – gives an idea of how well an electric field will penetrate and heat a material, and can give a rough estimate of its utility for thermal conversion. A high loss tangent will heat food well but not transmit energy to the interior of a large food mass, leaving it uncooked in the middle, whereas a low loss tangent may transmit energy through a material but may not heat well. Given that the loss tangents are a function of individual materials' properties such as phase and temperature, as previously discussed, only generalized predictions can be made about the ability of foods, which generally have non-linear loss characteristics and are anisotropic, to heat well in microwave fields. Most of the utilization has been based on empirical observation rather than a deep analysis of the mechanisms of action in food compounds.

Lossiness is therefore a desirable property in a material that is being heated in an EMF field because highly lossy materials heat more quickly and convert energy more efficiently when an EMF is applied. Conversely, a product that is extremely lossy will exhibit a high temperature gradient through the materials' section because most of the energy will be converted at or near the surface, leaving the core material unheated. The lossiness of a material, and particularly complex, non-linear materials such as foods, is a function of the geometry, temperature, and chemistry of material as well as several secondary factors. Composition factors include the moisture, solids, fats, and salts content as well as the temperature, and particularly phase of the material as well as the state of water in the product.

Lossiness changes dramatically during phase changes, with ice and other crystalline materials being orders-of-magnitude less lossy than liquid water, and cold liquid water being less lossy than warm water. This effect is enhanced even further with the addition of salts, sugars, and other compounds. Other compounds tend to increase their lossiness with temperature increases as well, leading to *runaway heating*, where hot areas heat faster and faster with increasing conversion efficiency, whereas cold or frozen ones change very little. This can cause the product to burn or even ignite in some areas while remaining frozen in others, and was one of the complaints with early-model ovens that lacked stirrers or turntables, because standing nodes and antinodes amplify the effect even further. A great deal of microwave oven design is concerned with power settings that pulse power on and off, allowing heat transfer and equilibration to occur, and with rotating turntables and *stirrers* – slowly rotating reflectors, typically in the roof of the oven, that try to even out the power distribution problems caused by node and antinode formation, and to prevent runaway heating.

An additional concern with home microwave heating is that microwave heating does not create surface browning effects that we have learned to expect while using conventional ovens that transfer heat to food products by conduction and radiation, which creates high surface temperatures. In an effort to counteract this, many food manufacturers have included microwave *susceptors* – patches or components that have a lossy coating or lamination – to provide direct thermal heating of a product, which are covered in Chapter 4.

Microwave Processing

As an industrial process, microwave heating suffers from high energy and equipment costs, safety concerns, and relatively poor conversion efficiency. Its primary use is in larger kitchens and commissaries, as well as commercial installations tempering frozen foods, efficiently bringing them to just below the freezing point for immediate use or further processing.

Refrigeration

Although vapor-compression refrigeration predominates in both domestic and commercial in-stallations, there are many types of processes that may be used to cool or freeze materials, from the simple use of water ice, dry ice, or liquid nitrogen phase-change cooling to sophisticated solid-state methods such as Peltier effect cooling modules. For vapor-compression refrigeration, working against the second law of thermodynamics and moving energy from a high energy (hot) area to a low energy (cool) one requires the addition of a substantial amount of energy, usually in the form of electricity or mechanical energy to drive refrigeration compressors. Most large-scale vapor-compression refrigeration processes rely on a simple chain of processes, all of which have been previously discussed:

1. A liquid refrigerant will absorb heat via a heat exchanger (the *evaporator*) during a change to a vapor state, whether the change is driven by adding heat or by changing pressure.
2. Vaporized refrigerant can then be condensed back to a liquid state by raising its pressure, usually by utilizing a mechanical compressor. When it does this, it will release (*reject*) the heat of condensation through a separate heat exchanger (the *condenser*) in another location.
3. By using a closed loop of refrigerant flow, a liquid refrigerant can be used to cool one location by vaporization in a heat exchanger, then transfer that heat energy as increased enthalpy in the vapor to another location, rejecting the heat via another heat exchanger after being recompressed to a liquid, thus creating a *heat pump*.

This provides a means of making heat flow from a region of low energy to a region of high energy – preferably in separate locations. This is not done without cost – remember that the second law of thermodynamics only addresses what energy flow will *spontaneously* occur. Heat pumps require a huge energy input to overcome this and may require additional energy input in the range of 10–40% of the heat energy transferred simply to operate the heat pump system.

To describe a classic vapor-compression refrigeration cycle, four steps are commonly used. The first of these is the flow of the refrigerant through a device called an *expansion valve*. In large refrigeration systems, this can be a complex device, but in home refrigerators and air conditioners, it may be nothing more than a constriction in a tube end, or a machined orifice. This allows a pressure drop as the liquid expands through the orifice, much like an aerosol spray, and is considered to be an isenthalpic process (no change in enthalpy at that particular point). After the refrigerant flows through the expansion valve, it is in a low-pressure region between the valve and the suction (low pressure) side of the refrigeration compressor, and is carried through a heat exchanger on the "cold side" of the refrigerator. The liquid refrigerant will change phase into a saturated vapor, and it absorbs the heat of vaporization in the process, removing heat from the cold side via a heat exchanger (an evaporator, introduced earlier) and cooling the air or material in contact with the evaporator. As it does so, the enthalpy of the material increases with the absorption of the heat energy, and the vaporized refrigerant is drawn into the compressor. For most simple refrigeration systems, it is assumed that the compression of the refrigerant occurs under isentropic conditions – the entropy of the system does not change – and this fact may be used to predict the pathway of the energy state of the refrigerant as it increases in pressure. In practical terms, the refrigerant is brought to a pressure higher than its equilibrium vapor pressure and returns to a liquid state while traveling through a heat exchanger called a condenser. When this phase change occurs, the heat of condensation is removed from the refrigerant via the condenser into the air or cooling water, leaving a relatively cool liquid refrigerant that once again flows through the expansion valve, repeating the process cycle. This is shown schematically in Figure 2.20 and the processes are shown on a Mollier curve chart in Figure 2.21. Mollier charts are provided in the chapter appendix.

Note that the energy rejected in the condenser is the sum of both the heat absorbed during the evaporation of the refrigerant and the heat added to the mixture by the work of compressing it. For many installations, particularly in large food-processing plants, the refrigeration cycle may look somewhat different than the idealized cycle shown here. In many installations, multistage compression is used to lower the cost and increase the effectiveness of the compressor. Additionally, the refrigerant may be allowed to cool past the saturated liquid state to increase the refrigeration capacity of the installation, as well as being allowed to evaporate slightly into the superheat range to both increase capacity and to avoid incompressible liquid refrigerant from damaging the compressor mechanism.
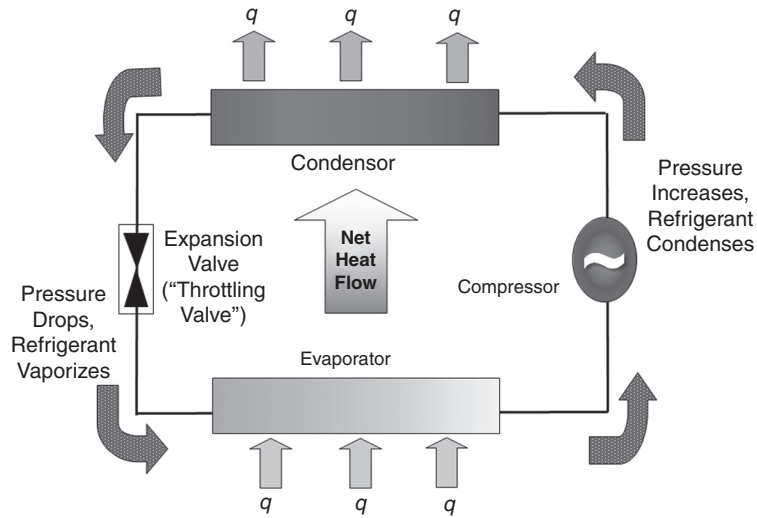
Figure 2.20. Diagram of Vapor-Compression Refrigeration Cycle

Calculation of Refrigeration Parameters

Three basic parameters are needed to calculate the heats that occur in a simple single-stage refrigeration cycle. The terminology for these is not standardized in engineering texts, so different notation may be used in different references. Thus, the generalized refrigeration equation is given in Equation 2.55:

$$\dot{q}: \text{is the heat flow,} \left(W, \frac{j}{s} \right) \tag{2.55}$$

Thus, at any stage in the refrigeration process,

$$\dot{q} = \dot{m}_r (h_{\text{final}} - h_{\text{initial}})$$

$\dot{m}_r$: refrigerant mass flow rate, $\left(\dfrac{kg}{s} \right)$

h_L: the enthalpy of the liquid refrigerant at the point that it is finished condensing and begins to moves through the expansion valve, kJ/kg

h_{cv}: the enthalpy of the liquid refrigerant at the point that represents the end of the evaporation and the beginning of compression, kJ/kg

h_{hv}: is the enthalpy value when the refrigerant has been compressed but has not yet begun to reject heat or change phase in the condenser, kJ/kg

This is considered to be the highest enthalpy state of the refrigerant.

Heat of Evaporation and Cooling Capacity

$$\dot{q}_{\text{evaporator}} = \dot{m}_r (h_{cv} - h_L)$$

$$\dot{q}_{\text{evaporator}} = \text{"Heat of Evaporation" or "Cooling Capacity", J/s or W} \tag{2.56}$$
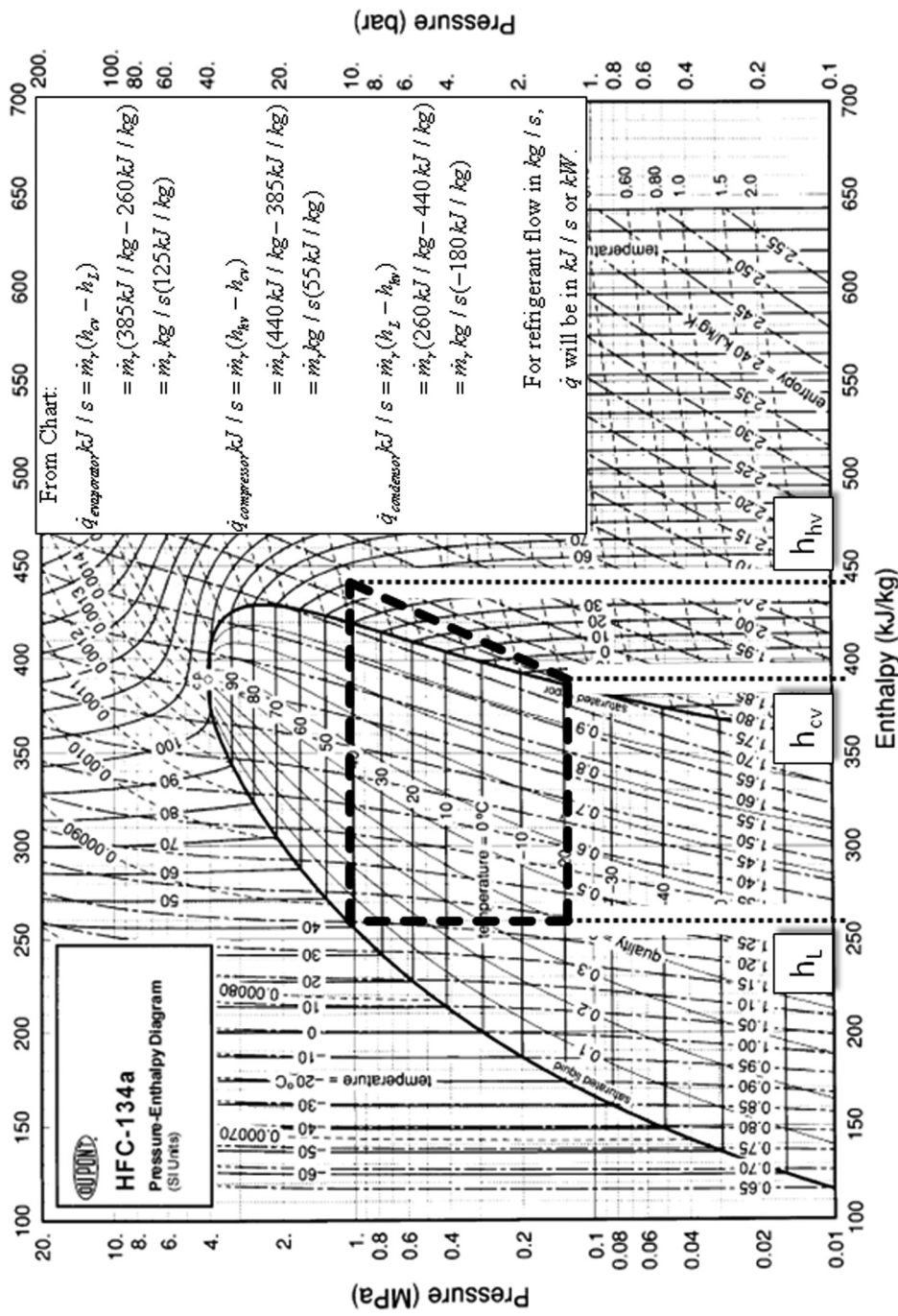
Figure 2.21. Diagram of Vapor-Compression Refrigeration Cycle Stages on Mollier Chart of R-134a
Source: DuPont, with Permission for Underlying Graph

From Chart:

$\dot{q}_{evaporator} kJ/s = \dot{m}_r(h_{cv} - h_L)$
$= \dot{m}_r(385 kJ/kg - 260 kJ/kg)$
$= \dot{m}_r kg/s(125 kJ/kg)$

$\dot{q}_{compressor} kJ/s = \dot{m}_r(h_{hv} - h_{cv})$
$= \dot{m}_r(440 kJ/kg - 385 kJ/kg)$
$= \dot{m}_r kg/s(55 kJ/kg)$

$\dot{q}_{condenser} kJ/s = \dot{m}_r(h_L - h_{hv})$
$= \dot{m}_r(260 kJ/kg - 440 kJ/kg)$
$= \dot{m}_r kg/s(-180 kJ/kg)$

For refrigerant flow in kg/s, $\dot{q}$ will be in kJ/s or kW.

HFC-134a
Pressure-Enthalpy Diagram
(SI Units)

Enthalpy (kJ/kg)

Pressure (MPa)

Pressure (bar)

h_{hv} h_{cv} h_L

75

The *heat of evaporation* (Equation 2.56) is the energy that will be absorbed during evaporation of the refrigerant and usually is equated with the cooling capacity, or *cooling load*. In conservative system, this heat must come from outside the refrigerant, and therefore will cause cooling (energy removal) of the material near the evaporator.

Cooling capacity is the ability of the system to absorb heat and in vapor-compression systems is usually taken to be the total Heat of Evaporation. In much the same fashion as early steam engines being rated in horsepower to demonstrate the effectiveness of their use compared to the horses they replaced, North American refrigeration systems have been rated in terms of *tons* of capacity to compare them to the amount of melting ice that would be needed to absorb an equivalent amount of heat energy. A ton of refrigeration capacity is defined as the equivalent heat energy of 2,000 lbs. of ice melting in 24 hours. In more practical terms, this is equivalent to 12,000 Btu/h or 12,660.5 kJ/h or 3.517 kW.

Heat of Compression

$$\dot{q}_{compressor} = \dot{m}_r (h_{hv} - h_{cv})$$

$$\dot{q}_{compressor} = \text{``Heat of Compression'', J/s or W} \tag{2.57}$$

This is the theoretical value for the amount of heat that is added to the refrigerant during compression (Equation 2.57). In a conservative system, this must be the work done by the compressor on the refrigerant and can be used to predict the power requirements of the refrigeration system. It should be noted that, like all fluid flow systems, the efficiency (ε) of the pump will be less than 100%, and thus the actual power requirements of the compressor may be much higher (Equation 2.58):

$$\text{Actual compressor power required} = \dot{q}_{actual} = \dot{q}_{compressor}/\varepsilon \tag{2.58}$$

For vapor-compression refrigeration, there is no equivalent turbine power-output state in these simple systems, although such systems can be run as closed-cycle heat engines, producing power.

Heat of Condensation

$$\dot{q}_{condensor} = \dot{m}_r (h_L - h_{hv})$$
$$\dot{q}_{condensor} = \text{``Heat of Condensation'' or ``Rejected Heat'', J/s or W} \tag{2.59}$$

The *heat of condensation* (Equation 2.59) is the heat that is given off during the condensation of the refrigerant (in most systems, this is a negative number, indicating heat rejection from the system). It is the sum of the heat absorbed during evaporation and the heat added during compression. In vapor-compression refrigeration systems, therefore, the condenser must usually be much larger than the evaporator to give off the increased heat that is contained in the fluid, and of course this must be done at another location, whether the outside of an insulated refrigerator or the outside of a building, to effectively move heat from the evaporator to the condenser. In large industrial refrigeration or office air-conditioning systems, the heat of condensation may be taken up by water flow that is then cooled via a cooling tower or natural water source such as a stream. Problems with refrigeration systems' loss of performance often can be traced to either mechanical problems (compressor malfunction or refrigerant leakage) or the system's

inability to reject heat properly. In industrial systems, solar heat load on exposed condensers can cause significant problems, and home refrigerators may run constantly because of lack of air circulation, or dust and pet hair accumulation in the condenser heat exchanger.

Coefficient of Performance (COP)

$$\text{COP} = \frac{\dot{q}_{\text{evaporator}}}{\dot{q}_{\text{compressor}}} = \frac{\dot{m}_r\left(h_{cv} - h_L\right)}{\dot{m}_r\left(h_{hv} - h_{cv}\right)} = \frac{\left(h_{cv} - h_L\right)}{\left(h_{hv} - h_{cv}\right)} \tag{2.60}$$

The Coefficient of Performance (Equation 2.60) gives a simple ratio of how much heat is removed by the evaporator in comparison to the energy required to drive the system. For many types of refrigeration systems such as a home refrigerator or a window air conditioner, the COP is usually somewhere between 2.0 and 5.0. This is illustrative of the extraordinary energy expenditures that are required by refrigerators and air conditioners (often the most energy-intensive devices in a home) that require high generating capacity in cities in the summer. Essentially this says that for every 2–5 watts of heat that are transported from the inside of the refrigerator to the outside (or from the inside of a home to the outside air), 1 watt of electrical energy is required. Thus, the refrigeration industry is constantly searching for more efficient ways of providing refrigeration and cooling capacity, which has resulted in the design of both new refrigeration methods, described later on in this section, and ultra-insulated home refrigerators that offer significant efficiency improvements.

Refrigerant Types

The general types of refrigerants include those that absorb latent heat, sensible heat, and those that use liquefiable agents or refrigerating media. Ice and chemical cooling are common methods used in some applications such as fishing vessels and "quick cool" medical devices. Most home vapor compression refrigerators use 1,1,1-trifluoroethane (R-134a) or purified isobutane (R-600a), which, although flammable, is present in such small quantities as to not be deemed a hazard in the event of leaks. Ammonia (R-717) is often used in large-scale industrial freezer systems, but is confined primarily to non-domestic applications (including food-processing plants) because of toxicity and flammability issues. There are literally hundreds of materials suitable for use as refrigerants, many of which are blends of hydrofluorocarbons, but any material that will provide the proper phase changes and will flow at low temperatures may be used as a refrigerant. Many of these are rejected because of either extraordinarily high pressure changes required for the necessary phase change to occur, and the attendant expensive pumping systems to drive it, or because of toxicity, corrosion, flammability, or environmental problems. Even water can be used as a refrigerant – in theory. In reality, it requires a great deal of pressure to change phase and freezes solid at temperatures well above the desired evaporator temperatures of most refrigeration systems.

Compressor Types

From a simplistic thermodynamic viewpoint, refrigeration is simply a heat engine run in reverse – apply mechanical power, and heat flow will occur. Compressors are simply devices that will cause both the refrigerant flow and a rise in pressure, and, in the case of many portable

refrigeration units used in trucking and rail shipment, are coupled directly to an engine such as a small-displacement diesel for power. Compressor design is similar to other types of pumps, with reciprocating piston or helical rotary screw (similar to Roots-type compressors) being the most commonly used in industrial refrigeration, as well as rotary, scroll, and centrifugal pumps used in other applications. Home refrigerators and air conditioners typically use a piston- or vane-type compressor that is hermetically sealed in a canister and cooled by the flow of refrigerant [18].

Other Refrigeration Systems

Absorption Refrigerators

These are simple devices commonly found in recreational vehicles and remote applications such as rural medical clinics because they can be powered by a simple flame or other heat source. The most common version of these uses the evaporation of ammonia in the presence of hydrogen to provide the cooling effect, with the gaseous ammonia then being absorbed by water. The water-ammonia mixture is then heated in another stage to re-separate the ammonia from the water, and the ammonia is condensed with gaseous hydrogen in a heat exchanger and rejects heat from the system to complete the cycle.

Peltier Effect Cooling

Jean-Charles Peltier observed that application of a current flow in dissimilar metals will create a heat flow – a reversal of the Seebeck Effect that is responsible for the application of thermocouples that generate a current in dissimilar metals on the application of heat flow. A Peltier module, then, is simply a junction of dissimilar metals or semiconductors that will generate a net heat flow when current flow is applied, resulting in one side of the module being chilled while the extracted heat plus heat of operation is emitted on the other side. Although very sturdy and small, these modules are not terribly efficient and are most often used in specialized electronics-cooling applications and consumer applications such as car beverage coolers.

Vortex Coolers

Vortex coolers operate by generating a centrifugal flow of air, essentially separating air on a density basis (although the exact physics are still a subject of some debate), and producing a stream of both hot and cold air. They are not thermodynamically efficient, but are very useful in systems that have an abundant supply of compressed air, such as locomotives. A similar cooling method is the Air Cycle Machine used in aircraft installations, which cools hot air from the primary stages of the engine's compressors, conditions it via heat exchangers and water separators, and then uses it for cabin ventilation and climate control.

Chemical Chillers

Often the basis for marketing self-cooling or self-freezing packaged foods, chemicals chillers rely on a binary mixture of chemicals that create an endothermic (heat-absorbing) reaction. Typically these include reacting water with ammonium nitrate, ammonium chloride, potassium chloride, or other materials such as ethanoic acid and sodium carbonate. The most common use

of these is for chiller packs used in first-aid applications, and the methods have not yet been proven economically feasible in most consumer food packaging applications.

Stirling Cycle Refrigeration

Stirling cycle refrigeration typically uses an oscillating piston, sometimes suspended in a sealed *free-piston* system and magnetically driven to increase efficiency, to achieve vapor compression and circulation through an internal heat exchanger. Although currently not common except in specialty applications such as liquid nitrogen production, these promise an increase in efficiency as demonstrated by a higher COP when compared to standard vapor-compression refrigeration systems, although their higher manufactured cost has slowed their commercial and domestic acceptance.

Magnetic and Acoustic Refrigeration

These methods, still largely under development, rely on very different principles. The first uses magnetic action on paramagnetic salts to induce a magnetocaloric effect. This shifts the entropy of the refrigerant and produces heat absorption and rejection depending on the orientation or randomness of magnetic dipoles in the refrigerant. Its primary application is for ultra-cold research applications, and the use of gadolinium salts allows the cooling to within a minute fraction of absolute zero [19]. Acoustic refrigeration uses acoustic energy to drive gas flow and heat exchange during what amounts to a pistonless Stirling cycle operation with the advantage of fewer parts and little or no mechanical wear. Acoustic refrigeration is currently used in cryogenic work and may offer efficiency improvements for domestic and commercial applications.

Mass Transfer

Mass transfer differs substantially from the mass flow concepts previously discussed in this chapter with regard to fluids, and they should not be confused, particularly when attempting to measure package barrier characteristics. Mass transfer processes are typically defined as involving the diffusion or molecular-level transport of one material through the structure of another, whereas mass flow is regarded as the macroscale bulk flow of a material – most often a fluid – through a physical aperture or channel in another material. The equations used to model these processes are quite different from those used for fluid flow and are very closely related to those describing the diffusion and transport of heat energy. Of course there are always grey areas in this taxonomy; for example, the flow of fluids through dense, porous media (slow, pressure-gradient-driven flow through very tiny voids) has aspects of both bulk flow and diffusion, but these will not be considered in this text.

Diffusion Processes

The simplest example of mass transfer is the Fickian diffusion model developed by Adolf Fick, a German physician, in 1855. The model describes the transport rate of one material through another bulk media, typically a solid or static liquid in terms of a *diffusion coefficient* that is a basic property of a material. It should be noted that although Fickian diffusion is a useful tool in many types of mass-transfer models for materials in a rubbery or liquid state, it does not work well with materials that are undergoing glass transition because the Fickian model does not

incorporate the necessary terms for viscoelastic changes in the bulk media as the glass transition occurs [20]. These types of transport require the use of more complex, continuum-mechanics-based diffusion models. Additionally, transport in rubbery or liquid materials, easily described by Fickian equations, is not well modeled in glassy regions where concentration profiles often change sharply.

One-Dimensional Diffusion

The generalized Fickian model for steady-state transport (Equation 2.61):

$$J = -D\nabla\oslash \tag{2.61}$$

can be reduced to the linear case, most often used when considering the one-dimensional linear cross-section of materials, to a simpler form (Equation 2.62):

$$J = -D\frac{d\oslash}{dx} \tag{2.62}$$

Where

J: diffusion flux in $\dfrac{\text{Quantity Permeated}}{\text{Length}^2 * \text{Time}}, \dfrac{\text{Mol}}{(\text{m}^2 * \text{s})}$

D: diffusion coefficient in $\dfrac{\text{length}^2}{\text{time}}, \dfrac{\text{m}^2}{\text{s}}$

$\oslash$: the concentration in $\dfrac{\text{Quantity}}{\text{Length}^3}, \dfrac{\text{Mol}}{\text{m}^3}$

x: the characteristic length dimension in length, m

The one-dimensional Fickian diffusion case is mathematically similar to the Fourier heat conduction equation, and many mass- and heat-transfer modeling systems are derived from the same mathematical basis. The unsteady-state case for Fickian diffusion requires Fick's Second Law to account for time changes in the transport rate (Equation 2.63):

$$\frac{\partial\oslash}{\partial t} = D\frac{\partial^2\oslash}{\partial x^2} \tag{2.63}$$

For either situation, D can be experimentally determined as described in Chapter 7, and is dependent on a host of other factors, often including temperature, existing concentrations of solvents, co-solvents, or other constituents of the bulk matrix.

Mass Transfer through Polymer Films

As discussed in Chapter 7, the permeability of polymer films common to food packaging is based on a sorption, Fickian diffusion, desorption model. Permeants such as oxygen or carbon dioxide are very often presumed to be non-reactive with the packaging materials and therefore not to affect the sorption/desorption or diffusion rates; however, surface modifications of the polymer, additives, and plasticizers in the polymer matrix, whether intentional or taken up from the product or environment, and a very high degree of variability in the polymer manufacturing process itself will result in permeation figures published in the literature that can often be order-of-magnitude estimates at best.

Mass Transfer into Moving Fluids

Heat transfer into moving fluids is described by the previously mentioned Nusselt number, a dimensionless characteristic number used to determine the overall heat transfer coefficient, (h). In much the same manner, the Sherwood number helps describe the mass transfer into a moving fluid (Equation 2.64):

$$Sh = \frac{K_c L}{D} \qquad (2.64)$$

Sh: Sherwood number, dimensionless

K_c: the mass-transfer coefficient, $\dfrac{\text{mol}/\left(\text{s} \cdot \text{m}^2\right)}{\left(\text{mol/m}^3\right)}$

L: the characteristic length dimension, often diameter, m (L is often kept
    to avoid confusing the diameter with the diffusion coefficient, D)

D: the diffusivity coefficient, $\dfrac{\text{m}^2/\text{s}}{\text{length}^2/\text{time}}$

In much the same manner as estimating the Nusselt number using the Prandtl and Reynolds numbers in heat transfer, the Sherwood number may be estimated using the Reynolds number as previously described and the Schmidt number (Equation 2.65):

$$Sc = \frac{\nu}{D} \qquad (2.65)$$

Sc: Schmidt Number, dimensionless

$\nu = \dfrac{\mu}{\rho}$: the kinematic viscosity, $\dfrac{\text{m}^2}{\text{s}}$

As with the estimation of the Nusselt number, there are estimation equations available for the Sherwood number based on empirical data for particular mass-transfer scenarios. Typical values for the Schmidt number are $0.5 < Sc < 3$ for gasses and $100 < Sc$ for liquids.

For evaporation via flow on the outside of a solid surface such as a flat plate and $Re < 15,000$, the Sherwood number may be approximated by (Equation 2.66):

$$Sh = 0.664 Re^{0.5} Sc^{0.33} \qquad (2.66)$$

and for the mass transfer on the outside of a sphere (usually taken to be a spherical droplet), the starting point is often the Ranz-Marshall equation (Equation 2.67) [21]:

$$Sh = 2 + 0.60 \, Re^{0.5} Sc^{0.33} \qquad (2.67)$$

where

$$2 \leq ReSc^{0.67} \leq 50,000$$

However, for practical applications, the Ranz-Marshall equation (which was developed to model a single droplet without interactions) is subject to considerable correction terms depending on the flow regime, ratio of boundary layer to droplet size, and the type of liquids and gasses in the particular system. In Ranz's words, "Today in designing a process it is much more difficult to find a general model for a general class of phenomena. However a miniaturized experiment,

observed in real time, is always necessary to simplify the theoretical models to a tractable form for computations" [22]. Although numerical analysis has helped this, allowing some types of experiments to be run as computer simulations, the complexity of interaction still provides a challenging subject for research.

As with convective heat transfer being impeded by laminar sublayers, fluid flows may form a laminar sublayer over the evaporating surface that contains a curvilinear concentration profile. The practical implications of this are that some form of turbulence may be induced to achieve better mixing over the surface and a higher rate of mass transfer, much as convective heat transfer may be manipulated to maximum effect.

Drying, Dehydration, and Psychrometry

Another major method of food preservation is the reduction of water content in the food product itself. Although the actual basis for drying to prevent quality loss in the product is discussed in Chapter 7, the drying mechanism is relatively simple in principle and can be somewhat confusing in application because of the information necessary to account for energy and mass transfers.

Like any mixture of components, the evaporation of water into air (or the condensation of water out of air) is determined by temperature and pressure. This segment will concentrate on changes that occur near atmospheric pressure, but it should be remembered that liquids can be evaporated and condensed by manipulating pressure as well. This has few applications in the food processing industry due to high costs, but there are occasional applications in products that have unusual characteristics (such as being extremely temperature sensitive) where low pressure moisture or solvent evaporation is used.

Types of Air-Drying Operations

There is any number of types of drying and evaporative operations in food processing, ranging from simple rack-drying in the open to sophisticated freeze-drying techniques. The simplest types of drying use heated air flowed over a sliced or fragmented product conveyed in trays or on belts to remove moisture, with the initial impinging air often containing some of the removed moisture to avoid damaging the product by contact with completely dry air. Other methods include fluidized bed drying, which involves the bubbling of air through a bed of particulate material until the particles are suspended in the airflow, and spray and pneumatic drying that disperses fluid or solid particles, respectively, into the drying airflow.

The Psychrometric Chart

There are several psychrometric charts that are commonly used, but most contain similar information, although it may be laid out in many different formats, or may be contained in interactive form in a computer program. There are full-scale psychrometric charts in the appendix at the end of this chapter. The information contained in a psychrometric chart will most often contain a large number of curves, representing many different quantities – most of which are self-explanatory, but the following necessary information should be described.

Dry Bulb Temperature

This is the temperature that an ordinary (*bulb type*) thermometer will indicate in air. This is the root of subsequent determination of air properties, because every property except absolute humidity (which is a temperature-independent mass ratio) will vary with temperature.

Wet Bulb Temperature

This term dates back to the early days of humidity measurement and refers to a second thermometer that had a moistened cloth sleeve around its bulb. Evaporative cooling would lower the temperature of the *wet bulb* thermometer, and the relative humidity of the air could be determined by the temperature difference between the wet bulb and dry bulb thermometers. Lower relative humidity would increase the cooling effect, and thus the temperature difference between wet bulb and dry bulb would be larger, giving a dependable basis of measurement.

Many psychrometric charts still allow the determination of the state of air simply based on the wet and dry bulb temperatures, and some newer solid-state instruments still indicate this measurement as well. *Sling* psychrometers are still available, although they are generally used for teaching.

Relative Humidity

Relative humidity is the amount of moisture that air will hold, relative to a completely saturated mass of air at that particular temperature. This is a temperature-dependent quantity; air with a constant mass of water dissolved into it will increase in relative humidity as the temperature drops. Given enough cooling, this will eventually result in the precipitation of water out of solution as condensate in processing and as fog or precipitation in naturally occurring systems.

Absolute Humidity

Absolute Humidity is the mass ratio of water to air (usually g H_2O/kg Dry Air, or lb H_2O/lb Dry Air). This does not change with temperature because it is independent of the air's capacity to saturate. Older references may use grains H_2O/lb Dry Air, where 1 grain is 0.0649g, or 1.43×10^{-4} lb.

Enthalpy of Dry Air

The intrinsic energy content of the air, typically given both in kJ/kg dry air (or KJ/kg D.A.) or in Btu/lb dry air.

Specific Volume of Dry Air

Specific Volume is the volume per unit mass of dry air at a particular state for the air-water mix, and can be thought of as the *inverse of density*. Typically this is given in m^3/kg or lb/ft^3. From inspecting the psychrometric chart, one can determine that changing the temperature has the obvious effect of changing the specific volume, but changes in humidity at a given temperature can have a minor effect on the specific volume as well. Considering that convective systems are driven by density or specific volume differentials, some degree of convection may occur as a result of humidity changes.

Correction Terms

Depending on the particular charts used, there may be minor correction terms that are applied to enthalpy and/or specific volume values. These are usually overlain on the charts (adding to an already complex mass of visual data). For the purposes of classroom exercises (and many

actual calculations), these are sometimes for the sake of simplification, though they should be considered for large-scale operations where their contribution may become significant.

Assumptions of Evaporating and Drying

In describing simplified drying and evaporator systems, there are two basic processes that occur: simple heating and cooling, which changes the dry bulb temperature at a constant absolute humidity; and adiabatic humidification or dehumidification of air via dehydration or hydration of the product that occurs along a line of constant enthalpy.

Simple heating and cooling affects only the dry bulb temperature of the air-water mix, and does not change the absolute humidity (moisture content), though it will change the relative humidity, specific volume, and other factors. Because the temperature of the air is changing, the process is assumed to change the enthalpy of the air-water mixture as well. Drying or humidifying the product releases moisture into the air, and in a conservative engineering system, the moisture released is considered to be completely taken up into the air without changing its energy value – an adiabatic process. Although this is a somewhat simplistic assumption for some applications, it illustrates quite well many of the principles involved, and is a good approximation of simple airflow drying operations as shown in Figure 2.22.

Thus, most drying operations can be seen as containing two or more discrete stages. The first stage is usually heating of ambient air to an elevated temperature, thus increasing its energy
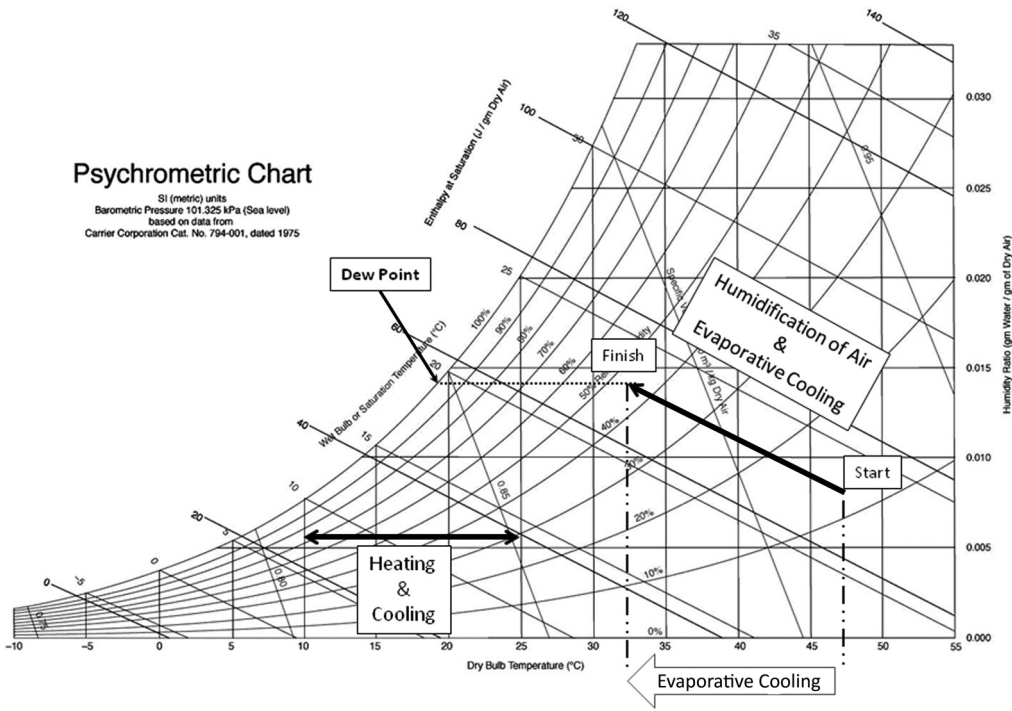
Figure 2.22. Psychrometric Chart with Process Lines for Typical Operations
Source: Underlying chart: Arthur Ogawa, with Permission

content and decreasing its relative humidity. The second step is exposing the product to the hot, dry air and allowing the product to be dried and the air to be similarly humidified – the moisture being taken up by the airflow being equal to the moisture being lost by the product, although it should be stressed that in an actual application, the heating stage will terminate at the beginning of the humidification stage providing a continuous process line. There may be systems that rely on multistage heating systems, or may have subsequent steps that occur, such as condensing moisture and recycling of moist drying air to "condition" the incoming product, but these simple rules and conservative engineering assumptions continue to allow reasonably straightforward analyses of the processes.

The Dew Point

The dew point, often mentioned in weather forecasts, is the temperature at which condensation or precipitation begins to occur. Cooling air will typically form fogs when the dry bulb temperature and the dew point are within about 3°C of one another and it is possible to supercool air-water mixtures to a certain extent, but this is not used for processing. In weather forecasting, the dew point is usually assumed to be the point where the air has cooled and dew, fog, rain, or snow begins. In broader terms, it represents a condensation temperature and can be observed on the sides of a cold beverage container on a humid day or in any situation with sufficient cooling.

To determine the dew point, the rules in the previous section can be applied. Simple cooling of the air will result in the movement of the air state along a line of constant absolute humidity until the saturation curve (relative humidity = 100%) is reached. That temperature at the saturation curve is then taken to be the dew point. A common mistake is to follow a line of constant enthalpy, which is incorrect because the air is neither gaining nor losing moisture as it is cooled.

Precipitating Moisture by Cooling

In engineering processes, removing heat from a humid air mass will cause the enthalpy value of the air mass to drop, with an attendant drop in temperature. If sufficient heat is removed, the air mass will be at the saturation curve. The air mass can be cooled further but because the air is already at the saturation point, it will begin to precipitate moisture and will continue to do so until the final dry bulb temperature state is reached. This is a ubiquitous occurrence when warm, humid air masses are cooled either by convection to higher altitudes or mixing with cold air masses, creating clouds or rain or other precipitation. Dehumidifiers are typically simply air conditioning systems that are used for moisture removal, and free-standing units have both the evaporator and condenser in the same air flow, temporarily dropping the temperature to remove water, then blowing the dry air over the condenser heat exchanger to reheat it. Larger cooling systems such as air conditioning units will precipitate excess humidity as a matter of course, an this can be seen dripping from window units or automobiles on hot, humid days.

Evaporative Cooling Effect

The evaporative cooling effect is the simplest of results from changes in the mass of water contained in air and is one of the oldest methods of cooling known because it is incorporated into human thermoregulation as the sweat response. Cooling can be measured as the reduction of dry bulb temperature that occurs as the airflow is adiabatically humidified. This adiabatic humidification will provide a change in temperature while holding the enthalpy of the air-water

mix constant, which is often counterintuitive. The cooling effect is exploited in evaporation towers used in process operations and in building climate control, as well as other process cooling operations. Because the amount of energy absorbed in evaporation is proportional to amount of air that the moisture can absorb, evaporative cooling is most effective at low relative humidities. Small evaporative cooling units called *swamp coolers* are common in the southwestern United States and the interior of Australia where dry conditions favor their use as a low-cost cooling system, and spray-type coolers that directly mist the air to provide spot evaporative cooling are used in both livestock and human environments.

Cooling Towers

Cooling towers are typically designed as either natural draft towers that use the lift from expanding hot air to drive airflow, such as the iconic hyperbolic cooling towers seen at nuclear reactors, or mechanical draft towers that use blowers to create airflow. A typical evaporative cooling tower is called a *chilling* tower and may reject heat from refrigeration condensers, power plant turbines, or other sources. The capacity of cooling towers is equal to the ability of the air to absorb moisture and thus create a cooling effect. This can be calculated by (Equation 2.68):

$$\dot{q}_{\text{cooling tower}} = \dot{M}_{\text{airflow}} \left(h_{\text{final}} - h_{\text{initial}} \right) \tag{2.68}$$

$$= FR_{\text{volumetric}} \cdot \rho_{\text{air}} \left(h_{\text{final}} - h_{\text{initial}} \right)$$

$$= \bar{V}_{\text{airflow}} \cdot A_{\text{cross section}} \cdot \rho_{\text{air}} \left(h_{\text{final}} - h_{\text{initial}} \right)$$

$\dot{q}_{\text{cooling tower}}$: heat flow from cooling tower, J/s

$\dot{M}_{\text{airflow}}$: mass airflow through cooling tower, $\dfrac{\text{kg Dry Air}}{\text{s}} = \dfrac{\text{kg DA}}{\text{s}}$

h_{final}: enthalpy of air at exit point of cooling tower, kJ/kg

h_{initial}: enthalpy of air at entrance point of cooling tower, kJ/kg

$FR_{\text{volumetric}}$: volumetric air flow rate through cooling tower, $\dfrac{\text{m}^3 \text{ Dry Air}}{\text{s}}$

$$= \bar{V}_{\text{airflow}} \cdot A_{\text{cross section}} = \dfrac{\text{m}}{\text{s}} \cdot \text{m}^2$$

$\bar{V}_{\text{airflow}}$: average airflow velocity through cooling tower, m/s

$A_{\text{cross section}}$: cross sectional area of airflow through cooling tower, m^2

ρ_{air} : air density, kg/m^3

Cooling towers generally are either cross-flow or counterflow types, and attention should be paid to the loss of cooling water into the air. This quantity can be substantial for large cooling operations, and provision should be made for make-up water to be added to the system to compensate for the evaporated water. Additionally, proper design practices and cleanliness should be observed as cooling water circulation systems have been implicated in health problems such as the Legionnaires disease outbreak at the Bellevue Stratford Hotel in 1976 in Philadelphia.

Legionella pneumophila organisms growing in the hotel's cooling tower water reservoir were carried back inside the building by ventilation air carrying droplets from the cooling tower's water spray, and were responsible for 235 cases of legionellosis and 34 deaths.

Evaporative Cooling as an Indicator of Process Control

In many processes, the evaporative cooling of the air as it flows through the system may be a primary indicator of whether the necessary evaporation (and thus dehydration) is occurring. Process controls in drying operations usually include a monitor of temperature both in the drying stages and in the exhaust to ensure that enough moisture is being removed from the system, with the cooling effect of the drying process being the primary indicator of moisture content being removed. Home clothes dryers often exploit this as well – the "automatic" setting is most often a simple temperature sensor that initiates the timed end of a drying cycle as the temperature of the exhaust air climbs past a certain generalized set point, typically $70°C$ ($160°F$), and indicates that the contents have reached a stage where they no longer contain high amounts of water. This can provide a simple process control for many types of drying operations, although for food operations, the drying characteristics will have to be described for each individual material being processed.

Other Types of Drying

Non-airflow types of drying will typically rely on contact heating to remove moisture or, in the case of freeze drying, the reduction of pressure to allow moisture to sublimate away. Drum or roller dryers rely on the fluid or particulate materials' contact with the drum for sufficient time to achieve the necessary drying and often utilize a scraper blade to separate the dried material from the drying surface. Plate dryers act similarly, although they are usually limited to items that can be easily removed from the drying surface. Freeze-drying relies on the ability of water to sublimate from frozen foods under reduced pressure when heated. These are discussed in more detail in Chapter 6.

Appendixes

Appendix 2.1. Heat Capacities of Selected Materials

Nonfood Material	Phase	Cp (kJ/Kg°C)
Air (Sea level, dry, 0°C)	gas	1.0035
Air (typical room conditions)	gas	1.012
Aluminium	solid	0.897
Animal (and human) tissue [15]	mixed	3.5
Ethanol	liquid	2.44
Glass [16]	solid	0.84
Helium	gas	5.1932
Hydrogen	gas	14.3
Iron	solid	0.45
Polyethylene (rotomolding grade) [17]	solid	2.3027
Polyethylene (rotomolding grade) [17]	liquid	2.9308
Water at 100°C (steam)	gas	2.08
Water at 25°C	liquid	4.1813
Water at −10°C (ice) [16]	solid	2.05

Source: http://en.wikipedia.org/wiki/Heat_capacity

Food Material	Above Freezing (KJ/kg°C)	Below Freezing (KJ/kg°C)
Apples	3.64	1.76
Bananas	3.35	1.67
Bass	3.43	1.72
Beef, carcass	2.85	2.01
Blueberries	3.64	1.76
Brains	3.52	1.72
Broccoli	3.85	1.84
Butter	1.26	1
Carrots	3.81	1.84
Chicken, broilers	3.22	1.59
Eggs	3.18	1.67
Flour	1.59	1.17
Grapes	3.6	1.76
Ice cream	3.1	1.67
Kidney beans, dried	1.17	0.96
Lard	2.26	1.3
Lamb, leg	2.97	1.55
Lemon juice	3.85	1.84
Lobsters	3.43	1.72
(Cow's) Milk	3.77	1.97
Nuts	1.17	1
Peas, medium	3.39	1.67
Pineapple, fresh	3.68	1.8
Pork, bacon	1.51	1.05
Pumpkin	3.85	1.84
Saurkraut	3.89	1.84
Sausage, bologna	2.97	1.55
Tomatoes, red	3.98	1.88
Tomato, juice	3.98	1.88
Turkey	2.81	1.47
Veal, carcass	3.1	1.59
Watermelon	3.94	1.88
Whitefish	3.18	1.63

Source: http://www.engineeringtoolbox.com/specific-heat-capacity-food-d_295.html

Appendix 2.2. Properties of Saturated Steam – SI Units

				Enthalpy of		
Absolute Pressure	Temperature	Specific Volume	Density	Liquid	Evaporation	Saturated Vapor
				h_l	h_{lv}	h_v
kPa	°C	m³/kg	kg/m³	kJ/kg	kJ/kg	kJ/kg
0.8	3.8	160	0.00626	15.8	2493	2509
2	17.5	67	0.0149	73.5	2460	2534
5	32.9	28.2	0.0354	137.8	2424	2562
10	45.8	14.7	0.0682	191.8	2393	2585
20	60.1	7.65	0.131	251.5	2358	2610
28	67.5	5.58	0.179	282.7	2340	2623
35	72.7	4.53	0.221	304.3	2327	2632
45	78.7	3.58	0.279	329.6	2312	2642
55	83.7	2.96	0.338	350.6	2299	2650
65	88	2.53	0.395	368.6	2288	2657
75	91.8	2.22	0.45	384.5	2279	2663
85	95.2	1.97	0.507	398.6	2270	2668
95	98.2	1.78	0.563	411.5	2262	2673
100	99.6	1.69	0.59	417.5	2258	2675
101.33	100	1.67	0.598	419.1	2257	2676
110	102.3	1.55	0.646	428.8	2251	2680
130	107.1	1.33	0.755	449.2	2238	2687
150	111.4	1.16	0.863	467.1	2226	2698
170	115.2	1.03	0.97	483.2	2216	2699
190	118.6	0.929	1.08	497.8	2206	2704
220	123.3	0.81	1.23	517.6	2193	2711
260	128.7	0.693	1.44	540.9	2177	2718
280	131.2	0.646	1.55	551.4	2170	2722
320	135.8	0.57	1.75	570.9	2157	2728
360	139.9	0.51	1.96	588.5	2144	2733
400	143.1	0.462	2.16	604.7	2133	2738
440	147.1	0.423	2.36	619.6	2122	2742
480	150.3	0.389	2.57	633.5	2112	2746
500	151.8	0.375	2.67	640.1	2107	2748
550	155.5	0.342	2.92	655.8	2096	2752
600	158.8	0.315	3.175	670.4	2085	2756
650	162	0.292	3.425	684.1	2075	2759
700	165	0.273	3.66	697.1	2065	2762
750	167.8	0.255	3.915	709.3	2056	2765
800	170.4	0.24	4.16	720.9	2047	2768
850	172.9	0.229	4.41	732	2038	2770
900	175.4	0.215	4.65	742.6	2030	2772
950	177.7	0.204	4.9	752.8	2021	2774

(*Continued*)

Appendix 2.2. (*Continued*)

Absolute Pressure	Temperature	Specific Volume	Density	Enthalpy of		
				Liquid	Evaporation	Saturated Vapor
				h_l	h_{lv}	h_v
kPa	°C	m³/kg	kg/m³	kJ/kg	kJ/kg	kJ/kg
1000	179.9	0.194	5.15	762.6	2014	2776
1050	182	0.186	5.39	772	2006	2778
1150	186	0.17	5.89	790	1991	2781
1250	189.8	0.157	6.38	807	1977	2784
1300	191.6	0.151	6.62	815	1971	2785
1500	198.3	0.132	7.59	845	1945	2790
1600	201.4	0.124	8.03	859	1933	2792
1800	207.1	0.11	9.07	885	1910	2795
2000	212.4	0.0995	10.01	909	1889	2797
2100	214.9	0.0945	10.54	920	1878	2798
2300	219.6	0.0868	11.52	942	1858	2800
2400	221.8	0.0832	12.02	952	1849	2800
2600	226	0.0769	13.01	972	1830	2801
2700	228.1	0.074	13.52	981	1821	2802
2900	232	0.0689	14.52	1000	1803	2802
3000	233.8	0.0666	15	1008	1794	2802
3200	237.4	0.0624	16.02	1025	1779	2802
3400	240.9	0.0587	17.04	1042	1760	2802
3600	244.2	0.0554	18.06	1058	1744	2802
3800	247.3	0.0524	19.08	1073	1728	2801
4000	250.3	0.0497	20.09	1087	1713	2800

Source: http://www.engineeringtoolbox.com/saturated-stream-properties-d_101.html

Appendix 2.3. Values of the Ideal Gas Constant

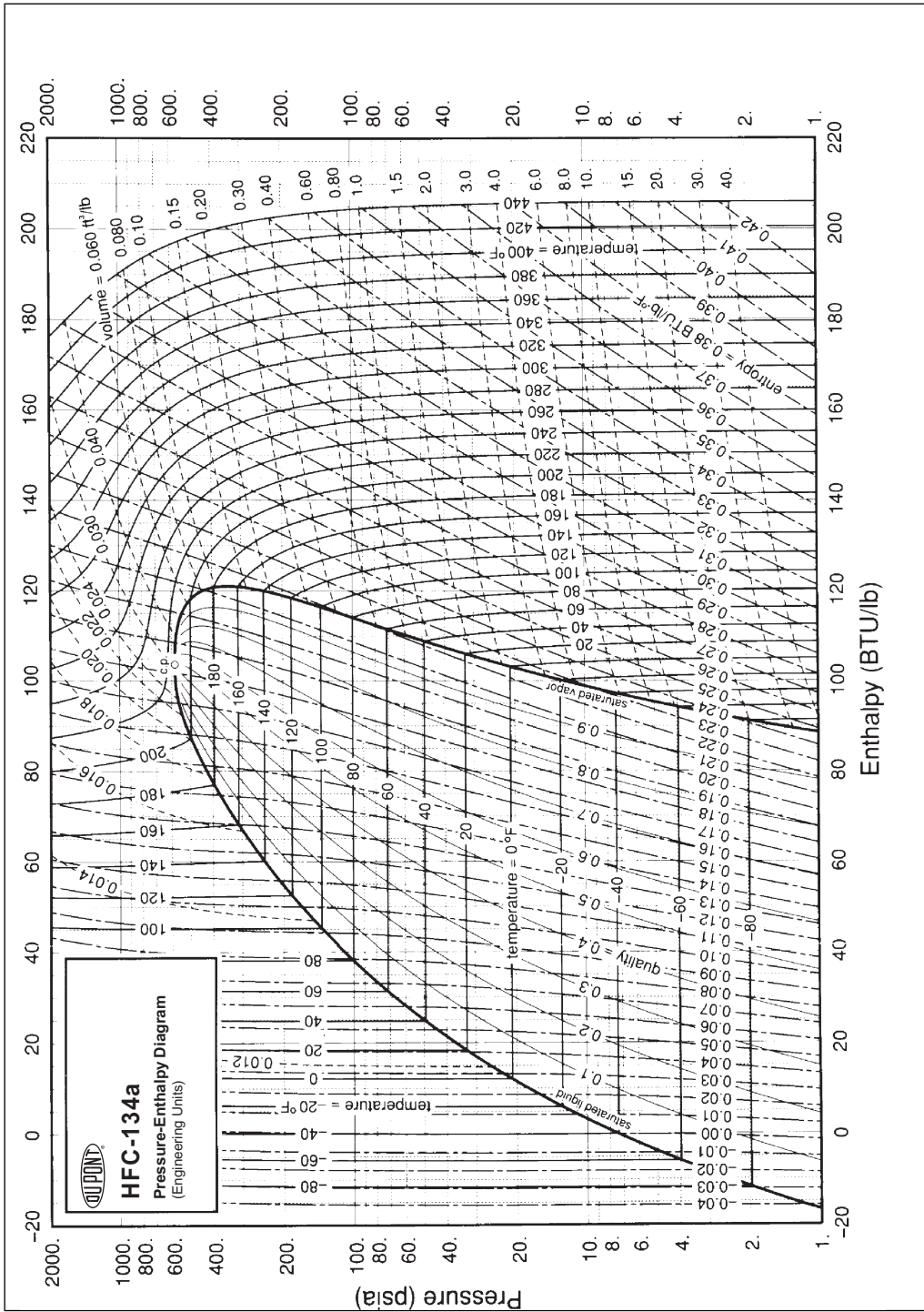| Values of R	Units
8.314472	$J\,K^{-1}\,mol^{-1}$
1.9858775	$cal\,K^{-1}\,mol^{-1}$
8.314472×10^7	$erg\,K^{-1}\,mol^{-1}$
8.314472	$L\,kPa\,K^{-1}\,mol^{-1}$
8.314472	$m^3\,Pa\,K^{-1}\,mol^{-1}$
8.314472	$cm^3\,MPa\,K^{-1}\,mol^{-1}$
8.205746×10^{-5}	$m^3\,atm\,K^{-1}\,mol^{-1}$
0.0821	$L\,atm\,K^{-1}\,mol^{-1}$
6.13244	$ft\,lb_f\,K^{-1}\,g\text{-}mol^{-1}$
1,545.35	$ft\,lb_f\,°R^{-1}\,lb\text{-}mol^{-1}$
10.73159	$ft^3\,psi\,°R^{-1}\,lb\text{-}mol^{-1}$
0.7302413	$ft^3\,atm\,°R^{-1}\,lb\text{-}mol^{-1}$
998.9701	$ft^3\,mmHg\,K^{-1}\,lb\text{-}mol^{-1}$
1.986	$Btu\,lb\text{-}mol^{-1}\,°R^{-1}$

Appendix 2.4. R-134 Refrigerant Table – SI Units

HFC-134a
Pressure-Enthalpy Diagram
(SI Units)

Source: DuPont, used with permission.

HFC-134a
Pressure-Enthalpy Diagram
(Engineering Units)

Enthalpy (BTU/lb)

Pressure (psia)
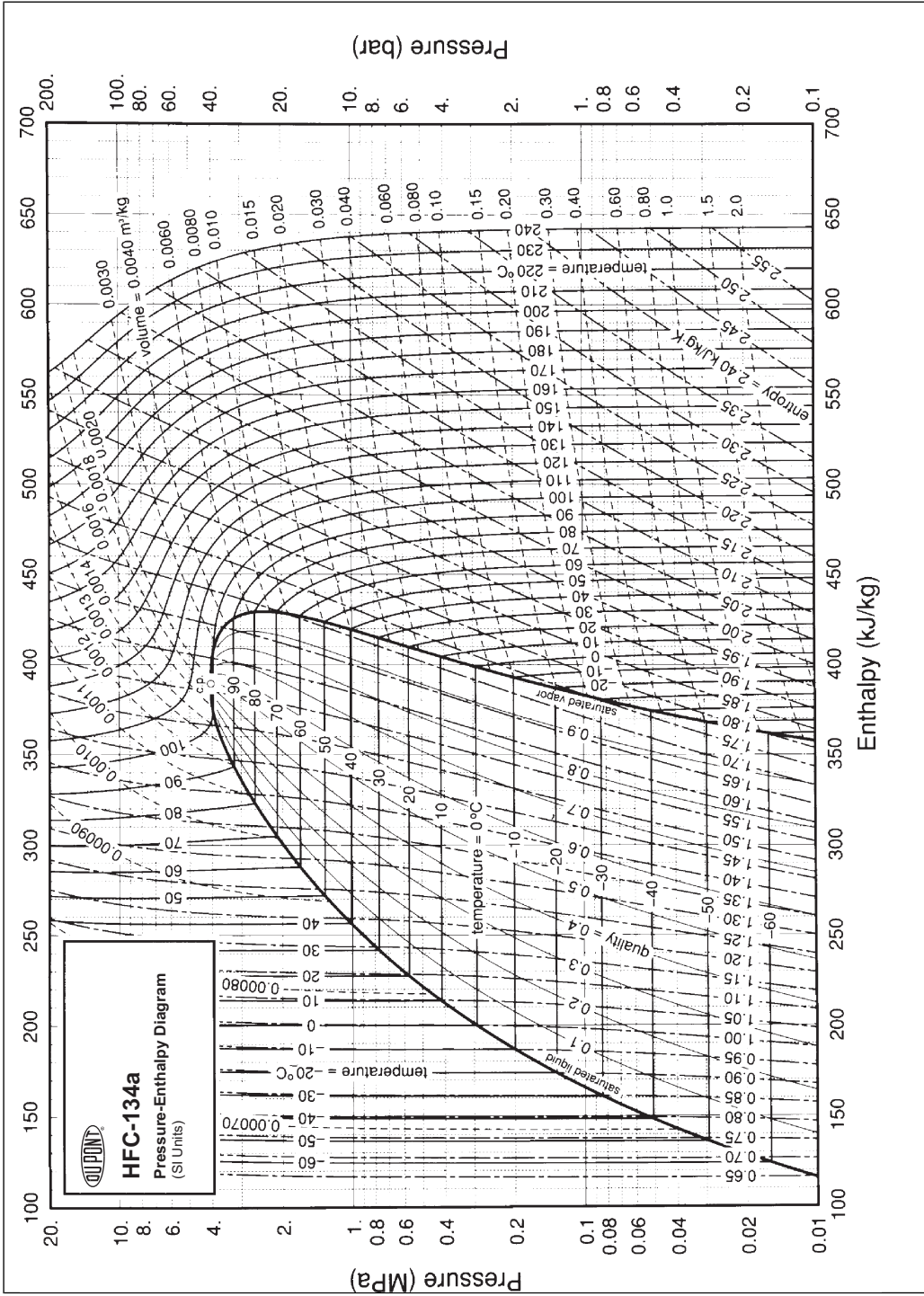
Source: DuPont, used with permission.

Appendix 2.6. Simple Psychrometric Chart, SI Units

Psychrometric Chart

SI (metric) units
Barometric Pressure 101.325 kPa (Sea level)
based on data from
Carrier Corporation Cat. No. 794-001, dated 1975

Humidity Ratio (gm Water/gm of Dry Air)

Dry Bulb Temperature (°C)

Enthalpy at Saturation (J/gm Dry Air)

Wet Bulb or Saturation Temperature (°C)

Relative Humidity

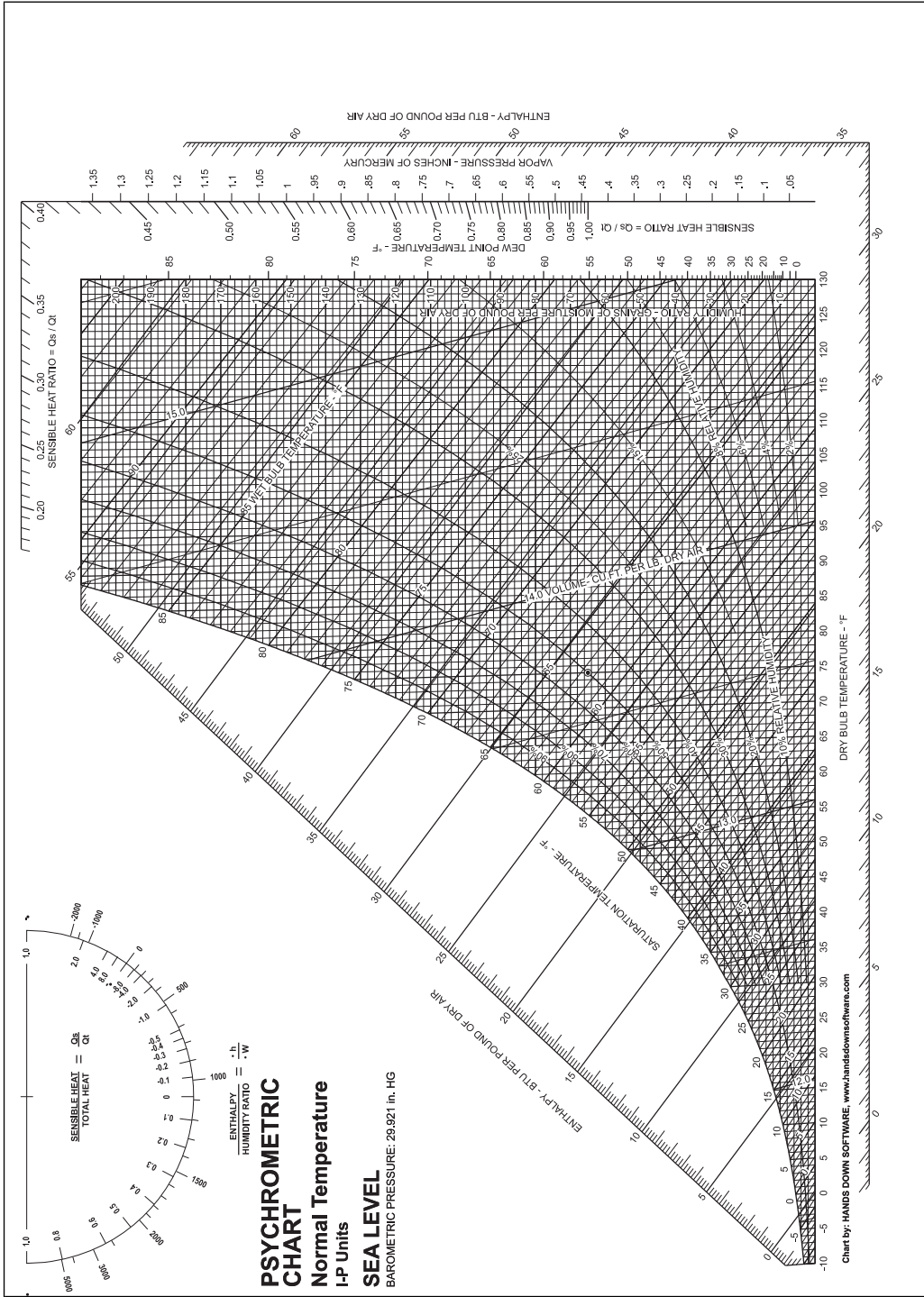Specific Volume 0.90 m³ / kg Dry Air
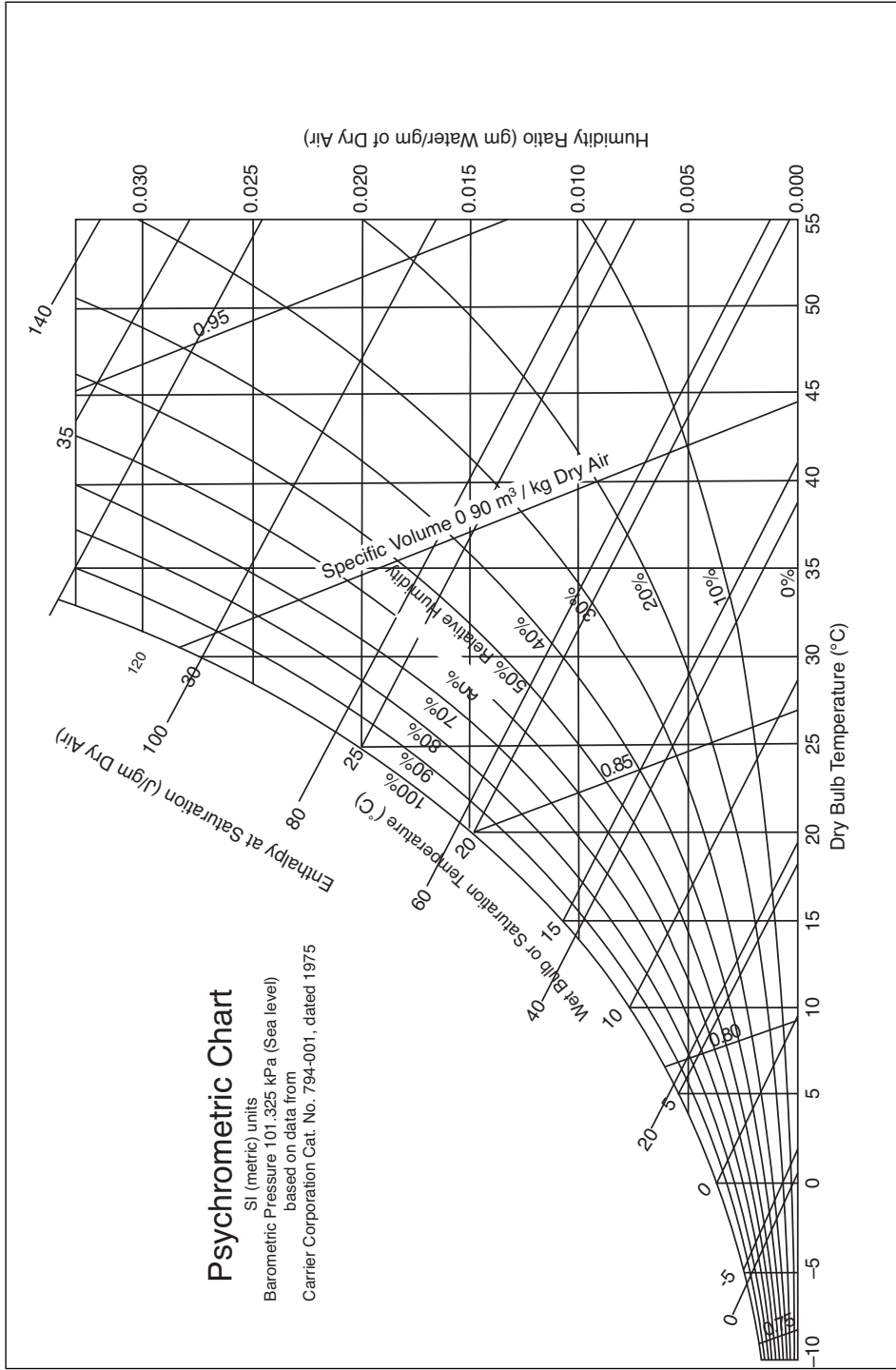
Source: Arthur Ogawa – Public Domain

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Appendix 2.7. Commercial Psycrometric Chart, SI Units
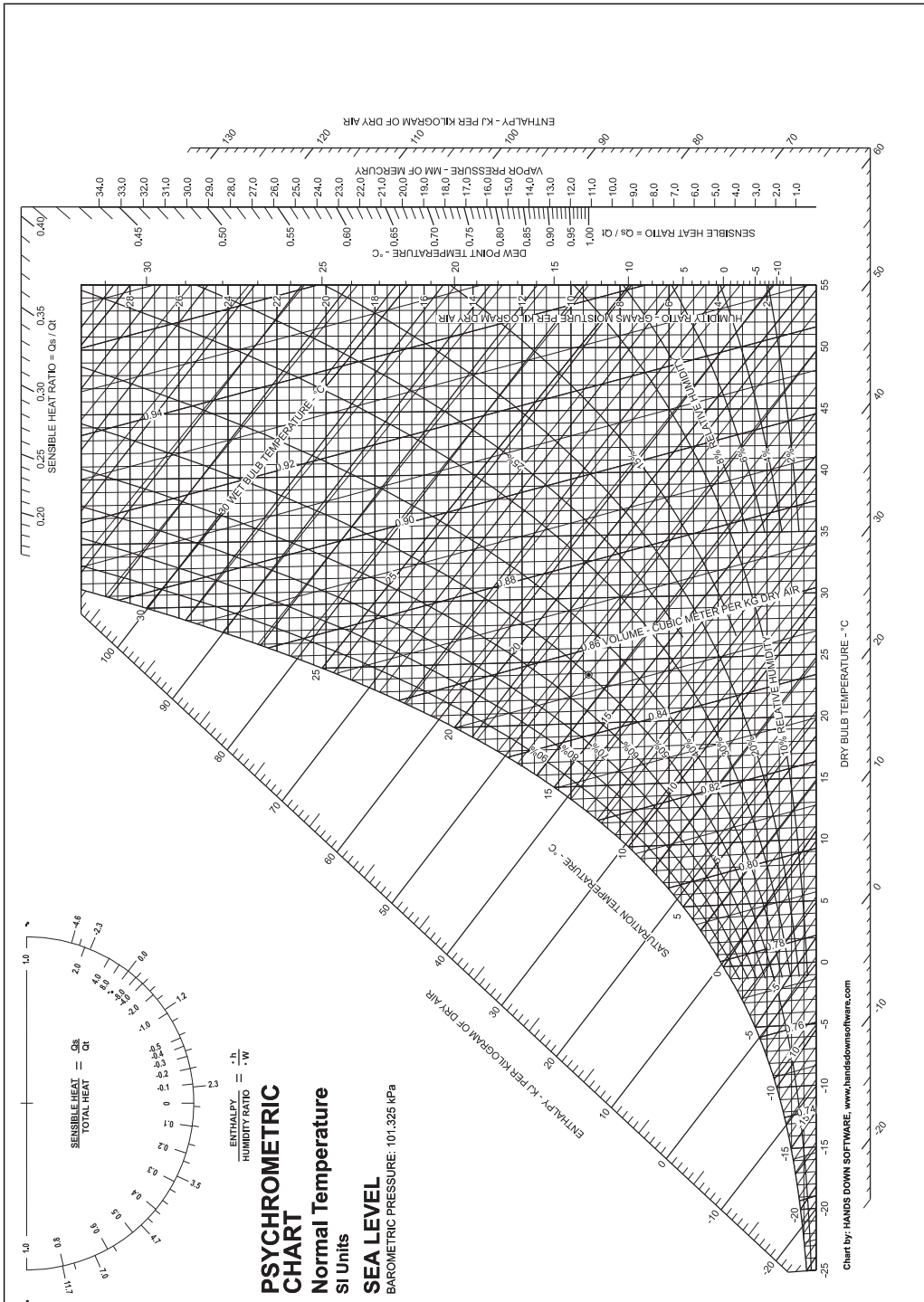
Source: Bob Hanna – Public Domain

Appendix 2.8. Commercial Psycrometric Chart, US Units

Source: Bob Hanna – Public Domain

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