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1 Basic Concepts

1.1 Overview

Thermodynamics is unquestionably the most powerful and most elegant of the engineering sciences. Its power arises from the fact that it can be applied to any discipline, technology, application, or process. The origins of thermodynamics can be traced to the development of the steam engine in the 1700's, and thermodynamic principles do govern the performance of these types of machines. However, the power of thermodynamics lies in its generality. Thermodynamics is used to understand the energy exchanges accompanying a wide range of mechanical, chemical, and biological processes that bear little resemblance to the engines that gave birth to the discipline. Thermodynamics has even been used to study the energy exchanges that are involved in nuclear phenomena and it has been helpful in identifying sub-atomic particles. The elegance of thermodynamics is the simplicity of its basic postulates. There are two primary 'laws' of thermodynamics, the First Law and the Second Law, and they always apply with no exceptions. No other engineering science achieves such a broad range of applicability based on such a simple set of postulates.

So, what is thermodynamics? We can begin to answer this question by dissecting the word into its roots: 'thermo' and 'dynamics'. The term 'thermo' originates from a Greek word meaning warm or hot, which is related to temperature. This suggests a concept that is related to temperature and referred to as heat. The concept of heat will receive much attention in this text. 'Dynamics' suggests motion or movement. Thus the term 'thermodynamics' may be loosely interpreted as 'heat motion'. This interpretation of the word reflects the origins of the science. Thermodynamics was developed in order to explain how heat, usually generated from combusting a fuel, can be provided to a machine in order to generate mechanical power or 'motion'. However, as noted above, thermodynamics has since matured into a more general science that can be applied to a wide range of situations, including those for which heat is not involved at all. The term thermodynamics is sometimes criticized because the science of thermodynamics is ordinarily limited to systems that are in *equilibrium*. Systems in equilibrium are not 'dynamic'. This fact has prompted some to suggest that the science would be better named 'thermostatics' (Tribus, 1961).

Perhaps the best definition of thermodynamics is this: *Thermodynamics is the science that studies the conversion of energy from one form to another*. This definition captures the generality of the science. The definition also introduces a new concept – energy. Thermodynamics involves a number of concepts that may be new to you, such as heat and energy, and these terms must each be carefully defined. As you read this, it may seem that heat and energy are familiar words and therefore no further definition of these concepts is necessary. However, the common understanding of these terms differs from the formal definitions that are needed in order to apply the laws of thermodynamics.

The First Law of Thermodynamics states that energy is conserved in all processes (in the absence of nuclear reactions). If energy is conserved (i.e., it is not generated or destroyed) then the amount of energy that is available must be constant. But if the amount of energy is constant then why do we hear on the news that the world is experiencing an energy shortage? How could we be ‘running out of energy’? Why do we receive monthly ‘energy’ bills?

The answer to these questions lies in the difference between the term energy as it is commonly used and the formal, thermodynamic definition of energy. These differences between common vernacular and precise thermodynamic definitions are a source of confusion. The term *energy* that is used in everyday conversations should be thought of as ‘the capacity to do work’. This definition is not consistent with the thermodynamic definition of energy, but rather refers to a different thermodynamic concept that is referred to as *exergy* and is studied in Chapter 7. The thermodynamic definition of energy is not as satisfying. Energy is not really ‘something’; rather, it is a property of matter. We cannot see, smell, taste, hear or feel energy. We can measure it, but only indirectly. Hopefully, the thermodynamic concept of energy will become clearer as you progress through this book.

The First Law of Thermodynamics is concerned with the conservation of energy. However, energy has both quantity and quality. The quality of energy is not conserved and the Second Law of Thermodynamics can be interpreted as a system for assigning quality to energy. Although energy is conserved, the quality of energy is always reduced during energy transformation processes. Lower quality energy is less useful to us in the sense that its capability for doing work has been diminished. The quality of energy is continuously degraded by all real processes; this observation can be expressed in lay terms as ‘running out of energy’.

The Second Law is responsible for the directional nature of all real processes. That is, processes can occur in only one direction and will not spontaneously reverse themselves because doing so would require a spontaneous increase in the quality of energy. The Second Law explains why heat flows from hot to cold and why objects at different temperatures will eventually come to the same temperature. The Second Law explains why gases mix and things break. It can be used to explain why we age and why time moves forward. The Second Law of Thermodynamics is likely the most famous law in all of the physical sciences.

Our society is now facing some very challenging problems. Some of these problems are related to the diminishing supply of petroleum, coal, natural gas, and the other combustible materials that provide the energy (the common definition rather than the thermodynamic definition) that powers our world. Even if these fuels were inexhaustible (which they are not), combustion of carbon-based fuels necessarily produces carbon dioxide, which has been linked to global warming and other climate change phenomena. What alternatives exist to provide the power that we need? Hydrogen-powered fuel cells, biomass, nuclear power plants, solar and wind energy systems have all been mentioned in the popular media as potential solutions. Which one of these alternatives is actually best? What role can each of them play in terms of displacing our current energy supplies? These are huge questions. The solution to our energy problem will likely be one of the biggest challenges facing our species this century. In one sense this is alarming, but it is also very exciting. You are reading this book because you have either a professional or personal interest in the subject of thermodynamics. Thermodynamics plays a major role in addressing these energy-related questions. It is clear that the demand for people who are well-educated in thermodynamics and capable of applying the discipline to a wide range of problems will only increase.

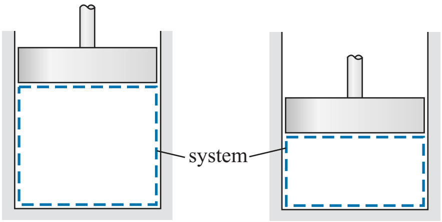

Figure 1-1: A system defined to contain all of the air in a piston-cylinder device.

1.2 Thermodynamic Systems

Every thermodynamic analysis begins with the specification of a *system*. A system is simply any object, quantity of matter, or region of space that has been selected for study. The system provides the precise specification for the focus of the analysis and enables the use of the First and Second Laws of Thermodynamics. Everything that is not part of the system is referred to as the *surroundings*.

The specification of a system requires the identification of its *boundary*, the surface that separates the system from its surroundings. The system boundary may correspond to a real surface. For example, Figure 1-1 illustrates a perfectly-sealed piston-cylinder device that is filled with air. The dashed blue line indicates the boundary of a system that is defined so that it contains all of the air within the cylinder. Notice that the boundary of this system must move as the position of the piston changes.

The laws of thermodynamics can be applied to any system and often there will be more than one logical system choice for a particular problem. For example, Figure 1-2 illustrates an air tank that is being filled from an air line. One choice for a system is the fixed region that corresponds to the internal volume of the air tank. An alternative system is defined by the dashed blue line in Figure 1-2 so that it contains all of the air that was initially in the tank. Notice that the boundary of this system must move as the tank is filled.

We classify systems according to their interactions with the surroundings. If mass does not cross the boundary of a system then it is referred to as a *closed system*. Mass does cross the boundary of an *open system*. An *adiabatic system* is one in which the boundary is impermeable to heat, i.e., the energy transfer that normally occurs when a temperature difference exists between the system and surroundings. A *steady-state* system is one in which all of the properties of the system do not change with time. An *isolated* system has no interaction of any kind with its surroundings.

The First and Second Laws of Thermodynamics apply regardless of the system choice. The definition of a system is dictated by convenience. While there is no wrong choice of system, some system choices simplify the mathematical description of a process whereas others cause the problem to become impossibly complicated. Your ability

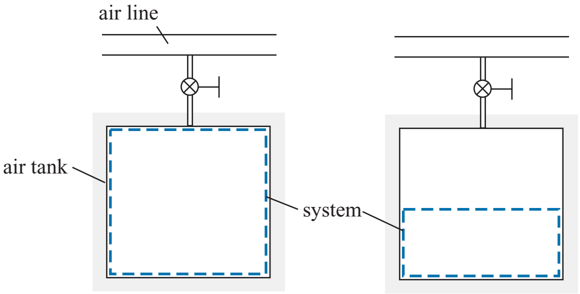

Figure 1-2: A system defined to contain all of the air that is initially in a tank that is being filled.

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to select an appropriate system will improve with experience. The first step in every thermodynamics problem is the selection of a system and this is accomplished by clearly indicating its boundaries so that it can be carefully analyzed.

1.3 States and Properties

1.3.1 State of a System

Once a system has been specified, it is next necessary to specify its *state*. The state is a description of the system in terms of quantities that will be helpful in describing its behavior and its interactions with the surroundings.

There are two very different ways to describe a thermodynamic system, referred to as the *microscopic* and *macroscopic* approaches. The microscopic approach recognizes that the system consists of matter that is composed of countless, discrete particles (molecules). These molecules often behave in a manner that may be non-intuitive based on our everyday experience with much larger amounts of matter. The fundamental particles move at high velocities and have kinetic energies in three dimensions. Depending on the complexity of the molecules, they may also store energy due to their rotation and the vibration of the bonds connecting the atoms. The particles interact with each other and with the walls of their container. There are so many particles that it is hopeless to attempt to represent the observed characteristics of a system by describing the behaviors of each of its individual particles. However, we may be able to formulate a molecular model that describes the attractive and repulsive forces between particles and the various ways that a particle can store energy. We cannot directly test the molecular model against the behavior of a single molecule. However, we can apply statistics and probability theory to the molecular model in order to deduce the macroscopic behavior that would result from a large number of particles. Agreement between the calculated statistical behavior and the observed macroscopic behavior lends confidence in the fidelity of the model.

The branch of science that describes the state of a system using this microscopic approach is called Statistical Thermodynamics. Statistical Thermodynamics directly integrates the properties of matter with the conservation of energy. It provides a molecular explanation for the Second Law of Thermodynamics and it allows some physical properties (e.g., the specific heats and entropy of low pressure gases) to be determined more simply than is possible using any alternative method. Chapter 15 provides an introduction to Statistical Thermodynamics.

This text will apply a macroscopic approach to describe thermodynamic systems. In the macroscopic approach, the state of the system is described by a relatively small set of characteristics that are called *properties*. Some of these properties are already familiar to you, such as mass, temperature, pressure and volume. This macroscopic approach works well when the system is sufficiently large such that it contains many molecules. However, the macroscopic approach would not work well for a system that consists of a rarefied gas (i.e., a vacuum with just a few molecules). For example, how would you measure the temperature of such a system that consists almost entirely of vacuum?

1.3.2 Measurable and Derived Properties

Thermodynamic properties are classified as being either *measurable* or *derived*. Measurable properties can be directly measured using an appropriate instrument. Examples of measurable properties include mass, temperature, pressure, volume, velocity, elevation, specific heat capacities, and composition. Derived properties cannot be directly

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measured. Derived properties include internal energy, enthalpy, entropy, and other related thermodynamic properties that will be defined in this text.

It is not always clear whether a property is measurable or derived. For example, temperature is normally considered to be a measurable property. But how does one actually measure temperature? The common thermometer consists of a precision bore within a transparent glass enclosure that is filled with a liquid that expands when its temperature is increased. By observing the height of the liquid in the bore, we can measure the volume of the fluid and infer the temperature. There are many other ways to measure temperature. For example, thermistors relate the electrical resistance of a material to its temperature. Thermocouples are junctions between two dissimilar metals that generate a voltage potential that is a function of temperature. In each of these instruments, however, something (e.g., volume, resistance, or voltage) is directly measured and temperature is then inferred from this measurement. Although we do not directly measure temperature, it is still considered to be a measurable property.

1.3.3 Intensive and Extensive Properties

Thermodynamic properties are also classified as being either *intensive* or *extensive*. Intensive properties are independent of the amount of mass in the system whereas the values of extensive properties depend directly on the amount of mass. Temperature and pressure, for example, are intensive properties. If you were told the temperature or pressure of a system and nothing more, you would have no idea of the size of the system. Volume and energy are extensive properties. The greater the volume of a system, the more mass it must have. Extensive properties are linearly related to the system mass.

A *specific property* is defined as the ratio of an extensive property of a system to the mass of the system. Thus specific volume, v, is the ratio of volume (an extensive property) to mass:

$$v = \frac{V}{m} \tag{1-1}$$

where V is the volume of the system and m is the mass of the system. The inverse of specific volume is density:

$$\rho = \frac{1}{v} = \frac{m}{V} \tag{1-2}$$

Specific volume and density are both intensive properties. We will encounter several other extensive properties, including internal energy (U), enthalpy (H), and entropy (S). The corresponding specific properties are specific internal energy (u), specific enthalpy (h), and specific entropy (s):

$$u = \frac{U}{m} \tag{1-3}$$

$$h = \frac{H}{m} \tag{1-4}$$

$$s = \frac{S}{m} \tag{1-5}$$

1.3.4 Internal and External Properties

Properties can also be classified as being either *internal* or *external*. The value of an internal property depends on the nature of the matter that composes the system. External

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properties are independent of the nature of the matter within the system. Examples of external properties include the velocity of the system ($\tilde{V}$) and its elevation in a gravitational field (z). These properties do not depend on whether we are talking about a system composed of helium or one composed of steel. For example, in Section 3.2.2 we will see that a system with a mass $m = 1$ kg that is elevated a distance $z = 1$ m in Earth's gravitational field ($g = 9.81$ m/s^2) will have a potential energy $PE = m\ g\ z = 9.81$ J regardless of the type of matter that the system is composed of. Internal properties depend on the nature of the matter in the system and, as a consequence, they depend upon each other. That is, internal properties are functionally related to one another.

The interdependence of internal properties is of fundamental importance because it allows us to completely fix the state of a system by specifying only a few internal properties. The values of other internal properties can be found by employing the relationships that exist between these properties. It will be shown in Chapter 2 that only two internal intensive properties are required to fix the state of a system containing a pure substance that consists of only one phase (i.e., solid, liquid, or vapor). For example, if the temperature and pressure of water vapor are specified, then the density, specific internal energy, and specific enthalpy all have fixed values. Any other intensive property of the water vapor could also be determined. It is only necessary to know the temperature and pressure of a single phase pure substance in order to determine the specific heat capacity at constant pressure, the magnetic moment, the surface tension, the speed of sound, the electrical resistivity, and many other properties.

You likely have already employed a property relationship in your chemistry class by using the absolute temperature (T) and absolute pressure (P) of a gas in order to calculate its specific volume (v) using the ideal gas law:

$$v = \frac{R\,T}{P} \tag{1-6}$$

where the parameter R is the ideal gas constant. The ideal gas law will be discussed in Section 2.5. It does not apply under all conditions. The accuracy of Eq. (1-6) is reduced as the pressure is increased or as the temperature is decreased. Under some conditions, the ideal gas law may not be sufficiently accurate to be of any use at all. However, this complication does not change the fact that the specific volume is fixed at some value (i.e., it is not an independent variable) when the temperature and pressure are specified. If the ideal gas law is not applicable, a more complicated relation between specific volume, temperature and pressure may be needed, as discussed in Chapter 10. The properties of many substances have been measured and the relationships between internal properties can be expressed using tables, charts, equations, and computer programs, as described in Chapter 2.

1.4 Balances

Balances are the basic tool of engineering. Once a system has been carefully defined, it is possible to apply a balance to the system. A balance is simply a mathematical statement of what we know to be true. Any number of quantities can be balanced for any arbitrary system. The general balance equation, written for a finite period of time and some arbitrary quantity is:

$$In + Generated = Out + Destroyed + Stored \tag{1-7}$$

where *In* is the amount entering the system by crossing its boundary, *Generated* is the amount generated within the system, *Out* is the amount leaving the system by crossing its boundary, *Destroyed* is the amount destroyed within the system, and *Stored* is the

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amount stored in the system (i.e., the change in the quantity during the period of time). A balance can also be written on a rate basis, in which case the rate of each of the terms in Eq. (1-7) must be balanced at a particular instant in time. It is important to emphasize that the balance provided by Eq. (1-7) makes no sense until you have carefully defined a system and its boundaries.

Every month, most of us define a system that is referred to as our *household* and carry out a money balance on this system:

$$D_{in} + D_{gen} = D_{out} + D_{des} + \Delta D \tag{1-8}$$

where D indicates the amount of money. The variable D_{in} is the amount of money that enters your household (from wages and other forms of income), D_{des} is the amount of money that is destroyed, D_{out} is the amount of money that leaves your household (expenses), and D_{gen} is the amount of money that is created in your household. The term ΔD in Eq. (1-8) is the amount of money stored in your household, i.e., the change in the amount of money contained within your household during the time period of interest. A positive value of ΔD indicates that you managed to save some money during the month while a negative value indicates that you had to dip into your savings. For most of us, D_{des} will be zero every month as we do not often literally burn up or destroy currency. Also, D_{gen} will be zero as we cannot (legally) generate money. Thus, balancing our monthly finances will result in the following equation:

$$D_{in} = D_{out} + \Delta D \tag{1-9}$$

Equation (1-9) shows that, at least on a personal level, money is a *conserved* quantity; that is, it is neither destroyed nor produced. Other quantities are not conserved. For example, we could define a system around the borders of the United States and balance people for a year:

$$P_{in} + P_{gen} = P_{out} + P_{des} + \Delta P \tag{1-10}$$

In Eq. (1-10), P_{in} is the number of people that enter the U.S. by crossing its borders (immigration) and P_{out} is the number of people leaving the U.S. by crossing its borders (emigration). The quantity ΔP is the change in the population of the U.S. during the year (i.e., the number of people at the end of the year less the number of people at the beginning of the year). People are, as you know, not a conserved quantity; they are both destroyed and generated. The quantity P_{des} is the number of people that die and P_{gen} is the number of babies born within the borders of the U.S during the year. Equation (1-10) must be satisfied as it is simply a mathematical statement of what we know to be true.

Mass is a conserved quantity since it cannot be generated or destroyed (in the absence of nuclear reactions). Therefore, a mass balance on a system for a finite period of time leads to:

$$m_{in} = m_{out} + \Delta m \tag{1-11}$$

where m_{in} is the amount of mass that enters the system by crossing its boundary and m_{out} is the amount of mass that leaves the system by crossing its boundary. Note that the quantities m_{in} and m_{out} must be zero for a closed system. The quantity Δm is the amount of mass stored in the system; this is the mass in the system at the end of time period less the mass in the system at the beginning of the time period. A mass balance written on a rate basis at a particular instant in time is:

$$\dot{m}_{in} = \dot{m}_{out} + \frac{dm}{dt} \tag{1-12}$$

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where $\dot{m}_{in}$ and $\dot{m}_{out}$ are the rates at which mass is entering and leaving the system, respectively, by crossing its boundaries, and $\frac{dm}{dt}$ is the rate of change in the mass of the system.

The laws of thermodynamics can be expressed most concisely in the form of balances. The First Law of Thermodynamics (which is introduced in Chapter 3) states that energy is a conserved quantity. For any system you care to define, energy cannot be destroyed or generated. Energy can flow into or out of a system (in various ways) and it can be stored in a system (in various forms). However, energy is never generated or destroyed in a system.

The Second Law of Thermodynamics states that the thermodynamic property entropy (which is introduced in Chapter 6) is not a conserved quantity; entropy is always generated and never destroyed. The Second Law suggests that the entropy of the universe is always increasing and it provides directionality to all processes. Any real process will result in the generation of entropy. Therefore, in order for the process to run in reverse (i.e., all inflows become outflows, outflows become inflows, etc.) it would be necessary to destroy entropy. Because it is not possible to destroy entropy, no real process is “reversible”. A theoretical process that results in no entropy generation is often referred to as a “reversible” process and provides a useful limit to the behavior of real processes.

1.5 Introduction to EES (Engineering Equation Solver)

Thermodynamics and related thermal science courses (e.g., fluid dynamics and heat transfer) focus on providing a mathematical description of physical phenomena (i.e., an engineering model). An engineering model increases our understanding of the underlying physics. Properly formulated, the model can be used in place of the actual physical system in order to do mathematical experiments that can be conducted more quickly and with less cost than their physical counterparts. A good model is predictive. The model therefore allows the behavior of a system to be explored at conditions that would be difficult or impossible to achieve and it provides resolved information that would be hard to measure in the actual physical system. Coupled with optimization techniques, a model can be used to improve equipment designs and therefore allow us to obtain a desired result at less expense or more quickly or with less effect on the environment.

An engineering model will consist of a set of algebraic and/or differential equations that may be challenging to solve. In general, the more faithfully a mathematical model represents a physical behavior, the more equations are required and the more complicated the model becomes. At one extreme, the model can require so much computational effort that it may be easier to conduct experiments using the actual physical system. At the other extreme, the model can be too simplistic. Although the equations are easy to solve, the model does not accurately represent the physics and therefore is not very useful. A useful model is a compromise between these extremes.

Engineering Equation Solver (EES) is a computer program that has been developed in order to numerically solve the type of algebraic and differential equations that typically appear in models of thermodynamic systems. EES can check the dimensional and unit consistency of the equations in order to catch many common programming errors. In addition, EES provides built-in functions for the thermodynamic and transport properties of many engineering fluids. EES provides the capability to carry out parametric studies and generate high-quality plots; it can do optimization, provide linear and non-linear regression, and automate uncertainty analyses. The combination of equation solving capability with access to engineering property data makes EES a powerful

```
X*ln(X)=Y^3
sqrt(X)=1/Y
```

Figure 1-3: Two non-linear equations entered in the EES Equations window.

tool for modeling thermal-fluid systems and it is used extensively in industry. EES will be used throughout this textbook.

An introduction to EES is presented in this section. If you have already become familiar with EES and are comfortable entering and solving equations then you can skip this section. The EES program is probably installed on your departmental computer system. If not, you can use the limited academic version that can be downloaded from www.fchart.com or www.cambridge.org/kleinandnellis. To start EES from the Windows File Manager or from Explorer, double-click on the EES program icon or on any file that was created by EES. EES begins by displaying a splash screen that shows the registration information, the version number and other information. Click the OK button in order to dismiss the splash screen.

You will next see the Equations window. The Equations window is where the mathematical equations that constitute your model are entered. EES is capable of solving large sets of non-linear, coupled algebraic and differential equations. Enter the following two equations on separate lines in the Equations window:

$$x \ln(x) = y^3 \tag{1-13}$$

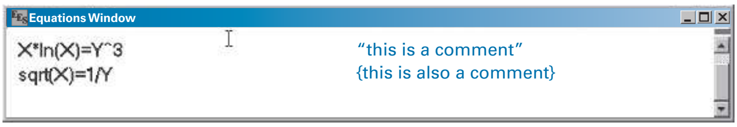
$$\sqrt{x} = \frac{1}{y} \tag{1-14}$$

Equations (1-13) and (1-14) have no physical significance. However, they are non-linear and coupled (i.e., they must be solved simultaneously) and, as a result, they would be difficult to solve by hand. Note that the equations are entered in the Equations window in the same manner that you would enter text into a word processor. However, there are some rules that must be followed in order for EES to understand your input.

1. Variable names must start with a letter and may consist of any keyboard character except ( ) ' | * / + − ^ { }: " or;. The maximum length of a variable name is 30 characters.
2. EES is not case-sensitive. That is, upper and lower case letters are not distinguished from one another. The variable `X` and the variable `x` are identical as far as EES is concerned.
3. Blank lines and spaces are ignored.
4. In general, each equation must be entered on a separate line. However, multiple equations may be entered on one line if they are separated by a semi-colon (;).
5. The caret symbol (^) and ** are both used to indicate the mathematical operation of raising a number to a power. For example, y^3 can be entered as `y^3` or `y**3`.
6. EES uses the standard order of operations that is used by most other computer languages.

After you have entered Eqs. (1-13) and (1-14), the Equations window should appear as shown in Figure 1-3.

It is always important to annotate the equations in the Equations window so that you and others who look at your model (e.g., your thermodynamics professor) can understand what each equation is intended to do. Annotation can be accomplished in EES by adding comments in the Equations window. Comments can be enclosed within curly braces {} or within double quotation marks " ", as shown in Figure 1-4. It is good



```
X*ln(X)=Y^3          "this is a comment"
sqrt(X)=1/Y          {this is also a comment}
```

Figure 1-4: Equations window with equations and comments.

practice to enter the comments immediately to the right of each equation; this process is facilitated by pressing the tab key. Information within comments is ignored by EES and comments may span as many lines as needed. EES will display the comments in blue.

It is sometimes difficult to interpret equations that have been entered in text format in the Equations window, particularly when many nested sets of parentheses or operations are employed. Therefore, EES provides a Formatted Equations window that displays the equations that are entered in the Equations window using a mathematical notation. Select Formatted Equations from the Windows menu in order to access the Formatted Equations window (Figure 1-5). Notice that the comments that are entered in the Equations window within quotes are also displayed in the Formatted Equations window whereas comments entered in curly braces are not displayed. Normally, comments within quotes are used to document the equations whereas curly braces are used to "comment out" text that you do not wish EES to use at this time. "Commenting out" a set of equations is a convenient way to remove these equations temporarily. To accomplish this, highlight the equation(s) to be removed and right-click. Select Comment {} from the pop-up menu that appears. To re-instate the equation(s), highlight them again, right-click, and select Undo Comment {}.

The equations in the Formatted Equations window can be copied and pasted, for example into a report documenting the model. Highlight the equation(s) of interest and right-click on the selection. Notice that it is possible to copy the equation as a picture that can be pasted into a word processor. The Professional version of EES can also copy the equation as a LaTeX object or a MathType® equation.

Select Solve from the Calculate menu. A dialog window will appear indicating the progress of the solution. Click the Continue button when the calculations are completed in order to display the Solution window that contains the solution to the set of equations (Figure 1-6). EES can solve thousands of equations very quickly, which makes it a very powerful tool.

The Equations window allows a free form input. As you can see in Figure 1-4, the position of variables within the equation does not matter and it is not necessary to isolate the unknown variable on the left side of an equal sign, as is required in formal programming languages. This capability is convenient because in many problems, it is not possible to isolate the unknown variable. Also, the order in which the equations are entered does not matter. Before the equations are solved, EES will (internally) rearrange them into an order that leads to the most efficient solution process, regardless

$$X \cdot \ln(X) = Y^3 \qquad \text{this is a comment}$$

$$\sqrt{X} = \frac{1}{Y}$$

Figure 1-5: Equations displayed in the Formatted Equations window.