Bahman Zohuri · Patrick McDaniel

Thermodynamics In Nuclear Power Plant Systems

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Springer

Bahman Zohuri
Department of Nuclear Engineering
University of New Mexico
Albuquerque
USA

Patrick McDaniel
Department of Chemical and Nuclear
Engineering
University of New Mexico
Albuquerque
USA

Printed on acid-free paper
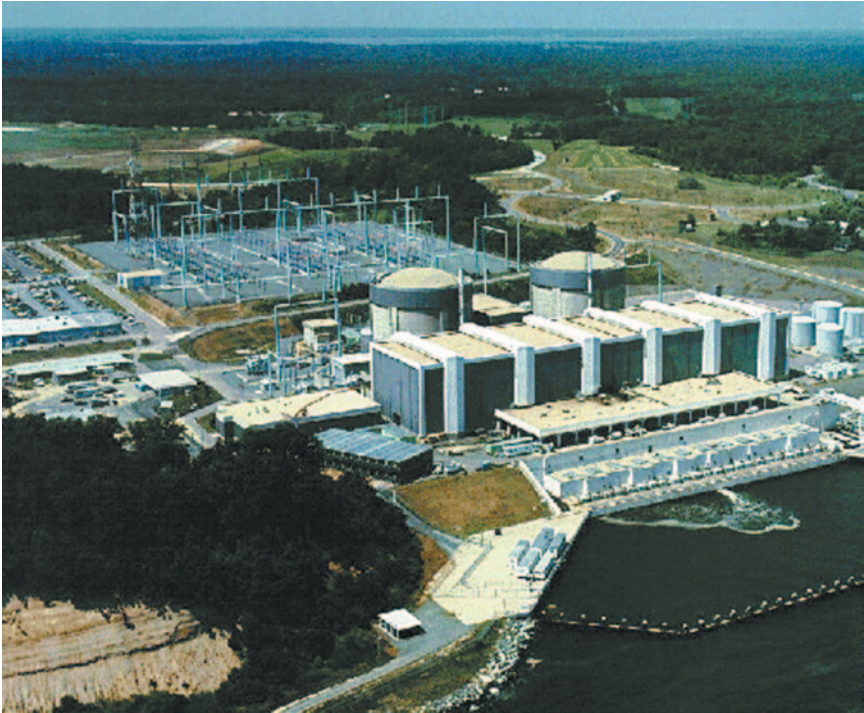
This book is dedicated to my Parents
Marzieh and Akbar Zohuri
Bahman Zohuri

This book is dedicated to Colonel Ben
Pollard
Patrick McDaniel

Preface

This text covers the fundamentals of thermodynamics required to understand electrical power generation systems. It then covers the application of these principles to nuclear reactor power systems. It is not a general thermodynamics text, but is a thermodynamics text aimed at explaining the fundamentals and applying them to the challenges facing actual nuclear power systems. It is written at an undergraduate level, but should also be useful to practicing engineers.

It starts with the fundamental definitions of thermodynamic variables such as temperature, pressure and specific volume. It defines the Zeroth Law of Thermodynamics. It then explains open and closed systems. The Ideal Gas law is introduced along with some of its limitations for real gases. Gas kinetic theory is then introduced to provide a background for the Ideal Gas Law and a foundation for understanding for the theory of specific heats. Then it moves on to the First Law of Thermodynamics and its realization in the internal energy and enthalpy potentials. After addressing several applications, it moves on to the Second Law of Thermodynamics and the concept of entropy. It then approaches entropy from the statistical mechanics viewpoint to validate that it truly is a measurable physical quantity. It concludes the fundamental theory portion of the book by discussing irreversibility, availability, and the Maxwell relations, touching slightly on the Third Law of Thermodynamics.

The second portion of the book is devoted to specific applications of the fundamentals to Brayton and Rankine cycles for power generation. Brayton cycle compressors, turbines, and recuperators are covered, along with the fundamentals of heat exchanger design. Rankine steam generators, turbines, condensers, and pumps are discussed. Reheaters and feed water heaters are also covered. Ultimate heat rejections by circulating water systems are also discussed.

The third part of the book covers current and projected reactor systems and how the thermodynamic principles are applied to their design, operation and safety analyses.

Detailed appendices cover metric and English system units and conversions, detailed steam and gas tables, heat transfer properties, and nuclear reactor system descriptions.

Acknowledgments

The authors would like to acknowledge all the individuals for their help, encouragement, and support. We have decided not to name them all since some of them may not be around to see the end result of their encouragement, but we hope they can at least read this acknowledgment wherever they may be.

Last but not least, special thanks to our parents, wives, children and friends for providing constant encouragement, without which this book could not have been written. We especially appreciate their patience with our frequent absence from home and long hours in front of the computer during the preparation of this book.

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About the Authors

Dr. Bahman Zohuri is currently at the Galaxy Advanced Engineering, Inc. a consulting company that he started himself in 1991 when he left both semiconductor and defense industries after many years working as a chief scientist. After graduating from University of Illinois in field of Physics and Applied Mathematics, he joined the Westinghouse Electric Corporation where he performed thermal hydraulic analysis and natural circulation for the inherent shutdown heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shut system for secondary loop heat exchange. All these designs were used for Nuclear Safety and Reliability Engineering for Self-Actuated Shutdown System. He designed the Mercury Heat Pipe and Electromagnetic Pumps for Large Pool Concepts of LMFBR for heat rejection purpose for this reactor around 1978 where he received a patent for it. He later on was transferred to defense division of Westinghouse where he was responsible for the dynamic analysis and method of launch and handling of MX missile out of canister. The results are applied to MX launch seal performance and muzzle blast phenomena analysis (i.e. missile vibration and hydrodynamic shock formation). He also was involved in analytical calculation and computation in the study of Nonlinear Ion Wave in Rarefying Plasma. The results are applied to the propagation of "Soliton Wave" and the resulting charge collector traces, in the rarefactions characteristic of the corona of the a laser irradiated target pellet. As part of his graduate research work at Argonne National Laboratory, he performed computation and programming of multi-exchange integral in surface physics and solid state physics. He holds different patent in areas such as diffusion processes and design of diffusion furnace while he was senior process engineer working for different semiconductor industries such as Intel, Varian, and National Semiconductor corporations. Later on, he joined Lockheed Missile and Aerospace Corporation as Senior Chief Scientist. At this position, he was responsible for Senior in R&D and the study of vulnerability, survivability and both radiation and laser hardening of different components of payload (i.e. IR Sensor) for Defense Support Program (DSP), Boost Surveillance and Tracking Satellite (BSTS) and Space Surveillance and Tracking Satellite (SSTS) against laser or nuclear threat. While in there, he also studied and performed the analysis of characteristics of laser beam and nuclear radiation interaction with materials, Transient Radiation

Effects in Electronics (TREE), Electromagnetic Pulse (EMP), System Generated Electromagnetic Pulse (SGEMP), Single-Event Upset (SEU), Blast and, Thermomechanical, hardness assurance, maintenance, device technology.

He did few years of consulting under his company Galaxy Advanced Engineering with Sandia National Laboratories (SNL), where he was supporting development of operational hazard assessments for the Air Force Safety Center (AFSC) in connection with other interest parties. Intended use of the results was their eventual inclusion in Air Force Instructions (AFIs) specifically issued for Directed Energy Weapons (DEW) operational safety. He completed the first version of a comprehensive library of detailed laser tools for Airborne Laser (ABL), Advanced Tactical Laser (ATL), Tactical High Energy Laser (THEL), Mobile/Tactical High Energy Laser (M-THEL), etc.

He also was responsible on SDI computer programs involved with Battle Management C3I and artificial Intelligent, and autonomous system. He is author few publications and holds various patents such as Laser Activated Radioactive Decay and Results of Thru-Bulkhead Initiation.

Recently he has published two other books with CRC and Francis Taylor on the subject of;

1. Heat Pipe Design and Technology: A Practical Approach
2. Dimensional Analysis and Self-Similarity Methods
3. Directed Energy Weapons Technologies

Dr. Patrick McDaniel is currently research professor at Department of Chemical and Nuclear Engineering, University of New Mexico. Patrick began his career as a pilot and maintenance officer in the USAF. After leaving the Air Force and obtaining his doctorate at Purdue University, he worked at Sandia National Laboratories in fast reactor safety, integral cross section measurements, nuclear weapons vulnerability, space nuclear power, and nuclear propulsion. He left Sandia to become the technical leader for Phillips Laboratory's (became part of Air Force Research Laboratory) Satellite Assessment Center. After 10 years at PL/AFRL, he returned to Sandia to lead and manage DARPA's Stimulated Isomer Energy Release project, a $ 10 M per year effort. While at Sandia, he worked on the Yucca Mountain Project and DARPA's classified UER-X program. Having taught at the University of New Mexico in the Graduate Nuclear engineering program for 25 years, when he retired from Sandia in early 2009, he joined the faculty at the University of New Mexico full time. He has worked on multiple classified and unclassified projects in the application of nuclear engineering to high energy systems. Dr. McDaniel holds PhD in nuclear engineering from Purdue University.

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Chapter 1
Definitions and Basic Principles

Nuclear power plants currently generate better than 20 % of the central station electricity produced in the United States. The United States currently has 104 operating power producing reactors, with 9 more planned. France has 58 with 1 more planned. China has 13 with 43 planned. Japan has 54 with 3 more planned. In addition, Russia has 32 with 12 more planned. Nuclear generated electricity has certainly come into its own existent and is the safest, cleanest and greenest form of electricity currently is in produced on this planet. However, many current thermodynamics texts ignore nuclear energy and use few examples of nuclear power systems. Nuclear energy presents some interesting thermodynamic challenges and it helps to introduce them at the fundamental level. Our goal here will be to introduce thermodynamics as the energy conversion science that it is and apply it to nuclear systems. Certainly, there will be many aspects of thermodynamics that are given little or no coverage. However, that is true for any textual introduction to this science; however by considering concrete systems, it is easier to give insight into the fundamental laws of the science and to provide an intuitive feeling for further study. Although brief summary of definition and basic principles of thermodynamic are touched up in this chapter for the purpose of this book, we encourage the readers to refer themselves to references [1–6] provided at the end of this chapter.

1.1 Typical Pressurized Water Reactor

By far the most widely built nuclear system is the Pressurized Water Reactor (PWR). There are a number of reasons for this. Steam turbines have for many decades been the dominant means of generating mechanical energy to turn electrical generators. The temperatures reached in the thermodynamic cycle of a PWR are within the range of fairly, common engineering materials. They were the first system built and operated reliably to produce electricity. A typical PWR system is described in Fig. 1.1.
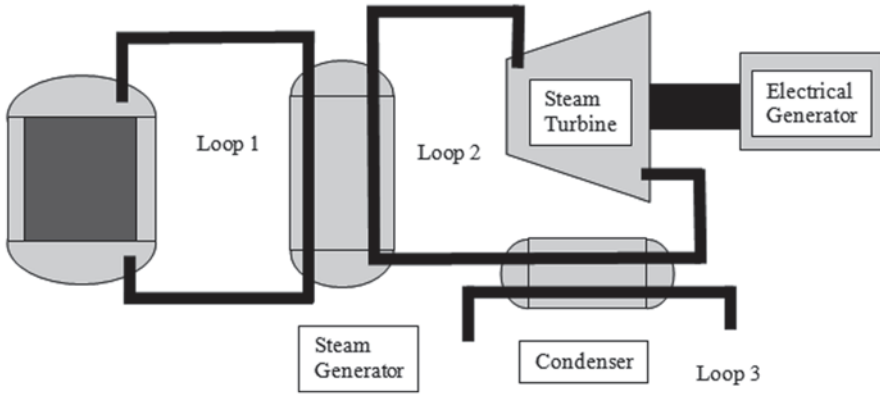
Fig. 1.1 Pressurized water reactor schematic

The basic PWR consists of five major components, the reactor core, steam generator(s), steam turbine, condenser, and electrical generator and three water/steam loops. Each loop requires a pump that is not shown to keep the diagram cleaner. The nuclear energy is converted to thermal energy in the reactor core. This thermal energy is then transported via the first loop to the steam generator where it is passed to the water in the second loop. The water in the second loop enters as a liquid and is turned to steam. The steam then passes to the turbine where the thermal energy is converted to mechanical energy to rotate the electrical generator. After the thermal energy has been converted to mechanical energy in the steam turbine, the low-pressure steam passes to the condenser to be cooled by the water in the third loop. The second law of thermodynamics tells us that we cannot simply expand the steam to a low enough energy state that it can return to the steam generator in its original liquid state. Therefore, we must extract more thermal energy from the low-pressure steam to return it to its liquid state where it can be pumped back into the steam generator. The third loop is called the circulating water system and it is open to the environment. There are multiple ways of providing this cooling water including intake and return to a river, or the ocean, intake and return to a cooling pond, or intake from a river and exhaust through a cooling tower. However, we are getting ahead of ourselves.

Consider for a minute why nuclear energy is so useful. A great deal of energy is produced by a very little mass.

Example Calculation: Calculate the U-235 consumed to produce 1 MW of thermal energy for 1 day. Note that a Megawatt is a unit of power, or energy per unit time,

$$1 \text{ MW} = 10^6 \text{ W} = 10^6 \text{ joules/s} \qquad 1 \text{ day} = 24 \text{ h} = 24 * 3600 \text{ s}$$

The energy released in fission of a U-235 atom is ~200 Mev

$$1 \text{ ev} = 1.6 \times 10^{-19} \text{ J} \qquad 1 \text{ Mev} = 1.6 \times 10^{-13} \text{ J} \qquad 200 \text{ Mev} = 32 \text{ pJ}$$

Fissioning 1 atom of U-235 produces 3.2×10^{-11} J

To produce 10^6 J requires $106/3.2 \times 10^{-11}$ atoms $= 3.125 \times 10^{16}$ atoms

And for a duration of 8.64×10^4 s

The total number of atoms consumed will be $3.125 \times 8.64 \times 10^{20}$ atoms

Therefore 2.7×10^{21} atoms will be consumed

A gram mole of U-235 is 6.022×10^{23} atoms

So a gram is $6.022 \times 10^{23}/235 = 2.563 \times 10^{21}$ atoms/gram

Therefore 1 Megawatt-Day of nuclear energy consumes 1.05 g of U-235

The fundamental thing to understand is that a PWR converts nuclear energy to electrical energy and it does this by converting the nuclear energy first to thermal energy and then converting the thermal energy to mechanical energy, which is finally converted to electrical energy. The science of thermodynamics deals with each of these conversion processes. To quantify how each of these processes takes place we must understand and apply the laws of thermodynamics.

1.2 Scope of Thermodynamics

Thermodynamics is the science that deals with energy production, storage, transfer and conversion. It is a very broad subject affects most fields of science including biology and microelectronics. The primary forms of energy considered in this text will be nuclear, thermal, chemical, mechanical and electrical. Each of these can be converted to a different form with widely varying efficiencies. Predominantly thermodynamics is most interested in the conversion of energy from one form to another via thermal means. However, before addressing the details of thermal energy conversion, consider a more familiar example. Newtonian mechanics defines work as force acting through a distance on an object. Performing work is a way of generating mechanical energy. Work itself is not a form of energy, but a way of transferring energy to a mass. So when one mass gains energy, another mass, or field, must lose that energy.

Consider a simple example. A 65-kg woman decides to go over Niagara Falls in a 25-kg wooden barrel. (The first person to go over the fall in a barrel was a woman, Annie Taylor.) Niagara Falls has a vertical drop of 50 m and has the highest flow rate of any waterfall in the world. The force acting on the woman and barrel is the force of gravity, which at the surface of the earth produces a force of 9.8 Newtons for every kilogram of matter that it acts on. So we have

$$W = F \times D \quad F = (65 + 25) \times 9.8 = 882.0 \text{ N} \quad D = 50 \text{ m}$$

$$W = 882.0 \times 50.0 = 44{,}100 \text{ N m} = 44.1 \text{ k J}$$

A Newton meter is a joule and 1000 J is a kilojoule. Therefore, when the woman and barrel went over the falls, by the time they had reached the bottom, the force of gravity had performed 44.1 kilojoules (kJ) of work on them. The gravitational field had 44.1 kJ of potential energy stored in it, when the woman and the barrel were at the top of the falls. This potential energy was converted to kinetic energy by the time the barrel reached the bottom of the falls. Kinetic energy is also measured in Joules, as with all other forms of energy. However, we are usually most interested in velocities when we talk about kinetic energies, so let us extract the velocity with which she hit the waters of the inlet to Lake Ontario.

$$\Delta KE = \Delta PE = 44.1 \text{ kJ} = 1/2 m V^2 = (90/2) \text{ kg} \times V^2 \quad V^2 = 44.1 \text{ kJ}/(90/2) \text{ kg}$$

Now it is a matter of converting units. A Joule is a Newton-meter. 1 Newton is defined as 1 kg accelerated at the rate of 1 m/second/second. So

$$44.1 \text{ kJ} = 44{,}100 \text{ N m}$$
$$= 44{,}100 \text{ kg m/s/s m}$$
$$= 44{,}100 \text{ kg} \left(\text{m/s} \right)^2$$

$$V^2 = 44{,}100 \text{ kg} (\text{m/s})^2 / (90/2) \text{ kg}$$
$$= 490/(1/2) = 980 \left(\text{m/s} \right)^2$$
$$V = 31.3 \text{ m/s} \ (\sim 70 \text{ mph})$$

Needless to say she recommended that no one ever try that again. Of course, others have, some have made it, and some have drowned.

Before leaving this example, it is worth pointing out that when we went to calculate the velocity, it was unaffected by the mass of the object that had dropped the 50 m. So one-half the velocity squared represents what we will call a specific energy, or energy per kilogram. In addition, the potential energy at the top of the falls could be expressed as a specific potential energy relative to the waters below. The potential energy per pound mass would just be the acceleration of gravity times the height of the falls. Typically, we will use lower case letters to represent specific quantities and upper case letters to represent extensive quantities. Extensive quantities are dependent upon the amount of mass present. Specific quantities are also referred to as intensive variables, though there are some intensive variables that have no extensive counterpart, such as pressure or temperature.

$$p.e. = mgh/m = gh = 9.8 \times 50 = 0.49 \text{ kJ/kg}$$

It is also worth pointing out that Newton's law of gravity states that

$$F = G\frac{m_1 M_2}{R^2} \qquad (1.1)$$

where m_1 is the smaller mass and M_2 is the mass of the Earth. We can find the specific force on an object by dividing the gravitational force by the mass of the object. For distances like 50 m on the surface of the Earth ($R = 6{,}378{,}140$ m) we can treat R as constant, but if the distance the gravitational force acts through is comparable to the radius of the Earth, an integration would be required. Even on the top of Mount Everest, the gravitational potential is within 0.25 % of that at Sea Level, so gravity is essentially constant for all systems operating on the face of the Earth.

1.3 Units

In this section, we will discuss the System International (SI) and English (E) Systems

1.3.1 Fundamental Units

The Before going further it will be a very good idea to discuss units for physical quantities and the conversion of units from one system to another. Unfortunately, the field of thermodynamics is beset with two popular systems of units. One is the System International (SI) system consisting of the kilogram, meter, and second. The other is the English (E) system consisting of the pound-mass, foot, and second.

Starting with the SI system, the unit of force is the Newton. The unit of work or energy is the Joule and the unit of pressure is the Pascal. We have,

$$1\,\text{N} = 1\,\text{kg m/s}^2$$

$$1\,\text{J} = 1\,\text{N m}$$

$$1\,\text{Pa} = 1\,\text{N/m}^2$$

Now the acceleration of gravity at Sea Level on Earth is 9.8066 m/s^2, so a 100 kg mass will weight 980.66 Newton. Also when we want avoid spelling out very large or small quantities we will usually use the standard abbreviations for powers of ten in units of 1000. We have,

$$\text{kilo} = 10^3$$

$$\text{mega} = 10^6$$

$$\text{giga} = 10^9$$

$$\text{deci} = 10^{-1}$$
$$\text{centi} = 10^{-2}$$
$$\text{milli} = 10^{-3}$$
$$\text{micro} = 10^{-6}$$
$$\text{nano} = 10^{-9}$$

For the English system, we have

$$\text{lbm} => 1\ \text{lbf}\ (\text{at Sea Level})$$
$$1\ \text{ft-lbf} = 1\ \text{lbf} \times 1\ \text{ft}$$
$$1\ \text{British Thermal Unit}\ (\text{BTU}) = 778\ \text{ft-lbf}$$
$$1\ \text{psi} = 1\ \text{lbf/in}^2$$

Note that the fact that 1 lbf=1 lbm at Sea Level on Earth, means that a mass of 100 lbm will weigh 100 lbf at Sea Level on Earth. The acceleration of gravity at Sea Level on Earth is 32.174 ft/s². Thus we have 1 lbf/(1 lbm-ft/s²)=32.174. If we move to another planet where the acceleration of gravity is different, the statement that 1 lbm=>1 lbf doesn't hold.

Consider comparative weights on Mars. The acceleration of gravity on Mars is 38.5% of the acceleration of gravity on Earth. So in the SI system we have

$$W = 0.385 * 9.8066\ \text{m/s}^2 \times 100\ \text{kg} = 377.7\ \text{N}$$

In the English system, we have,

$$W = 0.385 * 100\ \text{lbm} = 38.5\ \text{lbf}$$

1.3.2   Thermal Energy Units

The British thermal unit (Btu) is defined to be the amount of heat that must be absorbed by a 1 lb-mass to raise its temperature 1 °F. The calorie is the SI unit that is defined in a similar way. It is the amount of heat that must be absorbed by 1 g of water to raise its temperature 1 °C. This raises the question as to how a calorie compares with a joule since both appear to be measures of energy in the SI system. James Prescott Joule spent a major part of his life proving that thermal energy was simply another form of energy like mechanical kinetic or potential energy. Eventually his hypothesis was accepted and the conversion factor between the calorie and joule has been defined by,

1 calorie=4.1868 J

The constant 4.1868 is called the mechanical equivalent of heat.

1.3.3   Unit Conversion

As long as one remains in either the SI system or the English system, calculations and designs are simple. However, that is no longer possible as different organizations and different individuals usually think and work in their favorite system. In order to communicate with an audience that uses both SI and English systems it is important to be able to convert back and forth between the two systems. The basic conversion factors are,

$$1\,\text{kg} = 2.20462\,\text{lbm}$$
$$1\,\text{lbm} = 0.45359\,\text{kg}$$

$$1\,\text{m} = 3.2808\,\text{ft}$$
$$1\,\text{ft} = 0.3048\,\text{m}$$

$$1\,\text{J} = 0.00094805\,\text{Btu}$$
$$1\,\text{Btu} = 1055\,\text{J}$$

$$1\,\text{atm} = 14.696\,\text{psi}$$
$$1\,\text{atm} = 101325\,\text{Pa}$$
$$1\,\text{psi} = 6894.7\,\text{Pa}$$
$$1\,\text{bar} = 100000.0\,\text{Pa}$$
$$1\,\text{bar} = 14.504\,\text{psi}$$

The bar unit is simply defined by rounding off Sea Level atmospheric pressure to the nearest 100 kPa. There are many more conversion factors defined in the Appendix, but they are all derived from this basic few.

1.4   Classical Thermodynamics

Classical thermodynamics was developed long before the atomic theory of matter was accepted. Therefore, it treats all materials as continuous and all derivatives well defined by a limiting process. Steam power and an ability to analyze it and optimize it was one of the main drivers for the development of thermodynamic theory. The fluids involved always looked continuous. A typical example would be the definition of the density of a substance at a point. We have,

$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V} \tag{1.2}$$

As long as ΔV does not get down to the size of an atom, this works. Since classical thermodynamics was developed, however, we have come to understand that all

gases and liquids are composed of very small atoms or molecules and a limiting process that gets down to the atomic or molecular level will eventually become discontinuous and chaotic. Nevertheless, the continuous model still works well for the macroscopic systems that will be discussed in this text and Classical Thermodynamics is based on it.

At times, we will refer to an atomistic description of materials in order to develop a method of predicting specific thermodynamic variables that classical thermodynamics cannot predict. A typical example is the derivative that is called the constant volume specific heat. This variable is defined as the rate of change of the internal energy stored in a substance as a function of changes in its temperature. Classical thermodynamics demonstrates that this variable has to exist and makes great use of it, but it has no theory for calculating it from first principles. An atomistic view will allow us to make some theoretical estimates of its value. Therefore, at times we will deviate from the classical model and adopt an atomistic view that will improve our understanding of the subject.

Classical thermodynamics is also an equilibrium science. The laws of thermodynamics apply to objects or systems in equilibrium with themselves and their surroundings. By definition, a system in equilibrium is not likely to change. However, we are generally interested in how systems change as thermal energy is converted to and from other forms of energy. This presents a bit of a dilemma in that the fundamental laws are only good for a system in equilibrium and the parameters we want to predict are a result of thermal energy changes in the system. To get around this dilemma, we define what is called a quasi-equilibrium process. A quasi-equilibrium process is one that moves from one system state to another so slowly and so incrementally, that it looks like a series of equilibrium states. This is a concept that classical thermodynamics had a great deal of difficulty clarifying and quantifying. Basically, a process was a quasi-equilibrium process if the laws of equilibrium thermodynamics could characterize it. This is sort of a circular definition, but once again, we will find that the atomistic view allows us to make some predictions and quantifications that identify a quasi-equilibrium process. Quasi-equilibrium processes can occur very rapidly on time scales typical of human observation. For example, the expansion of the hot gases out the nozzle of a rocket engine can be well described as a quasi-equilibrium process with classical thermodynamics.

1.5   Open and Closed Systems

In the transfer and conversion of thermal energy, we will be interested in separating the *entire universe* into a *system* and its *environment*. We will mainly be interested in the energy transfers and conversions that go on within the *system*, but in many cases, we will need to consider its interactions with the rest of the world or its *environment*. Systems that consist of a *fixed amount of mass* that is contained within fixed boundaries are called *closed systems*. Systems that *pass the mass back and forth* to the environment will be called *open systems*. Both *open* and *closed systems*
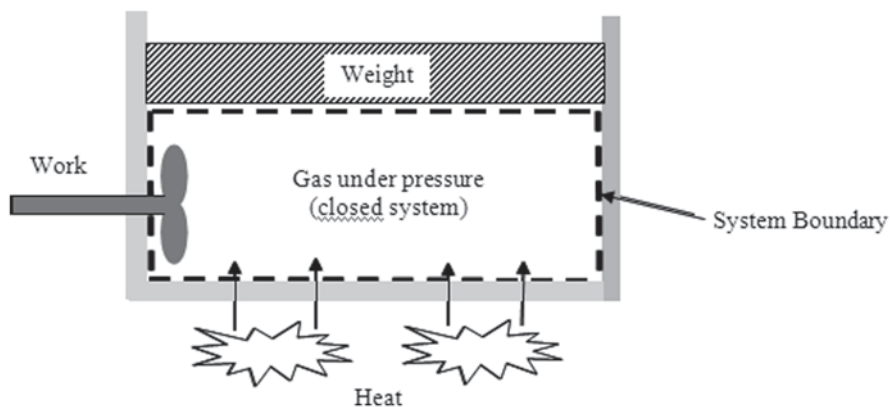
Fig. 1.2 A closed system

allow energy to flow across their borders, but the flow of mass determines whether they are *open* or *closed systems*. *Open systems* will also carry energy across their borders with the mass as it moves. Consider the simple compressed gas in the piston below as a *closed* system (Fig. 1.2).

In analyzing the closed system, we will be concerned about the changes in the internal energy of the compressed gas as it interacts with its environment and the transfers of mechanical and thermal energies across its boundary.

In analyzing open systems, the concept of a ***control volume*** comes into play. The ***control volume*** is the boundary for the open system where the energy changes that we are interested in takes place. The thing separates the open system from its environment. Consider the following open system where we have now allowed mass to flow in and out of the piston of our closed system above (Fig. 1.3).
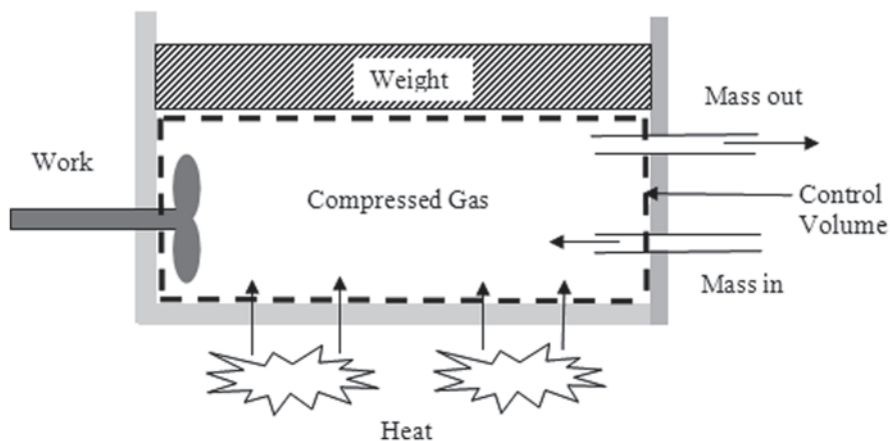
Fig. 1.3 An open system

The *control volume* looks a lot like our system boundary from before, and it is. The only difference is that we now allow mass to flow in and out of our *control volume*. Thermal and mechanical energy can still flow across the boundary, or in and out of the *control volume*. The mass flowing in and out can also carry energy with it either way.

1.6 System Properties

In order to characterize a system we will have to identify its properties. Initially there are three main properties that we will be concerned with—density, pressure and temperature all of which are *intensive* variables. We will use intensive properties to characterize the equilibrium states of a system. Systems will be composed of *pure substances* and *mixtures of pure substances*. A *pure substance* is a material that consists of only one type of atom, or one type of molecule. A *pure substance* can exist in multiple phases. Normally the phases of concern will be gas, liquid, and solid, though for many pure substances there can be several solid phases. Water is an example of a pure substance that can readily be observed in any of its three phases.

A solid phase is typically characterized as having a fixed volume and fixed shape. A solid is rigid and incompressible. A liquid has a fixed volume but no fixed shape. It deforms to fit the shape of the container that is in it. It is not rigid but is still relatively incompressible. A gas has no fixed shape and no fixed volume. It expands to fit the container that is in it. To characterize a system composed of one or more pure components and one or more phases we will need to specify the correct number of intensive variables required to define a state. Gibbs Phase Rule named after J. Willard Gibbs who first derived it gives the correct number of intensive variables required to completely define an equilibrium state in a mixture of pure substances. It is

$$V = C - P + 2 \tag{1.3}$$

V = Number of variables required to define an equilibrium state.
C = The number of pure components (substances) present.
P = The number of phases present.

So for pure steam at Sea Level and above 100 °C, we have one component and one phase so the number of variables required to specify an equilibrium state is 2, typically temperature and pressure. However, temperature and density would also work. If we have a mixture of steam and liquid water in the system, we have one component and two phases, so only one variable is required to specify the state, either pressure or temperature would work. If we have a mixture like air that is composed of oxygen, nitrogen, and argon, we have three components and three phases (the gas phase for each component), we are back to requiring two variables. As we progress, we will introduce additional intensive variables that can be used to characterize the equilibrium states of a system in addition to density, pressure, and temperature.

1.6.1   Density

Density is defined as the mass per unit volume. The standard SI unit is kilograms per cubic meter (kg/m³). The Standard English unit is pounds mass per cubic foot (lbm/ft³). If the mass per unit volume is not constant in a system, it can be defined at a point by a suitable limiting process that converges for engineering purposes long before we get to the atomistic level. The inverse of density is specific volume. Specific volume is an intensive variable, whereas volume is an extensive variable. The standard unit for specific volume in the SI system is cubic meters per kilo-gram (m³/kg). The standard unit in the English system is cubic feet per pound mass (ft³/lbm).

1.6.2   Pressure

Pressure is defined as force per unit area. The standard unit for pressure in the SI system is the Newton per square meter or Pascal (Pa). This unit is fairly small for most engineering problems so pressures are more commonly expressed in kilo-Pascals (kPa) or mega-Pascals (MPa). The standard unit in the English system really does not exist. The most common unit is pounds force per square inch (psi). However, many other units exist and the appropriate conversion factors are provided in the Appendix.

   Pressure as an intensive variable is constant in a closed system. It really is only relevant in liquid or gaseous systems. The force per unit area acts equally in all directions and on all surfaces for these phases. It acts normal to all surfaces that contain or exclude the fluid. (The term fluid includes both gases and liquids). The same pressure is transmitted throughout the entire volume of liquid or gas at equilibrium (Pascal's law). This allows the amplification of force by a hydraulic piston. Consider the system in the following Figure. In the Fig. 1.4, the force on the piston at B is greater than the force on the piston at A because the pressure on both is the same and the area of piston B is much larger.
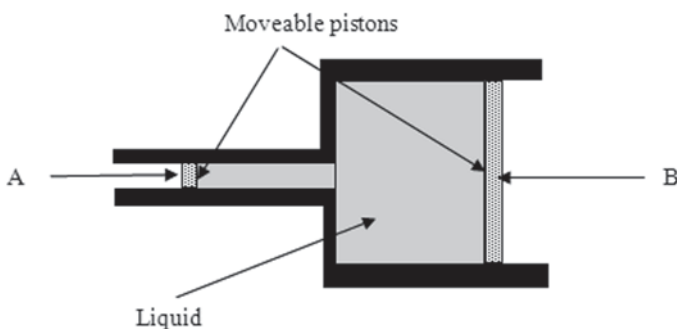

Fig. 1.4 A hydraulic amplifier