SANJEEV CHANDRA

ENERGY, ENTROPY AND ENGINES

AN INTRODUCTION TO THERMODYNAMICS

with website

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AN INTRODUCTION TO THERMODYNAMICS

Sanjeev Chandra
University of Toronto, Canada

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Preface

This book is a text for teaching a one-semester, introductory engineering thermodynamics course. Its most important goal is to make students understand the meaning of fundamental concepts such as energy, entropy, equilibrium and reversibility, which form the foundation of engineering science. It uses simple, direct language and relies on physical rather than abstract, mathematical definitions. Every new concept is introduced starting from first principles, and only after explaining why it is necessary.

Thermodynamics is different from most other engineering courses, in that it expects students to grasp an entirely new concept, entropy, which they have never encountered before. Traditional thermodynamics texts resort to giving a purely mathematical definition of entropy, and students learn to use the property for solving problems without ever forming a physical picture of what it means. This book introduces entropy by combining macroscopic definitions with statistical descriptions based on the energy distribution of molecules. Readers are not expected to learn statistical mechanics but use analogies to acquire an intuitive grasp of the concept of entropy and understand why the second law of thermodynamics is a result of the laws of probability.

Chapters 1 to 3 are intended for students to read on their own, with only selected portions being discussed in lectures. Chapter 1 describes how thermodynamics grew out of attempts to understand and improve steam engines and puts the first and second laws in context. It is useful in motivating the study of thermodynamics and explaining why it is such a fundamental part of science and engineering. Most students will already be familiar with some of the material covered in Chapters 2 and 3, including Newton's laws, the definitions of kinetic and potential energy, molar quantities and the ideal gas equation and can review these sections independently.

Thermodynamics textbooks typically start, immediately after the introduction, by teaching how to read tabulated properties of saturated liquids and vapours. Students are immediately overwhelmed by terms such as internal energy and enthalpy before they understand how these properties are used, and they are left with the impression that thermodynamics is largely an exercise in reading tables and charts. In the first six chapters of this book, while students are still becoming familiar with the laws of thermodynamics, there is no discussion of phase change. Once the second law has been understood liquid–vapour mixtures are treated as systems in equilibrium that can be analysed using the laws of thermodynamics. Chapter 7 starts with a brief discussion of the chemical potential and the Clausius–Clapeyron equation. Covering this material takes only one or two lectures and makes it much easier to understand phase equilibrium and the significance of property tables. However, if instructors prefer not to include it, it is possible to omit the relevant sections (Sections 7.3–7.7) without any loss of continuity.

It should be possible to cover the entire book in a one-semester introductory course that teaches the fundamentals of thermodynamics and their application in the analysis of heat engines and refrigerators. A slower paced course may leave out discussions of exergy (Section 6.14) and review only a selection of the engine and refrigeration cycles described in Chapters 9 and 10.

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/chandraSol16
The website includes:

- Solutions for the Problems given at the end of each chapter.

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1

Introduction: A Brief History of Thermodynamics

In this chapter you will:

- Review the historical development of heat engines.
- Learn how thermodynamics grew out of efforts to improve the performance of heat engines.
- Gain an overview of concepts such as energy and entropy and the laws of thermodynamics.

1.1 What is Thermodynamics?

When earth's creatures were created, according to Greek legends, each received its own gift of speed or strength or courage. Some animals received wings to soar on, others claws to defend themselves, but finally, when it was the turn of humans, nothing remained. Prometheus saved mankind by stealing fire from the gods, making people far more powerful than any animal. Such myths – and similar stories exist in almost every society – trace the birth of human civilisation to the discovery of fire, which gave warmth, nourishment and the ability to craft objects out of stone and metal.

Fire alone would not have allowed humans to survive in the wilderness – they also needed tools. Life without sharp claws or fangs is possible if you can make knives and spearheads. Humans may not have the speed of a gazelle but they discovered wheels; levers and pulleys can lift heavier loads than any elephant. Tools improved slowly over time as wheelbarrows evolved into horse drawn carts and stones for grinding grain became windmills, but there were

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few gains made in the power used to drive them. Animals, water and wind were all harnessed to drive machines, but there is a limit to how effective any of these power sources are. Winds are unreliable, there are a finite number of sites with running water, and only a few horses can be hitched to a cart at one time. This lack of power sources limited how fast technology could evolve over most of human history. An ancient Egyptian, transported 30 centuries forward to medieval Europe, would have had little difficulty in recognising the machines used.

Then, a little over 300 years ago, fire was used as a power source for the first time. The first practical steam engine marked a turning point in human history, for it put enormous reserves of energy at our disposal. We are no longer restricted to capturing forces exerted by the elements or animals. Gases expand when heated and exert tremendous pressures that can be exploited to drive power plants, aircraft and automobiles. The only constraint on generating power is the amount of heat available, and the technology used to generate heat has advanced rapidly, whether it is by burning fuel, capturing solar radiation, or splitting atoms in nuclear reactions. Today, machines that use heat to produce work are everywhere.

As steam engines became more common, questions about them multiplied. What is the relation between heat and work? How much work can be obtained if a given amount of fuel is burned? Can the performance of engines be improved? Thermodynamics was the science that grew from efforts to answer these questions. The word itself is a combination of the Greek *therme*, meaning heat, and *dynamis*, meaning force, and thermodynamics is often defined as the science that studies the relationship between heat and work. Engineers struggling to understand how engines work formulated the principles of thermodynamics, but they have since been used in the study of all phenomena that involve changes in energy. Astrophysicists use the laws of thermodynamics to predict the fate of an exploding star, biologists apply them to the metabolism of animals and chemists rely on them to determine the products of chemical reactions.

1.2 Steam Engines

Using heat to produce motion is not a very novel achievement. As early as the first century a Greek inventor had designed a toy in which steam escaping from nozzles mounted on the surface of a metal sphere made it spin, but there seems to have been no practical application of this device. In subsequent centuries cannons became the most impressive illustrations of how objects could be transported by generating heat. But, no matter how spectacular the discharge of a cannon, it is difficult to harness it for any constructive purpose. For that we need a "heat engine", defined as a device that operates continuously, producing work as long as heat is supplied to it.

We can mark precisely the date when the first industrial heat engine was invented, for in 1698 the king of England was pleased to grant Thomas Savery a patent for a "fire engine" to be used "... for raising of water, and occasioning motion to all sorts of mill works ...". Savery's machine did not resemble our typical image of a steam engine, for it had no furiously driving pistons or spinning flywheels. It consisted (see Figure 1.1) of a large chamber that was first filled with steam from a boiler, sealed and then sprayed with cold water to condense the steam in the vessel and create a partial vacuum that sucked water up from an underground mine. High-pressure steam was used to empty the chamber by pushing the water in it up to a

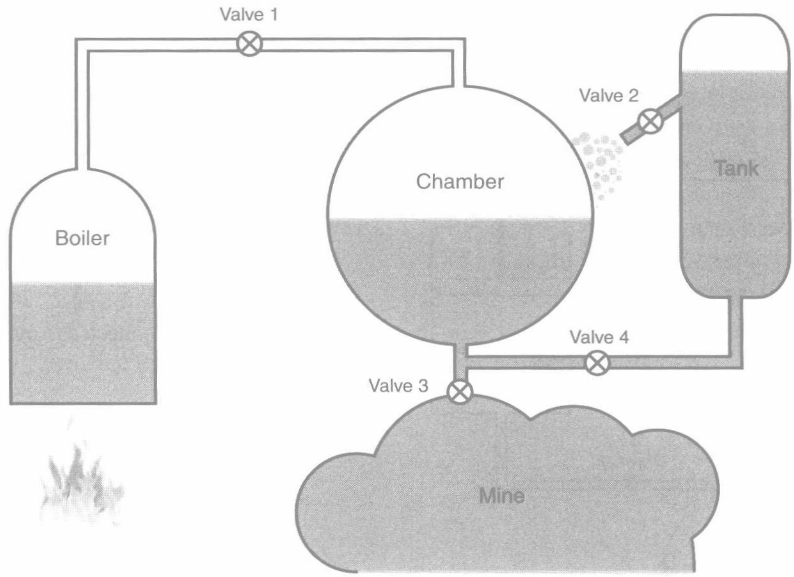

Figure 1.1 Savery Engine. Opening valve 1 fills the chamber with steam. Opening valve 2 douses the chamber with cold water, condensing the steam and creating a partial vacuum. Opening valve 3 sucks water into the evacuated chamber from the flooded mine. Opening valve 4 while filling the chamber with steam pushes water into the tank.

higher level. Valves controlling the flow of steam and water were operated manually and a good operator could complete several cycles in a minute.

Savery intended to sell his pumps to English coal mines where flooding was a frequent occurrence, so that water had to be drained by hand or horse driven pumps. Sadly, his pumps proved to be rather leaky so that it was hard to hold a very good vacuum in the chamber. Savery claimed that his engine could raise water by about 80 feet (24.4 m), which would have required steam pressures of almost three atmospheres. Frequent explosions of poorly made boilers were so common that high-pressure steam was viewed with fear and not used again for more than a century when manufacturing techniques had greatly improved.

Savery was unable to produce a commercially successful engine, but he proved that steam could be used to drive machines. By the time Savery's 14-year patent expired in 1712 Thomas Newcomen was ready with his design for a new engine, which looks far more recognisable to us as a steam engine (Figure 1.2). Newcomen had a piston moving back and forth in a cylindrical chamber, one side of which was connected to a boiler producing steam. When the chamber was filled with steam the piston rose up. Spraying water into the chamber condensed the steam, producing a partial vacuum so that atmospheric pressure forced the piston down. A beam connected to the piston oscillated as the piston moved up and down, which could be used to drive a pump or some other machine. This was an "atmospheric engine", in which work was done by the atmosphere pushing a piston against a vacuum. Steam pressure was never much higher than one atmosphere, minimising the hazard of explosions.

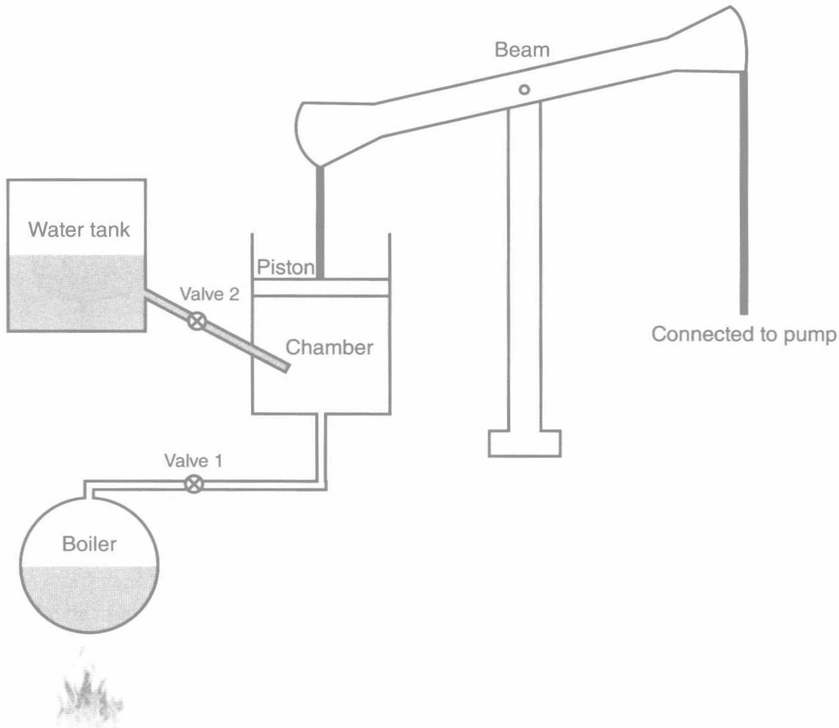

Figure 1.2 Newcomen Engine. Opening valve 1 sends steam into the chamber and raises the piston. Opening valve 2 sprays water into the chamber, condensing the steam so that atmospheric pressure forces the piston down. A beam connected to the piston oscillates up and down and drives the pump.

Newcomen's engine was an immense success and hundreds were built and sold. They were initially used to power pumps in coalmines but soon found new applications in textile mills and other factories. For over 50 years Newcomen's engines represented the most sophisticated technology available and sparked a remarkable technical and social transformation that changed human history. For the first time machines could work non-stop without depending on beasts of burden or being subject to the vagaries of weather. Any factory had access to as much power as it needed, no matter where it was located. The steam engine gave birth to the industrial revolution and created the modern world.

Newcomen's engines were a tremendous accomplishment but consumed enormous amounts of coal to generate steam, most of which was wasted. At the start of each cycle, when steam entered the cylinder, much of its energy went into heating the walls of the cylinder, only to have to cool them down again when the steam was condensed with a water spray. While engines were confined to coalmines this was not of great concern since fuel was practically free, but when they began to be used in factories far from fuel supplies operating costs became a serious problem.

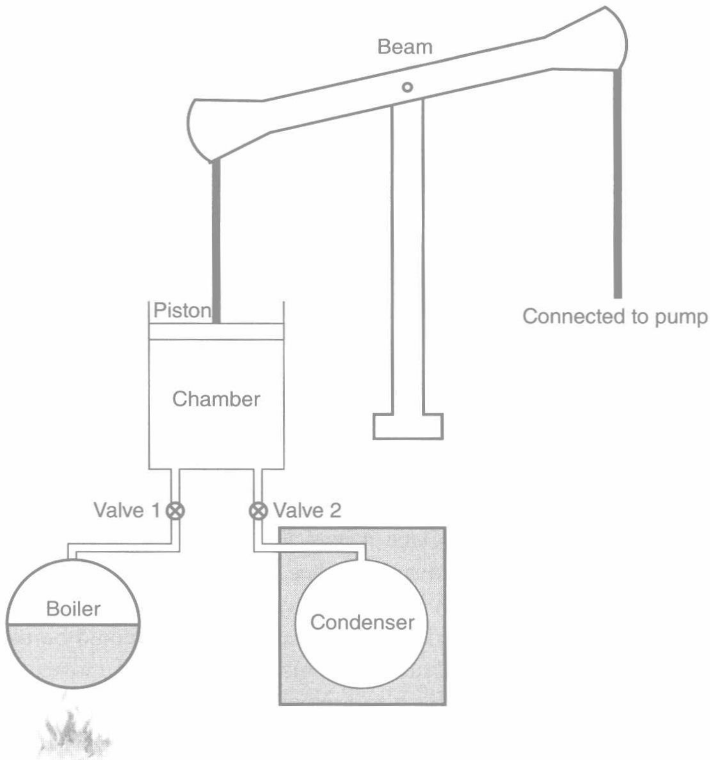

Figure 1.3 Watt's engine with an external condenser. Opening valve 1 allows steam from the boiler to fill the chamber and raises the piston. Opening valve 2 lets steam from the chamber escape into the condenser, creating a vacuum under the piston so that atmospheric pressure pushes the piston down.

James Watt, a young instrument maker at the University of Glasgow, proposed a solution. Watt had been assigned the job of fixing a model of a Newcomen engine used for laboratory demonstrations. He found that the model worked as designed, but consumed all the steam supplied simply to heat the cylinder wall. After much thought he solved the problem by adding an external chamber in which steam was condensed (Figure 1.3). In 1769 Watt obtained a patent for the external condenser, entitled a "new method for lessening the consumption of steam and fuel in fire engines". The new engines were so much more efficient than the older Newcomen engines that it became feasible to use them in many new industrial applications.

Many brilliant inventors have pioneered new technologies, only to see others reap the profits. Watt escaped this fate for he had the good fortune of entering into partnership with Matthew Boulton, an extremely shrewd businessman and manufacturer. For decades the firm of Boulton and Watt held the most important patents related to steam engines, enforced them vigorously and dominated the steam engine manufacturing industry. They produced atmospheric engines that used the pressure of the atmosphere to drive their pistons; steam was used only to produce a vacuum. Watt strongly opposed the use of high-pressure steam to drive engines, firmly convinced that they were too dangerous, and even tried to get the British parliament to pass a law banning high-pressure steam. Even without the law, his control of patents on the external condenser and several other technologies essential to steam engines ensured that he could block any new development that he did not agree with. Watt's fear of high-pressure engines was well founded in his experience of boiler explosions in the early days of steam, but manufacturing techniques were also improving rapidly. In 1776 John Wilkinson invented a new type of lathe that made it possible to bore cylinders up to 18 inches (46 cm) in diameter with great precision. Wilkinson had designed his machines to produce better cannon barrels, but they also proved eminently suitable for making engine cylinders with piston seals strong enough to withstand high pressures.

James Watt's patent on the external condenser finally expired in 1800 and the field of engine design was again open to new developments. That same year, Richard Trevithick built a high-pressure steam engine to operate a pump in a Cornish mine. In his engine, steam at more than twice atmospheric pressure pushed against the piston to deliver power and was then released into the air instead of being condensed. The sound of steam being vented led to the engines being popularly known as "puffers". Once it was demonstrated that high-pressure engines could be safely built and run, their advantages became immediately obvious. A relatively small engine could deliver more power than a much larger atmospheric engine and, even better, it had no need for a heavy condenser. Such a light engine could be used to power a vehicle and by 1804 Trevithick had built a locomotive that could move 25 tons (25.4 t) at a speed of 3.7 miles / h (6 km / h). This was a remarkable machine for no one had ever seen a self-propelled vehicle before, but it was not a commercial success since it frequently broke down and the iron rails available at that time could not withstand the weight of the locomotives for long. The now elderly James Watt launched virulent attacks, railing that Trevithick "deserved hanging for bringing into use the high-pressure engine".

George Stephenson finally solved the technical problems related to both engines and rails when he built his locomotive in 1813 and was operating a commercial train service by the time Trevithick died in poverty in 1833. Stephenson is now acclaimed as the inventor of the locomotive while Trevithick is rarely remembered, but Trevithick's firm belief that high-pressure engines could be safely operated and would prove more efficient was vindicated as operating pressures steadily increased.

It is frequently said that the great age of steam is over, and it is certainly true that there are not many steam locomotives running today. However, steam is used to produce electricity in power plants in every part of the world. In a modern steam power plant water is pumped into boilers where it is heated as it flows through tubes (Figure 1.4). Hot gases flow across the outer surfaces of the boiler tubes, heating the water until it emerges as high-pressure steam. The heat source is most often a burning fuel, but can also be a nuclear reaction or a renewable source such as sunlight. The steam is fed into a turbine, jetting out of nozzles at velocities greater than the speed of sound, and impinges on turbine blades projecting from a rotating shaft. The turbine shaft spins and when connected to an electric generator produces electricity. Low-pressure steam emerging from the turbine passes through a condenser, where it flows through tubes that are cooled by water running over them. Water condensing in the tubes is collected and pumped back into the boiler to complete the cycle.