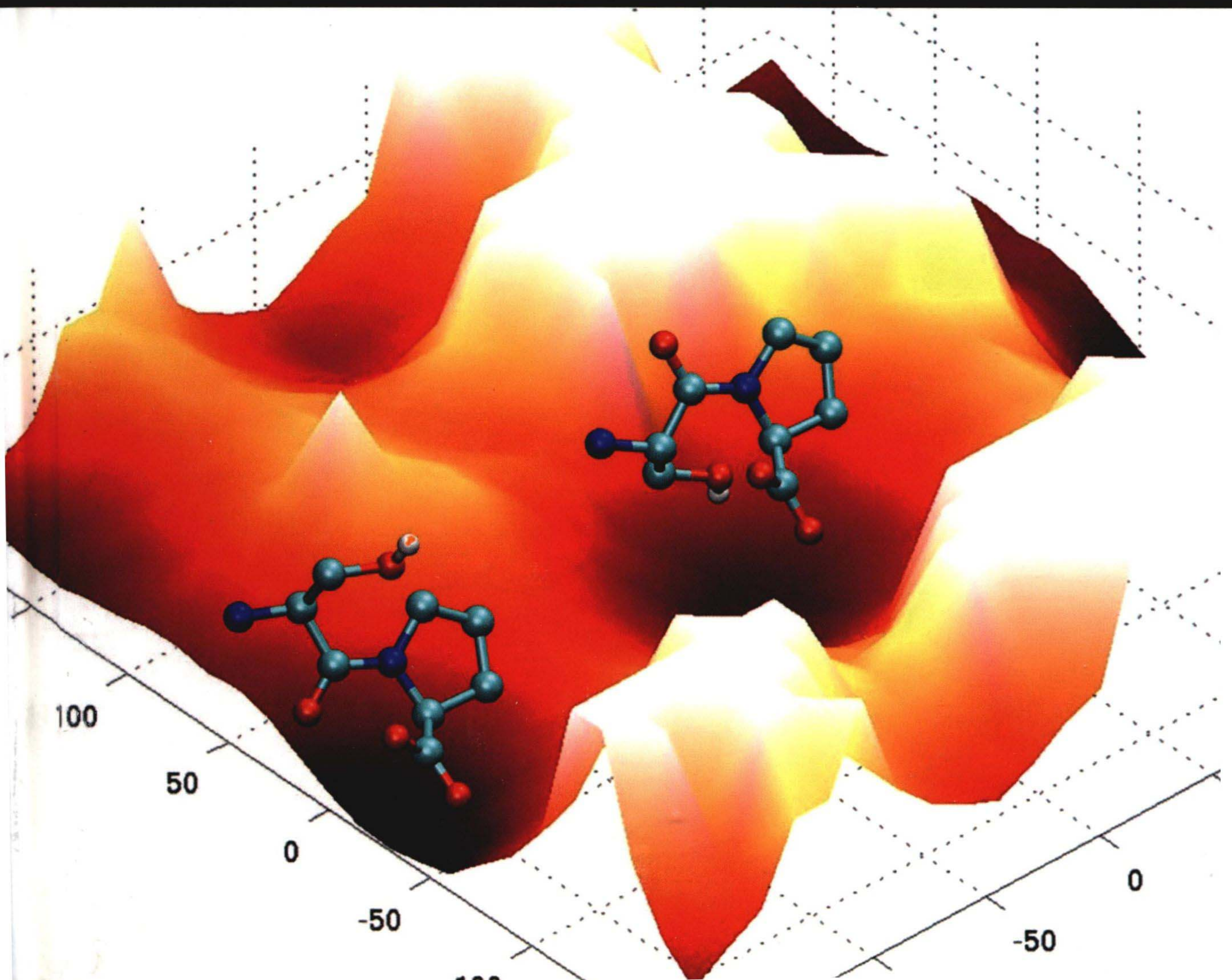
Engineering Thermodynamics and Statistical Mechanics

Cornelius Hall
Editor



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Preface

Thermodynamics defines macroscopic variables that characterize materials and radiation, and explains how they are related and by what laws they change with time. Thermodynamics describes the average behaviour of very large numbers of microscopic constituents, and its laws can be derived from statistical mechanics. Thermodynamics applies to a wide variety of topics in science and engineering—such as engines, phase transitions, chemical reactions, transport phenomena, and even black holes. Results of thermodynamic calculations are essential for other fields of physics and for chemistry, chemical engineering, aerospace engineering, mechanical engineering, cell biology, biomedical engineering, and materials science—and useful in other fields such as economics. Thermodynamics arose from the study of energy transfers that can be strictly resolved into two distinct components, heat and work, specified by macroscopic variables. A thermodynamic operation is a conceptual step that changes the definition of a system or its surroundings. For example, the partition between two thermodynamic systems can be removed so as to produce a single system. There is a sense in which Maxwell's demon if he existed would be able to violate the laws or of thermodynamics because he is permitted to perform thermodynamic operations, which are permitted to be unnatural.

The rapid atomic mechanisms mediate the macroscopic changes that are of interest for thermodynamics and statistical thermodynamics, because they quickly bring the system near enough to thermodynamic equilibrium. "When intermediate rates are present, thermodynamics and statistical mechanics cannot be applied." Such intermediate rate atomic processes do not bring the system near enough to thermodynamic equilibrium in the time frame of the macroscopic process of interest. This separation of time scales of atomic processes is a theme that recurs throughout the subject. Originally thermodynamics concerned material and radiative phenomena that are experimentally reproducible. For example, a state of thermodynamic equilibrium is a steady state reached after a system has aged so that it no longer changes with the passage of time. But more than that, for thermodynamics, a system, defined by its being prepared in a certain way must, consequent on every particular occasion of preparation, upon aging, reach one and the same eventual state of thermodynamic equilibrium, entirely determined by the way of preparation. Such reproducibility is because the systems consist of so many molecules that the molecular variations between particular occasions of preparation have negligible or scarcely discernable effects on the macroscopic variables that are used in thermodynamic descriptions.

The present book 'Engineering Thermodynamics and Statistical Mechanism' has been designed for students of all branches of engineering specially undergraduate students of Mechanical Engineering. The book will also serve as reference manual for practising engineers. The book has been written in simple language and systematically develops the concepts and principles essential for understanding the subject.

—Editor

Contents

Chapter 1

Internal Combustion Engine

The internal combustion engine is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidiser (usually air) in a combustion chamber. In an internal combustion engine, the expansion of the high-temperature and high -pressure gases produced by combustion apply direct force to some component of the engine. This force is applied typically to pistons, turbine blades, or a nozzle. This force moves the component over a distance, transforming chemical energy into useful mechanical energy.

The term *internal combustion engine* usually refers to an engine in which combustion is intermittent, such as the more familiar four-stroke and two-stroke piston engines, along with variants, such as the six-stroke piston engine and the Wankel rotary engine. A second class of internal combustion engines use continuous combustion: gas turbines, jet engines and most rocket engines, each of which are internal combustion engines on the same principle as previously described.

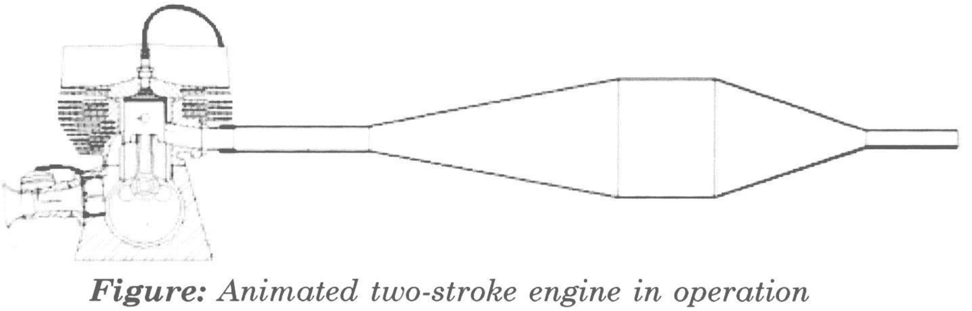

Figure: *Animated two-stroke engine in operation*

The internal combustion engine (or ICE) is quite different from external combustion engines, such as steam or Stirling engines, in which the energy is delivered to a working fluid not consisting of, mixed with, or contaminated by combustion products. Working fluids can be air, hot water, pressurised water or even liquid sodium, heated in some kind of boiler. A large number of different designs for ICEs have been developed and built, with a variety of different strengths and weaknesses. Powered by an energy-dense fuel (which is very frequently gasoline, a liquid derived from fossil fuels). While there have been and still are many stationary applications, the real strength of internal combustion engines is in mobile applications and they dominate as a power supply for cars, aircraft, and boats.

Applications

Internal combustion engines are most commonly used for mobile propulsion in vehicles and portable machinery. In mobile equipment, internal combustion is advantageous since it can provide high power-to-weight ratios together with excellent fuel energy density. Generally using fossil fuel (mainly petroleum), these engines have appeared in transport in almost all vehicles (automobiles, trucks, motorcycles, boats, and in a wide variety of aircraft and locomotives).

Where very high power-to-weight ratios are required, internal combustion engines appear in the form of gas turbines. These applications include jet aircraft, helicopters, large ships and electric generators.

History of the Internal Combustion Engine

Although various forms of internal combustion engines were developed before the 19th century, their use was hindered until the commercial drilling and production of petroleum began in the mid-1850s. By the late 19th century, engineering advances led to their widespread adoption in a variety of applications.

Timeline of Development

Various scientists and engineers contributed to the development of internal combustion engines:

Prior to Modern Era

- 13th century: The rocket engine, an internal-combustion engine, was developed by the Chinese, Mongols and Arabs.

1600 to 1860

- 17th century: Christiaan Huygens designs gunpowder to drive water pumps, to supply 3000 cubic metres of water/day for the Versailles palace gardens, essentially creating the first idea of a rudimentary internal combustion piston engine.

- 1780s: Alessandro Volta built a toy electric pistol in which an electric spark exploded a mixture of air and hydrogen, firing a cork from the end of the gun.
- 1791: John Barber receives British patent #1833 for *A Method for Rising Inflammable Air for the Purposes of Producing Motion and Facilitating Metallurgical Operations*. In it he describes a turbine.
- 1794: Robert Steele built a compressionless engine whose principle of operation would dominate for nearly a century.
- 1798: Tippu Sultan, the ruler of the city-state of Mysore in India, uses the first iron rockets against the British Army.
- 1807: Nicephore Niepce installed his 'moss, coal-dust and resin' fuelled Pyreolophore internal combustion engine in a boat and powered up the river Saône in France. A patent was subsequently granted by Emperor Napoleon Bonaparte on 20 July 1807.
- 1807: Swiss engineer Francois Isaac de Rivaz built an internal combustion engine powered by a hydrogen and oxygen mixture, and ignited by electric spark.
- 1823: Samuel Brown patented the first internal combustion engine to be applied industrially. It was compressionless and based on what Hardenberg calls the "Leonardo cycle," which, as the name implies, was already out of date at that time.
- 1824: French physicist Sadi Carnot established the thermodynamic theory of idealised heat engines. This scientifically established the need for compression to increase the difference between the upper and lower working temperatures.
- 1826 April 1: American Samuel Morey received a patent for a compressionless "Gas or Vapour Engine."
- 1833: Lemuel Wellman Wright, UK patent 6525, table-type gas engine. Double acting gas engine, first record of water jacketed cylinder.
- 1838: A patent was granted to William Barnett (English). According to Dugald Clerk, this was the first recorded use of in-cylinder compression.
- 1854-57: Eugenio Barsanti & Felice Matteucci invented an engine that was possibly the first 4-cycle engine, but the patent was lost.

- 1856: in Florence at *Fonderia del Pignone* (now Nuovo Pignone, later a subsidiary of General Electric), Pietro Benini realised a working prototype of the Italian engine supplying 5 HP. In subsequent years he developed more powerful engines—with one or two pistons—which served as steady power sources, replacing steam engines.
- 1857: Eugenio Barsanti & Felice Matteucci describe the principles of the free piston engine where the vacuum after the explosion allows atmospheric pressure to deliver the power stroke (British patent No 1625). Otto and Langen were the first to make a marketable engine based on this concept 10 years later.

1860-1910

- 1860: Belgian Jean Joseph Etienne Lenoir (1822–1900) produced a gas-fired internal combustion engine similar in appearance to a horizontal double-acting steam engine, with cylinders, pistons, connecting rods, and flywheel in which the gas essentially took the place of the steam. This was the first internal combustion engine to be produced in numbers.
- 1861 The earliest confirmed patent of the 4-cycle engine, by Alphonse Beau de Rochas. A year earlier, Christian Reithmann made an engine which may have been the same, but it's unknown since his patent wasn't clear on this point.
- 1862: German inventor Nikolaus Otto was the first to build and sell the engine. He designed an indirect-acting free-piston compressionless engine whose greater efficiency won the support of Eugen Langen and then most of the market, which at that time was mostly for small stationary engines fuelled by lighting gas.
- 1865: Pierre Hugon started production of the Hugon engine, similar to the Lenoir engine, but with better economy, and more reliable flame ignition.
- 1867: Otto and Langen introduced their free piston engine at the Paris Exhibition. It had less than half the gas consumption of the Lenoir or Hugon engines.
- 1870: In Vienna, Siegfried Marcus put the first mobile gasoline engine on a handcart.
- 1872: In America George Brayton invented Brayton's Ready Motor and went into commercial production, this used constant

pressure combustion, and was the first commercial liquid fuelled internal combustion engine.

- 1876: Nikolaus Otto, working with Gottlieb Daimler and Wilhelm Maybach, started the genesis of the four-cycle engine. The German courts, however, did not hold his patent to cover all in-cylinder compression engines or even the four-stroke cycle, and after this decision, in-cylinder compression became universal.
- 1878: Dugald Clerk designed the first two-stroke engine with in-cylinder compression. He patented it in England in 1881.
- 1879: Karl Benz, working independently, was granted a patent for his internal combustion engine, a reliable two-stroke gas engine, based on the same technology as De Rochas's design of the four-stroke engine. Later, Benz designed and built his own four-stroke engine that was used in his automobiles, which were developed in 1885, patented in 1886, and became the first automobiles in production.
- 1882: James Atkinson invented the Atkinson cycle engine. Atkinson's engine had one power phase per revolution together with different intake and expansion volumes, potentially making it more efficient than the Otto cycle, but certainly avoiding Otto's patent.
- 1884: British engineer Edward Butler constructed the first petrol (gasoline) internal combustion engine. Butler invented the spark plug, magneto, coil ignition and spray jet carburettor, and was the first to use the word petrol.
- 1885: German engineer Gottlieb Daimler received a German patent for a supercharger
- 1891: Herbert Akroyd Stuart built his oil engine, leasing rights to Hornsby of England to build them. They built the first cold-start compression-ignition engines. In 1892, they installed the first ones in a water pumping station. In the same year, an experimental higher-pressure version produced self-sustaining ignition through compression alone.
- 1892: Dr. Rudolf Diesel developed his Carnot heat engine type motor.
- 1887: Gustaf de Laval introduces the de Laval nozzle

- 1893 February 23: Rudolf Diesel received a patent for his compression ignition (diesel) engine.
- 1896: Karl Benz invented the boxer engine, also known as the horizontally opposed engine, or the flat engine, in which the corresponding pistons reach top dead centre at the same time, thus balancing each other in momentum.
- 1900: Rudolf Diesel demonstrated the diesel engine in the 1900 *Exposition Universelle* (World's Fair) using peanut oil fuel.
- 1900: Wilhelm Maybach designed an engine built at Daimler Motoren Gesellschaft—following the specifications of Emil Jellinek—who required the engine to be named *Daimler-Mercedes* after his daughter. In 1902 automobiles with that engine were put into production by DMG.
- 1903 - Konstantin Tsiolkovsky begins a series of theoretical papers discussing the use of rocketry to reach outer space. A major point in his work is liquid fuelled rockets.
- 1903: Ægidius Elling builds a gas turbine using a centrifugal compressor which runs under its own power. By most definitions, this is the first working gas turbine.
- 1905 Alfred Buchi patents the turbocharger and starts producing the first examples.
- 1903-1906: The team of Armengaud and Lemale in France build a complete gas turbine engine. It uses three separate compressors driven by a single turbine. Limits on the turbine temperatures allow for only a 3:1 compression ratio, and the turbine is not based on a Parsons-like "fan", but a Pelton wheel-like arrangement. The engine is so inefficient, at about 3% thermal efficiency, that the work is abandoned.
- 1908: New Zealand inventor Ernest Godward started a motorcycle business in Invercargill and fitted the imported bikes with his own invention – a petrol economiser. His economisers worked as well in cars as they did in motorcycles.
- 1908: Hans Holzwarth starts work on extensive research on an "explosive cycle" gas turbine, based on the Otto cycle. This design burns fuel at a constant volume and is somewhat more efficient. By 1927, when the work ended, he has reached about 13% thermal efficiency.
- 1908: Rene Lorin patents a design for the ramjet engine.

1910-1960

- 1916: Auguste Rateau suggests using exhaust-powered compressors to improve high-altitude performance, the first example of the turbocharger.
- 1920: William Joseph Stern reports to the Royal Air Force that there is no future for the turbine engine in aircraft. He bases his argument on the extremely low efficiency of existing compressor designs. Due to Stern's eminence, his paper is so convincing there is little official interest in gas turbine engines anywhere, although this does not last long.
- 1921: Maxime Guillaume patents the axial-flow gas turbine engine. It uses multiple stages in both the compressor and turbine, combined with a single very large combustion chamber.
- 1923: Edgar Buckingham at the United States National Bureau of Standards publishes a report on jets, coming to the same conclusion as W.J. Stern, that the turbine engine is not efficient enough. In particular he notes that a jet would use five times as much fuel as a piston engine.
- 1925: The Hesselman engine is introduced by Swedish engineer Jonas Hesselman represented the first use of direct gasoline injection on a spark-ignition engine.
- 1925: Wilhelm Pape patents a constant-volume engine design.
- 1926: Alan Arnold Griffith publishes his groundbreaking paper *Aerodynamic Theory of Turbine Design*, changing the low confidence in jet engines. In it he demonstrates that existing compressors are "flying stalled", and that major improvements can be made by redesigning the blades from a flat profile into an airfoil, going on to mathematically demonstrate that a practical engine is definitely possible and showing how to build a turboprop.
- 1926 - Robert Goddard launches the first liquid fuelled rocket
- 1927: Aurel Stodola publishes his "Steam and Gas Turbines" - basic reference for jet propulsion engineers in the USA.
- 1927: A testbed single-shaft turbo-compressor based on Griffith's blade design is tested at the Royal Aircraft Establishment.
- 1929: Frank Whittle's thesis on jet engines is published
- 1930: Schmidt patents a pulse-jet engine in Germany.

- 1936: French engineer Rene Leduc, having independently rediscovered Rene Lorin's design, successfully demonstrates the world's first operating ramjet.
- 1937: The first successful run of Sir Frank Whittle's gas turbine for jet propulsion.
- March, 1937: The Heinkel HeS 1 experimental hydrogen fuelled centrifugal jet engine is tested at Hirth.
- 27 August, 1939: The Heinkel He 178 V1 pioneer turbojet aircraft prototype makes its first flight, powered by an He S 3 engine.
- July 18, 1942: The Messerschmitt Me 262 first jet engine flight
- 1946: Sam Baylin develops the Baylin Engine a three cycle internal combustion engine with rotary pistons. A crude but complex example of the future Wankel engine.
- 1954: Felix Wankel's first working prototype DKM 54 of the Wankel engine

1960 to Present

- 1986 Benz Gmbh files for patent protection for a form of Scotch yoke engine and begins development of same. Development subsequently abandoned.
- 1999: Brothers, Michael and Peter Raffaele file patent application seeking protection for new form of Scotch yoke engine known as the Slider Engine.
- 2004 Hyper-X first scramjet to maintain altitude
- 2004 Toyota Motor Corp files for patent protection for new form of Scotch yoke engine.

Engine Starting

Early internal combustion engines were started by hand cranking. Various types of starter motor were later developed. These included:

- An auxiliary petrol engine for starting a larger petrol or diesel engine. The Hucks starter is an example
- Cartridge starters, such as the Coffman engine starter, which used a device like a blank shotgun cartridge. These were popular for aircraft engines
- Pneumatic starters
- Hydraulic starters
- Electric starters.

Electric starters are now almost universal for small and medium-sized engines, while compressed-air starting is used for large engines.