

Maximilian Lackner, Árpád B. Palotás
and Franz Winter

Combustion

From Basics to Applications



*Maximilian Lackner,
Árpád B. Palotás, and
Franz Winter*

Combustion

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From Basics to Applications

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Foreword

Combustion is a fascinating process which has been quite instrumental in civilization and industrialization. From the hearth fire and cooking stove, via techniques for ore smelting, glass blowing and porcelain making, to steam engines, cars and power plants, combustion has accompanied the history of humankind. Now, in a situation where global warming and air quality deterioration are associated with combustion-generated carbon dioxide and pollutants, it is at the same time important to provide access to affordable but clean and sustainable energy. Combustion as mature technology still dominates today's power generation and transportation, and it is used in a number of important industrial processes and applications. Many professions, trades and businesses are linked to combustion, and many people world-wide depend on their work for car and aircraft manufacturers, for the petroleum, cement or steel industry or even as safety engineers and firefighters. This global situation is not likely to be changed rapidly, in spite of considerable effort to replace fossil by renewable energy, regarding the increase in world population and the desire to raise living standards and productivity accordingly. Combustion thus shows its Janus face today with promises of high-density fuels for an energy-hungry and mobile society on the one hand and threatening pictures of smog-polluted megacities without blue skies on the other.

It is thus time for the present volume as a summary and introduction to combustion fundamentals and applications for the more generally interested reader, including students and practitioners. With a fundament in physics and chemistry, modern concepts of combustion are presented in the necessary detail for a broad overview, without an excess of detail, in coherent and comprehensible fashion. The book provides a clear structure with seven Chapters, starting with some historical facts and interesting details in Chapter 1. The second Chapter introduces fuels with respect to their important properties and physic-chemical characteristics, accompanied by useful tables and literature. With Chapter 3, the fundamental principles of combustion are provided in an instructive form with some illustrative and facile calculation examples. The reader is introduced to the concepts of stoichiometry, the conservation equations and transport processes as well as to the basics of chemical reaction mechanisms and ignition processes. Pollutants are characterized in Chapter 4, which mainly gives some classifications and describes the main sources for specific emissions. For a more in-depth understanding of the different categories

of pollutants and their chemical formation and destruction pathways, readers are referred to relevant original literature. The very important aspect of carbon dioxide formation from combustion processes and concepts for carbon dioxide management are presented in Chapter 5. The next Chapter is very instructive regarding the typical technical environments in which combustion is encountered, and it explains many interesting features of combustion devices including those found in heating, power generation, transportation, and in certain industries. As a modern concept, combustion and gasification are seen as somewhat related subjects, with a short access also to gasification strategies. The book concludes with important safety aspects, especially also regarding industrial-scale applications.

In a timely manner, the book offers an overview on an introductory level, and in this respect, it will be useful to a broad community. Certainly, huge tomes could be written for each subject treated in these Chapters, and substantial reviews and literature exists on individual facets of combustion – as for example, conventional and bio-derived fuels, combustion kinetics or specific combustion systems and applications. For a field that is as complex as that of combustion, a guided tour – as in the present case – is helpful to not lose orientation! I wish that you, the reader, may find combustion, not only at a candle-light dinner or for a barbecue, a fascinating object for study, in spite or because of the many challenges presented by its use. I also hope that by understanding the fundamental principles and limitations of combustion better, the community might find suitable replacement strategies for the systems in use today to contribute to a more efficient and cleaner energy use in the near future.

Bielefeld, April 2013

Prof. Dr. Katharina Kohse-Höinghaus

Preface

Combustion, the source of comfort and fear, warmth as well as devastation, has always fascinated mankind. It has been and still is one of the most important and most widely used technologies. In 2010, the authors published the “Handbook of Combustion” [1], a five-volume reference work that was very well received by the scientific community. Soon the idea was born to distill the knowledge from the approximately 3200 pages into a digestible textbook for students.

This book is designed to be a compilation of up-to-date knowledge in the field of combustion in a way that even a reader from a different field of expertise can understand the basic principles and applications. The purpose of this textbook is to provide an introduction to combustion science and technology, spanning from fundamentals to practical applications. It deliberately does not dwell too much on the details, although the book aims at providing the necessary knowledge for those wishing to move further into the various sub-disciplines, such as energy efficiency, oxyfuel combustion, gasification, pollutant reduction, or combustion diagnostics.

This book is written not only for undergraduate and graduate students of chemistry, chemical engineering, materials science, engineering and related disciplines, but also for practitioners in the field.

Topics covered are:

- History of combustion
- Fuels
- Combustion principles
- Environmental impacts
- Measurement methods
- Applications
- Safety issues

Each chapter can be studied independently. For further reading, web resources are suggested at the end of each chapter.

The authors are proud to present this textbook and hope that it will serve many technicians, scientists and engineers throughout their studies and careers.

Vienna, June 2013

M. Lackner, Á. B. Palotás, F. Winter

Reference

- 1 Lackner, M., Winter, F., and Agarwal, A.K. (eds) (2010) *Handbook of Combustion*, Wiley-VCH Verlag GmbH, Weinheim, 978-3527324491.

1

History of Combustion

1.1

Introduction

Combustion can be considered the oldest technology of mankind, and one of our most important discoveries/inventions. There are numerous legends around fire, for example, how it was handed to mankind by Prometheus. In Greece and India, there are stories and myths about eternally burning fires, often in relation to religious or supernatural phenomena. Legend has it that the Oracle of Delphi is located at the site of just such a fire [1]. Our ancestors used fire for various purposes, and today it accounts for the major share of primary energy production, approximately 85%. The science of combustion has a long history. Fire was one of the four elements in alchemy, and combustion processes were used for many transformations. Figure 1.1 depicts an alchemist's laboratory from ~ 1600 , where combustion plays a pivotal role.

Fire has been used by man for a long time for various purposes, such as cooking, metal production and warfare. However, as combustion phenomena are complex, significant advances in the understanding of combustion theory were only made in the last decades by a close collaboration between experimentalists and theoreticians.

An early observation made by the Flemish alchemist *Johann Baptista van Helmont* (1580–1644) was that a burning material results in smoke and a flame. From this, he concluded that combustion involved the escape of a “wild spirit” (*spiritus silvestre*) from the burning substance. Van Helmont's theory was further developed by the German alchemist *Johann Becher* (1635–1682) and his student *Georg Ernst Stahl* (1660–1734) into the phlogiston theory, according to which all combustible materials contain a special substance, the so-called phlogiston, which is released during combustion. This theory stayed in place for two centuries and was strongly defended by *Joseph Priestley* (1733–1804), who, with *Carl Wilhelm Scheele*, is also credited with the discovery of oxygen. Figure 1.2 shows Priestley's laboratory.

A classic textbook on combustion history is *Michael Faraday's “The Chemical History of a Candle”* [2]. Other names associated with the development of combustion technology are *James Watt* (1736–1819), the inventor of the steam engine (more precisely, he made improvements to the Newcomen steam engine), plus *Rudolf*



Figure 1.1 Alchemist's laboratory, around 1600. Source: Deutsches Museum, Munich, Germany.

Diesel (1858–1913) and *Nikolaus Otto* (1832–1891), the inventors of their homonymous engines.

During the *Industrial Revolution* (~1750–1850), combustion of fossil fuels began to be used on a large scale for energy production, raw materials, the manufacture of various goods, mainly from steel, and transportation, for example, via steam engines, see Figure 1.3.

The black smoke coming out of factory chimneys during the Industrial Revolution (compare Figure 1.3) was seen as a sign of progress and prosperity.

In archeology and physical anthropology, one uses the so-called three-age system for the periodization of human prehistory into three consecutive time periods,

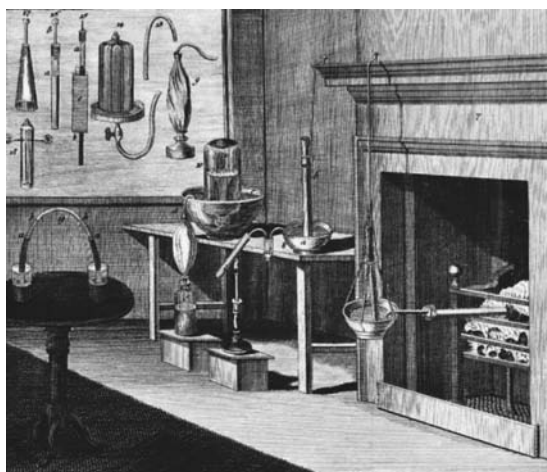


Figure 1.2 Joseph Priestley's laboratory, around 1773. Source: Deutsches Museum, Munich, Germany.



Figure 1.3 Industrial Revolution (Vintage engraving from 1878 of the Shipyards and shipping of the Clyde, Scotland).

which are named for their respective tool-making technologies: Stone Age, Bronze Age and Iron Age. The latter two are intimately associated with combustion. One can draw an analogy to energy and speak about the “coal age”, “nuclear age” and “renewables age”, while some observers are talking about a “second coal age” with the renewed interest in energy production from coal. Historically, the coal age – also termed the carboniferous period – is the time when coal was formed: 360 to 290 million years ago. Without doubt, mankind has lived in a “combustion age” for the last centuries.

1.2 Timetable

The following section lists key milestones in man’s “taming” of fire, compiled from [3–9].

The process started 1–2 million years ago with natural fires, for example, triggered by a flash of lightning, that man could grab, and progressed to primitive ways of creating fire, for example, by friction (Figure 1.4) or flint stones (Figure 1.5) almost 10 000 years ago, followed by a rapid evolution of technologies:

First 500 000 years and beyond . . .

1–2 million years BC: Man discovers fire

Before our time . . .

~ 7000 BC: Man uses flint stones

~3000 BC: Egyptians invent candles, made from beeswax



Figure 1.4 Making fire (Image from the Dutch stone age theme park Archeon).

- ~1000 BC: Chinese use natural gas for lamps [1]
- 500 BC: Greeks describe combustion with the 4 elements earth, water, air and fire
- 450 BC: Herodotus describes oil pits near Babylon
- Approaching the middle ages . . .**
- ~100 AD: Chinese invent gunpowder and fireworks
- 1242: Roger Bacon, an English friar, publishes gunpowder formula [9]



Figure 1.5 Flintstone, found in the Cliffs of Dover/UK.

fifteenth century:	Candles are used for street lighting
500 years ago . . .	
1556:	Georgius Agricola publishes “ <i>De re metallica</i> ”, a book cataloging the state of the art in mining, refining, and smelting of metals.
400 years ago . . .	
1627:	First recorded use of black powder for rock blasting in Hungary [9]
1650:	Otto von Guericke demonstrates that a candle does not burn in a vacuum
1678:	Abbé Hautefeuille describes an engine for raising water, powered by burning gun powder
1698:	Thomas Savery builds a steam-powered water pump for removing water from mines
~1700:	Christiaan Huygens comes up with the idea of an internal combustion engine
300 years ago . . .	
1712:	Thomas Newcomen builds a piston-and-cylinder steam-powered water pump for use in mines (Figure 1.6). It is the first practical device to harness the power of steam to produce mechanical work [10]
1772:	Carl Wilhelm Scheele carries out experiments to split air and discovers oxygen (Figure 1.7).
1778:	Alessandro Volta discovers the analogy between the ignition of combustible gases and fen fire (ghost light) in swamps (Figure 1.8).

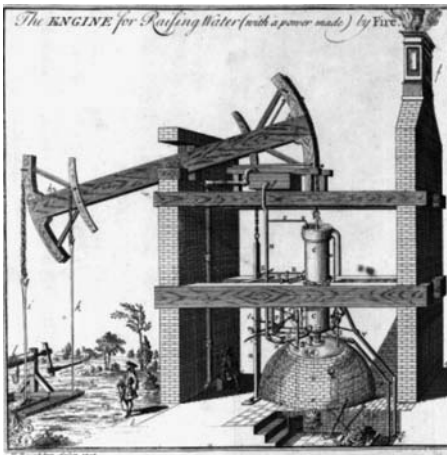


Figure 1.6 Newcomen engine [10].

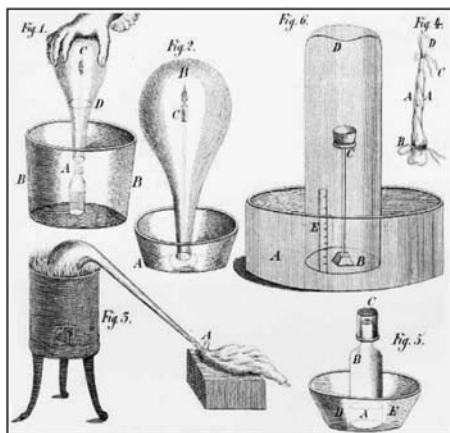


Figure 1.7 Experiments by C.W. Scheele to investigate the composition of air and to explain combustion and breathing processes. Source: Deutsches Museum, Munich, Germany.

1750–1850:	Industrial Revolution
1769:	James Watt (Figure 1.9) patents a steam engine
1790s:	Steam ship pioneer Samuel Morey invents a steam-powered paddle wheel
1791:	John Barber obtains a patent for a gas turbine
1792:	William Murdoch discovers the distillation of gas from coal and its use for lighting purposes
1794:	Concept for the first internal combustion engine by Robert Street
1800:	Phillippe Lebon patents an engine that uses compressed air and electricity for ignition
1801:	First coal powered steam engine
1806:	François Isaac de Rivaz invents a hydrogen-powered internal combustion engine
200 years ago . . .	
1814:	George Stephenson builds a steam locomotive
1815–1819:	Sir Humphry Davy discovers catalytic combustion
1816:	Robert Stirling invents his hot air Stirling engine
1824:	Nicolas Léonard Sadi Carnot publishes that the maximum efficiency of a heat engine depends on the temperature difference between an engine and its environment
1834:	Joseph Morgan develops a machine that allowed the continuous production of molded candles
1837:	First American patent for an electric motor (US Patent 132)
1850:	Rudolf Clausius describes the first and second law of thermodynamics



Figure 1.8 The gases which are formed in swamps are comparable to combustible gases from the lab. Source: Deutsches Museum, Munich, Germany.

~1855:	Robert Bunsen builds the Bunsen burner
1855:	Johan Edvard Lundstrom (Sweden) patents his safety match
1857:	Development of the kerosene lamp
1859:	John Tyndall discovers that some gases block infrared radiation. He suggests that changes in the concentration of the gases could bring climate change [4]

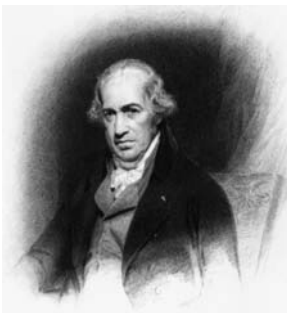


Figure 1.9 James Watt [10].

- 1860: Étienne Lenoir and Nikolaus Otto build an internal combustion engine
- 1860: Invention of fire extinguishers
- 1863: J.D. Rockefeller opens an oil refining company in Cleveland
- 1863: Julius Bernhard Friedrich Adolph Wilbrand invents trinitrotoluene (TNT) [9]
- 1866: Swedish chemist Alfred Nobel invents dynamite by mixing kieselguhr with nitroglycerine [9]
- 1877: Nikolaus Otto patents a four-stroke internal combustion engine (US Patent 194 047)
- 1880: Thomas Alva Edison opens an electric power plant
- 1882: James Atkinson invents the Atkinson cycle engine, which is used in some hybrid vehicles
- 1884: Charles Parsons develops the steam turbine
- 1885: Karl Benz builds a gasoline-powered car
- 1885: Gottlieb Daimler patents the first supercharger
- 1892: Rudolf Diesel patents the Diesel engine (US Patent 608 845)
- 1896: Svante Arrhenius publishes the first calculation of global warming from human emissions of CO₂
- 1899: Ferdinand Porsche creates the first hybrid vehicle
- 1903: First flight by the Wright Brothers, Orville and Wilbur, at Kitty Hawk
- 1906: Frederick Gardner Cottrell invents the electrostatic smoke precipitator

100 years ago . . .

- 1913: René Lorin invents the ramjet
- 1915: Leonard Dyer invents a six-stroke engine, now known as the Crower six-stroke engine named after its reinventor Bruce Crower
- 1920: Robert H. Goddard develops the principle of a liquid-fueled space rocket
- 1923: Fritz Pregl receives the Nobel Prize for combustion analysis
- 1929: Felix Wankel patents the Wankel rotary engine (U.S. Patent 2 988 008)
- 1930s: Global warming trend since late nineteenth century reported [4]
- 1936: Maiden flight of the “Hindenburg” LZ 129 airship (volume 200 000 m³, hydrogen-filled)
- 1954: Foundation of the “Combustion Institute”
- 1957: Russia launches “Sputnik I”, the first artificial Earth satellite

50 years ago . . .

- 1969: The USA land men on the moon, propelled by the Saturn V booster rocket developed by Wernher von Braun
- 1970s: Electronically controlled ignition appears in automobile engines
- 1973: Oil embargo and price rise bring first “energy crisis“
- 1975: Catalytic converters are introduced on production automobiles in the US, co-invented by Carl Donald Keith
- 1979–1981: Oil prices rise from \$13.00 to \$34.00/barrel
- 1981–2011: The Space Shuttle, a partially reusable launch system and orbital spacecraft, is operated by the US National Aeronautics and Space Administration (NASA) for human spaceflight missions
- 1980s: Electronic fuel injection appears on gasoline automobile engines
- 1986: World car population exceeds 500 million vehicles [11]

25 years ago . . .

- 1990: First IPCC (Intergovernmental Panel on Climate Change) report says world has been warming and future warming seems likely
- 1990s: Market introduction of hybrid vehicles that run on an internal combustion engine and an electric motor charged by regenerative braking
- 1990s: CFD (computational fluid dynamics) is widely used as a tool for combustion simulation
- 1997: Toyota introduces the Prius in Japan, the first mass-market electric hybrid car
- 1997: The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) sets binding obligations on industrialized countries to reduce emissions of greenhouse gases
- 1998: 50 year moratorium on mining and oil exploration in Antarctica approved

Current century . . .

- 2002: Güssing’s biomass gasification (demonstration plant with 8 MW_{th} combined heat and power) in operation [12]
- 2003: The US government announces its plan to build a near zero-emission coal-fired power plant for hydrogen and electricity production using carbon capture and storage (CCS)
- 2007: European Union introduces new environmental regulations to reduce GHG (greenhouse gases) emissions by 20% by 2020

2008:	Wärtsilä builds the world's largest reciprocating engine, a two-stroke turbocharged diesel engine designed for large container ships with a power of 80 000 kW
2009:	Level of CO ₂ in the atmosphere reaches 385 ppm [4]
2010:	1 000 000 000 cars on the road [11]
2013:	World's largest fluidized bed boiler (600 MW _{el}) is expected to be in operation in China
In future . . .	
2020–2030:	Peak oil expected [5]

1.3

Outlook

Combustion has been a science and engineering discipline for several hundred years, and it has driven the industrial revolution. Today, combustion plays an important role in our lives, from transportation to energy production, and it will continue to do so.

The focus of combustion research in the last decades has moved to pollution abatement, energy efficiency and alternative fuels (green combustion, zero emission combustion and near-zero emission combustion) [13]. Biomass – a renewable fuel – is expected to gain an increasing share over fossil fuels, as well as hydrogen as a clean energy carrier [14].

Today, energy is largely used inefficiently, because we deploy it as heat, where the limitations of Carnot apply, which are far from the thermodynamic limits. The Carnot efficiency is defined as

$$\eta = \frac{T_h - T_c}{T_h}$$

where T_h is the absolute temperature of the hot body and T_c that of the cold body for a heat engine. So instead of talking about an “energy crisis” we could talk about a “heat crisis” of technical processes. Organisms, on the contrary, do not thermalize their energetic compounds, but rather utilize their chemical energy in a more efficient way: in a cascade of molecular-scale mechanisms that approach the reversible limit set by the difference in free energy. As these processes occur around room temperature, the irreversible losses ($T\Delta S$) are significantly smaller. A short-term technical realization of this concept is the *fuel cell* [15]. It is expected that fuel cells will gain importance as an efficient and clean “special” mode of combustion. There are various concepts and technologies, for example, proton exchange membrane (PEM) and molten carbonate (MC) fuel cells. Fuel cells can be combined with on-board fuel processing. *Gasification* can be used to obtain the feed for fuel cells from solid fuels.

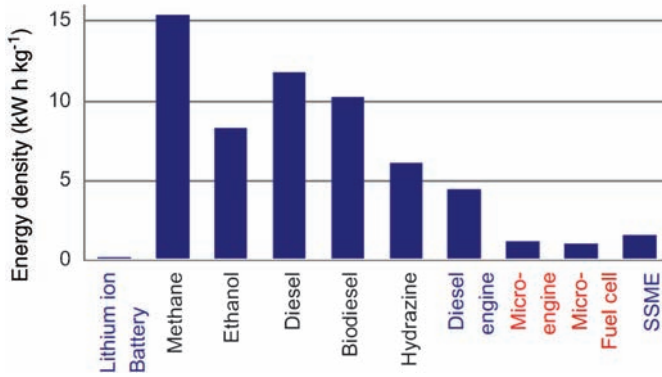


Figure 1.10 Comparison of specific energy densities of lithium ion batteries with hydrocarbon and oxygenated hydrocarbon fuels as well as different engines. SSME = space shuttle main engine. Reproduced with permission from [16].

When combustion processes are miniaturized, one talks about “*microscale combustion*”. This technology has attracted the interest of researchers recently. Microscale combustion differs fundamentally from “normal” combustion processes, since the vessel walls are closer than the quenching distance, so catalytic combustion processes are applied. Microscale combustion [16] might soon replace conventional batteries, as liquid fuels such as hydrocarbons have a high energy density, see Figure 1.10.

Figure 1.11 depicts a micro-gas turbine.

As mentioned, pollutant formation and reduction has become an important field of study in combustion in the recent decades as environmental awareness has increased. The study of health effects from combustion products [17] is also gaining importance.

Concerning fossil fuels, *oil sands* [18] will receive increased research attention. With respect to engines, *homogeneous charge compression ignition* (HCCI) [19] and various alternative ignition systems [20] are promising concepts, see Figure 1.12.

HCCI is difficult to control. The use of two fuels with different reactivities (such as gasoline and diesel) can help to improve this situation. Such a fuel is called *gasoline/diesel blend fuel* (GDBF) [22].

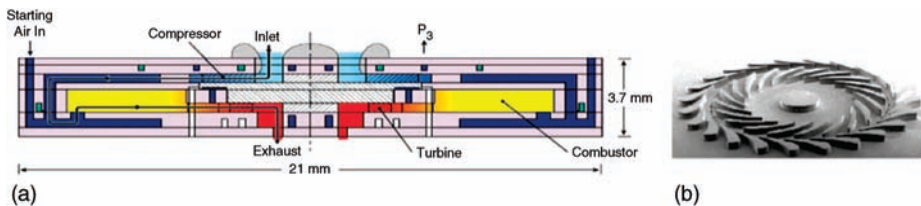


Figure 1.11 Scheme of a micro-gas turbine (a) and image of the turbine blade (b). Reproduced with permission from [16].