Introduction

Brief Historical Introduction

Fire, Humanity and Civilisation

Combustion has played a decisive role in the development of mankind and civilisation. At the present time it is the principal source of energy and the main support of economic development. Mastering the use of fire was the first major step in the development of humanity and marked a decisive step in its evolution. The oldest traces of the use of fire, limited to the occasional use of naturally occurring embers, date back to more than one million years, after the emergence of *Homo erectus*. However, the first fireplaces in dwellings appeared much later in Eurasia, about 450000 years ago. Neanderthal man had well mastered the art of fire, greatly improving living conditions through the ability to create light after sunset, to fight against cold, and to cook food. The first technical uses of fire were limited to hardening the points of wooden arrows and spears. Small lamps made of stone, bone or shells burning animal fat or vegetable oil, and dating back to the upper Palaeolithic 35000 years ago, can be directly associated with the development of parietal arts.

The development of other technologies using fire appeared with the advent of farming and a more sedentary existence in the Neolithic era and the early Bronze Age, some 10 000 years ago. At this time, fire was used to transform clay into pottery, and ore into metals. Because of its capacity to transform and purify(?) or destroy matter and its dancing flames, source of light and heat, fire quickly acquired a mystical dimension as attested by the central place of fire in the Vedic ritual and in the legends of antique Greece. Let us cite, for example, the legend of Prometheus, a Titan who stole fire from Zeus and gave it to the mortals, as did his Hindu counterpart, Pramatha, the hero who brought civilising fire to earth. The holders of the secrets of fire were at the same time priests and scientists, as for example the 'Guild of Chinese Blacksmiths' (eighth century BC), which was at the origins of Taoism at the time of Laozi (sixth century BC). From this stems the Taoist alchemy, more than one and a half millenniums before the alchemy of the Middle Ages, whose esoteric gnosis reserved a major role for the sacred fire.

Fire, War and Industry

The mastery of bronze, iron and steel is a marker in the history of a civilisation that evolved with the progress of metallurgy in the hands of the master blacksmiths, controlling the quality of tools and weapons.

In the fifteenth century, the arrival of gunpowder changed the tactics of combats. The earliest known formula is mentioned in a Chinese military text, the *Wujing Zongyao*, and the transfer of knowledge to Western Europe probably occurred via Arabian literature.[1] Its composition – approximately 70% saltpetre, 15% sulphur and 15% charcoal – was known in western Europe as early as the thirteenth century, and more precisely in 1267 by Roger Bacon, the ‘Doctor Mirabilis’, in his description of firecrackers. However the effective use of firearms commenced only towards the end of the fourteenth century, first during sieges and a little later on the battlefield, changing the course of history. During the Middle Ages they were a decisive help to the armies of Charles VII in bringing the Hundred Years’ war to an end (the battles of Formigny and Castillon).[1] In Russia, as early as 1480, it was the use of cannons and muskets that permitted the Muscovite princes to overcome the Tatar domination (Mongol invaders, called ‘Tatars’ by the Russians), the Muscovite Tsar then replacing the Khan of the Golden Horde. As noted by Fernand Braudel:[2] ‘The Asian invader had penetrated Occident with its horses, but was finally halted by gunpowder.’ Despite this decisive technical advantage, the fight was long and difficult, and it was not until a century later that Ivan the Terrible managed to take control of Kazan (1551) and Astrakhan (1556). In France towards 1580, during the wars of religion, the invention of cannons made town walls an illusory defence.[3] A century later, during the reign of Louis XIV, a new generation of fortresses, adapted to artillery, were built by Vauban on the borders of the country.

Coal was the primary ingredient of the Industrial Revolution that took place at the end of the eighteenth and during the nineteenth centuries. It was marked by the development of thermal machines and heavy industry, with its blast furnaces for the production of steel and coke. The internal combustion engine, invented at the end of the nineteenth century, revolutionised terrestrial and maritime transportation before giving birth to aeronautics. This latter had its own revolution in the 1950s with the development of the turbo-reactor. Rocket engines, propelled by liquid fuels or solid propellants, were developed at the same time, giving rise to a new era in communications with the advent of artificial satellites.

Science and Combustion

The scientific comprehension of combustion progressed tardily, perhaps because of the strong symbolism attached to flames. With few exceptions, the pre-scientific mind was ‘very symptomatic of the dialectics of ignorance that goes from darkness to blindness’, as

[1] Contamine P., 1999, *La guerre au Moyen Âge*. PUF, 5th ed.
[2] Braudel F., 1987, *Grammaire des civilisations*. Arthaud.
[3] Ferro M., 2001, *Histoire de France*. Odile Jacob.

Gaston Bachelard said so beautifully in the middle of twentieth century, adding that 'fire, unlike electricity, has not found its science'.[4] Nevertheless, the first scientific observations of a candle flame date back to Francis Bacon in 1600, followed half a century later by Boyle and Hooke. But understanding was obscured by European alchemy, reviewed by the Abbot Lenglet-Dufresnoy,[5] one of the first historians of alchemy in the eighteenth century. The alchemists, who were qualified as *the most illustrious dreamers that humanity has produced*, considered flames and combustion to be the release of an imponderable agent, or phlogiston, contained within each combustible body. This view was still shared by most of the scientists up to the end of the eighteenth century.

The first decisive progress was made in the eighteenth century. An original reflexion is presented in the 1738 dissertation of Leonhard Euler, *Dissertatio de igne in qua ejus natura et proprietates explicantur*[6] (Dissertation on fire in which its nature and properties are explained). How can one explain that a small local cause can have a significant effect on a large scale, such as a spark that lights a huge fire, or a charge of explosive that explodes from the combustion of one of its grains? To answer this question, Euler proposed that a combustible material be assimilated to a network of fragile hollow spheres containing a compressed 'igneous' fluid. These spheres can break as a result of a perturbation caused by the destruction of their neighbours. They thus release their 'igneous' material (subtle matter) which, 'expanding' into the surrounding atmosphere in the form of flames, breaks other spheres. In more technical modern terms, Euler proposes an analogy between a fire and a nonlinear wave: a disturbance of finite amplitude propagates over a network of metastable elements whose state is changed by the passage of the wave, the initial shock acting as the initiator. Assimilating heat to the agitation of particulate matter, he introduced the concept of thermal runaway: combustion is accompanied by heat release which, in turn, can 'give birth to and spread' fire. Indeed, the spheres break more easily and more frequently when they move and collide more violently. What a great insight! The 'illustrious' Royal Academy of Sciences of Paris, in the words of Euler, therefore showed great discretion in awarding him the prize it had put to contest on the theme of fire, a competition in which Voltaire and the Marquise of Chǎtelet had also participated. Far ahead of his time, the ideas of Euler were not followed and did not give rise to any experimental study, the first experiments being performed at the end of the eighteenth and early nineteenth century. It was not until the middle of the twentieth century that the speed and structure of flames were described correctly through the analysis of a mathematical model actually quite close to that of Euler.

The 'igneous' matter of Euler's model, enclosed in spheres that break open in cascade, is reminiscent of the phlogiston of alchemists. However, it anticipates with great discernment the release of energy by the formation of strong chemical bonds and the subsequent thermal runaway in combustion. Two key concepts were unknown to Euler; one is chemical, the

[4] Bachelard G., 1928, *La psychanalise du feu*. Gallimard.
[5] Lenglet-Dufresnoy N., 1742, *Histoire de la philosophie hermétique*. Coustelier, Quai des Augustins.
[6] Euler L., 1944, *Cinq mémoires sur la nature et la propagation du feu*. Association pour la sauvegarde du patrimoine métallurgique du Haut-Marnais.

notion of species (fuel, oxidant and combustion products), the other physical, conservation of mass and total energy (kinetic plus chemical). Based on experiments more detailed than those of Boyle, Lavoisier, the founder of modern chemistry, refuted the concept of phlogiston in his 1777 book *Reflections on Phlogiston*, more than a century after its introduction. Combustion was described for the first time as a chemical reaction between two bodies, fuel and an oxidant, primarily oxygen, that are transformed into products, the total mass remaining unchanged. The analogy with breathing was also highlighted. In the same period, soon after the discovery of hydrogen, the introduction of a burner into a tube produced the ‘singing flame’[1] that became an attraction in nineteenth-century parlours lit by gas chandeliers. However, the analyses of Lavoisier lacked the concept of energy conservation. Despite ideas dating back to the seventeenth century on the nature of heat being linked to the agitation of matter (Francis Bacon, Robert Boyle, etc.), and despite the first quantitative experiments of Benjamin Thompson (Count Rumford) in the late eighteenth century on the transformation of work into heat, a misconception of heat, called ‘caloric’, considered to be a self-repellent indestructible fluid, persisted until the middle of nineteenth century.

This misconception is found in 1824 in the remarkable work of Sadi Carnot,[2] self-published by the author at the age of 28. He postulates that the production of work requires the existence of at least two sources of heat, a hot source from which heat is extracted and a cold source into which it is ejected. He then considers an alternating succession of irreversible cycles and reversible inverse cycles. Based on the inability to produce work without extracting heat from the outside environment, he concludes that the maximum efficiency of a heat engine is obtained with reversible cycles. He also shows that the performance depends only on the temperature of the sources, independent of the nature of the fluid used to perform the cycles. Despite the misconception of heat, based on an analogy with the flow of water from a mill (the amount of heat extracted from the hot source is equal to that discharged into the cold source), the reasoning leads Carnot to a brilliant and exact conclusion concerning the maximum efficiency of a heat engine. Made public in 1834 by Clapeyron, this work served as the foundation for the introduction of entropy a few years later by Clausius. This new concept, unknown to Newtonian mechanics, opened opportunities hitherto unsuspected in thermodynamics and physics. The next milestones were the works of Maxwell in 1860 and Boltzmann in 1872. Meanwhile, it was not until the first work of Joule, published in 1847, that the equivalence between heat and work was established experimentally[3] and fully recognised, half a century after the experiments of Benjamin Thompson.[4] In notes written after the publication of his book, but published only later after his untimely death in 1832, Carnot imagined experiments to demonstrate the equivalence of heat and work.[5] This would surely have led him to correct the initial error in his work if he had had the time.

[1] Rayleigh J., 1945, *The theory of sound*, vols. 1 and 2. New York: Dover.
[2] Carnot S., 1824, *Réflexions sur la puissance motrice du feu et sur les machines propres à développer cette puissance*. Bachelier.
[3] Prigogine I., Kondepudi D., 1999, *Thermodynamique: Des moteurs thermiques aux structures dissipatives*. Odile Jacob.
[4] Longair M., 2003, *Theoretical concepts in physics*. Cambridge University Press.
[5] Mendoza E., ed., 1977, *Reflections on the motive power of fire by Sadi Carnot and other papers*. Gloucester, Mass: Peter Smith.

Mention should also be made of a result obtained during the same period concerning the propagation of sound waves. In 1823, realising that the compressions and expansions of the gas in an acoustic wave are adiabatic, and not isothermal (as supposed by Newton), the marquis Pierre-Simon Laplace corrected the speed of sound predicted by Newton a century earlier but with a value that was too low. This problem had also been discussed by Euler in his 1738 dissertation, but without providing a relevant insight.

The systematic study of flame propagation was motivated by accidents in mines caused by the explosion of firedamp. The earliest work, dating back to 1830, is due to Sir Humphry Davy, who gave his name to the miners' safety lamp. Some time later, his former student Michael Faraday gave the Royal Society a famous series of conferences entitled 'The chemical history of a candle'.[6]

Detonations, or supersonic combustion waves, were discovered in a condensed explosive, gun-cotton, by Sir Frederick Abel. He measured the propagation velocity of these waves, of the order of 6000 m/s,[7] a remarkable feat for the time. In the October 1873 issue of *Nature*[8] it was remarked that 'Indeed with the exception of light and electricity the detonation of gun-cotton travels faster than anything else we are cognizant of'. Detonations were discovered in gases later, in 1882, by Berthelot and Vieille. At about the same time, Mallard and Le Chatelier,[9] two engineers of the French Corps des Mines, charged by La Commission du Grisou to study the propagation of flames in various mixtures of reactive gases, submitted their report presenting a detailed series of measurements on the propagation of subsonic combustion waves.

During the same period, Lord Rayleigh[1] established his famous criterion for the stability of combustion confined in an enclosure (combustion chamber): an instability of the acoustic modes can develop if the energy release rate fluctuates in phase with pressure. This thermo-acoustic instability is responsible both for the singing flame discovered a century earlier and also much later, from the middle of the twentieth century, for the violent vibrations observed in rocket engines that became the nightmare of engineers in charge of propulsion in astronautics. At the beginning of twenty-first century, these issues remain relevant in the engines of the Space Shuttle and the Ariane rockets.

The internal structure of the two types of combustion waves, flames and detonations was not fully understood and described theoretically until 1938, thanks, in particular, to the work of Zeldovich.[10] The understanding of the instabilities, the dynamics and the spatio-temporal structure of these fronts did not really progress until 1975 for flames, following the pioneering work of Landau and Darrieus in 1940, and only after 1990 for detonation fronts, although their cellular structure had been observed experimentally in the early 1950s[11].

Optical diagnostics for nonintrusive measurements of concentration and temperature, as well as visualisations and fast scans, were developed in research laboratories in the years

[6] Bibliothèque des succès scolaires, ed., 1868, *Histoire d'une chandelle*. J. Hetzel et Cie.
[7] Abel F., 1874, *Philos. Trans. R. Soc. London*, **164**, 337–395.
[8] Editorial, 1873, *Nature*, **8**(208), 534.
[9] Mallard E., Le Chatelier H., 1883, *Annales des Mines, Paris*, **Series 8**(4), 296–378.
[10] Ostriker J., ed., 1992, *Selected works of Ya.B. Zeldovich*, vol. I, p. 193. Princeton University Press.
[11] Markstein G., 1953, *Proc. Comb. Inst.*, **4**, 44–59.

1970–80 thanks to lasers and the development of electronics and information technology. These methods have opened a new era in experimental studies of combustion. They are now currently used in industrial combustion chambers (engines, turbo-machines, furnaces, etc.).

Energy and Modern Society

The production and use of energy are essential elements of economic activity. In the second half of the twentieth century, the global annual production of energy doubled in less than half a century, reaching about 13 gigatonnes (Gt) (1 Gt is equivalent to one billion metric tons) of oil equivalent per year, composed of 31.5% oil, 21% natural gas and 29% coal, according to the figures given in 2014 by the International Energy Agency (IEA) of the Organization for Economic Cooperation and Development (OECD). Renewable energies, hydropower, geothermal, wind, solar, biofuels, biomass, and others, along with waste combustion together represent 13.5% of the overall production; nuclear power contributes less than 5%. Fossil fuels currently provide more than 80% of the energy used by man. In France the share of nuclear power is much higher than the rest of the world; it represents approximately 76% of electricity production. In 2014 the average annual energy consumption per capita in industrialised countries was around 4.2 tons of oil equivalent, to be compared with the total consumption of 13 Gt for 7 billion people, or 1.9 tonnes on average per inhabitant of the planet (1 ton of oil is roughly equivalent to 11.6 MWh).

Based on current consumption in Western countries and the rapid development of the economy of countries like China, India and Africa, representing more than half the population on earth, energy consumption could continue to increase at a pace not only harmful to the health of our planet, but also worrying with regard to the reserves of fossil fuels accessible by current technologies. At its present trend, the total energy consumption of the planet will more than double over the next half-century to come. The assessment of usable fossil fuel reserves is subject to discussion; it depends on the extraction efficiency which is currently 30% for oil, but could fairly quickly reach 40%. The figures announced by companies and oil exporting countries are unreliable and the IEA calls for more transparency and rigour in the assessment. At the end of 2011, recoverable reserves were estimated to be about 1030 Gt (10^{12} tonnes) of oil equivalent, consisting of 22% oil, 17% gas and 61% coal (World Energy Council 2013). The reserves of shale oil are estimated to be around 655 Gt; however, the economic and ecological viabilities of this resource remain uncertain. Other major unconventional resources such as methane hydrates under the oceans are also known to exist[1], but accurate data is not available.

The production peak of oil will mark the beginning of the depletion of resources, when supply can no longer meet demand, creating a very high tension on the oil market that will disturb the world economy. There is no general consensus when this will occur but it could be in the second half of the century.

[1] Dautray R., 2004, *Quelle énergie pour demain*. Odile Jacob.

To address both the limitation of the release of CO_2 into the atmosphere and the inevitable decline of fossil fuel reserves, major changes in energy policy will be needed in the next decade. Technologies for renewable energies, currently under-utilised, as well as energy storage, will grow at a much faster rate than today. These technologies will soon become competitive. However, even associated with a drastic reduction of wastage, especially in housing and transport, renewable energy alone will not meet the needs.

Nuclear fusion will never replace all other energy sources, even supposing that it will be available in the foreseeable future. The scientific and technical problems to be solved are so gigantic that there can be no serious prognosis for the date of its industrial use. The feasibility of the process is far from proven. Also there are serious problems for the preservation of materials in the neutron flux, with no prediction for when they will be resolved, not to mention possible risks of accidental pollution by tritium.

It will be necessary to use other technologies whose medium-term prospects are more realistic. Nuclear fission is a more serious asset, at least for several decades, even if the technical solutions and the actual costs of reprocessing waste and the demolition of obsolete plants are always controversial, to say nothing of the risk of proliferation of nuclear weapons. These difficulties can be overcome within a reasonable time provided that the will and the effort are coordinated across the planet.

The production of biofuels and the use of solar technologies and wind power will continue to increase, but will ultimately represent only a fraction of the total energy production. The combustion of hydrogen and/or its use in fuel cells are viable solutions. However it will still be necessary to produce it in sufficient quantities – by electrolysis using nuclear electricity or from renewable energy sources? – and store it at a low cost without risk of leakage. Consumption of coal has more than doubled since 1973 with the industrialisation of China and other parts of Asia. Its substantial reduction is not an easy task, and cannot be expected in a near future in underdeveloped countries that have an increasing growth of population. Clean combustion of fossil fuels remains a priority in research and technology. Burning coal and oil shale or their derivatives is expected to continue for one more century in thermal power plants from which the emissions of carbon dioxide and pollutants like sulphur dioxide and nitrous oxides will be captured.

The necessity to develop scientific knowledge and technological expertise of combustion phenomena remains more important than ever. Many scientific problems whose applications are important, especially for the production and economy of energy, as well as for safety, require further fundamental analyses for a better control of the technologies. In addition to issues of thermal and chemical pollution, let us cite micro-combustion; the deflagration-to-detonation transition, a phenomenon of importance for safety, including major incidents in nuclear power plants; the critical conditions for the spontaneous initiation and dynamic extinction of detonations; cellular detonations; turbulent and even the self-turbulent flame propagation; combustion chamber instabilities, a serious problem in rocket engines; super knock in gasoline engines working at high compression ratios; lean combustion of hydrocarbon fuels, more economical and less polluting, but difficult to ignite and to stabilise with the risk of flash-back in the injectors of turbo-reactors; and so on.

Combustion and Related Phenomena

The study of flames, detonations and explosions on earth shows they generally have aspects in common with other phenomena of great importance.

This is the case with inertial confinement fusion, the principle of the H-bomb, currently being studied for both military and civilian purposes. The principle of this method is to generate energy by micro-explosions in which thermonuclear ignition is obtained by the implosion of a shell of combustible material.[1] Such small-scale experiments of nuclear explosions can be used to test the numerical codes that are used in the development of nuclear weapons. Civilian production of energy is also envisaged in this way as a competitor for magnetic confinement fusion, but with not much chance of success, to say the least. The most advanced programs were launched in the 1970s and 1980s in the United States and in France. In 2007 the European Union funded a civil scientific research program on the subject.

Similar phenomena occur at a very different scale in the gravitational collapse and subsequent explosion of dying stars and white dwarfs. These *supernovae* merit interest; for the astrophysicists they are the 'candles of the universe'. They are also responsible for the production and dissemination into the cosmos of the heavier elements forming the planets and are necessary for the emergence of life forms. Despite more than 40 years of intense research in nuclear physics and impressive numerical simulations, the basic mechanism of the explosion of supernovae, responsible for the liberation of huge quantities of energy, partly of gravitational origin and partly from nuclear reactions, is still not understood

Scope of the Book

This book is mainly concerned with the properties, structure and dynamics of wave propagation in fluids. Subsonic waves, flames, deflagrations (fast flames) or ablation fronts and supersonic waves, shocks and detonations share similar properties. First, the front and the flow are strongly coupled. This is a consequence of the density variation across the wave, produced by the quasi-isobaric expansion associated with heat release in subsonic propagation and/or by compression in supersonic propagation. Moreover the upstream flow of subsonic waves is modified by wrinkling of the front. Second, their structure is controlled by coupled nonlinear mechanisms of different origins (fluid mechanics, chemical kinetics or dissipative transports). Consequently, different time and length scales (having many orders of magnitude difference) are involved in the dynamics and the geometry of the front, so that multiple-scale methods are required in the analyses.

Generally speaking, the understanding of combustion waves and/or explosions is a difficult task and the research in the field is still very active. Flames, shocks, detonations and explosions have been investigated for a long time. Their understanding has greatly improved during the three last decades, but many aspects, in particular those concerning the strongly nonlinear regimes and their transition, require further investigation.

[1] Atzeni S., Meyer-Ter-Vehn J., 2004, *The physics of inertial fusion*. Clarendon Press–Oxford Science Publications, 1st ed.

The success of the approach of Ya. B. Zeldovich for the study of combustion waves has served as a guide in the analyses of the last 50 years. Understanding is greatly improved by the analytical studies of simplified models, obtained in a systematic way through deep physical insight. A relevant reduction of the complexity is the main difficulty. Efficient perturbation analyses have then to be carried out to solve the simplified models. Usually, the purely mathematical contents of the technical part are not the most useful points, and many of the perturbation methods have been set up by a physical approach. The essential ingredient for a successful input is the development in parallel of small-scale, carefully controlled laboratory experiments. The lack of such controlled experimental input is a major obstacle to progress in the understanding of astrophysical phenomena such as the explosion of stars.

The main body of the book concerns combustion waves on earth. It differs in spirit and in content from other books on combustion. It is a successor to three pioneering works in the theory of combustion[2,3,4] and is complementary to more recent books.[5,6,7] Two other topics that may benefit from the advances in the theory of flames and detonations are also discussed: ablation fronts in inertial confinement fusion and the explosion of massive stars. According to the current views, the formation and the propagation of a shock wave in the flow of the imploding stellar core is the key mechanism for turning the gravitational collapse into a devastating explosion of the star. Mechanisms that have been identified in combustion on earth could be useful to help decipher the explosion of stars (supernovae), a subject that is still not well understood.

The book is split into three parts. Part I is written for physics-oriented readers. Physical insights are provided by solutions to well-posed problems. Here, the physical analyses are almost free from the technical difficulties inherent in perturbation methods, used in the second part. The small-scale experiments on flames, which have proved to be essential to develop a relevant flame theory, are also reported in the first part. A chapter is also devoted to the systematic reduction of chemical kinetic schemes in combustion, illustrating the power of multiple-time-scale considerations. It also points out the limitations of the simplest models. This can serve as an interesting example for nuclear reactions. The prerequisites in applied mathematics and physics are those taught during the first year at university, some useful complements being given in appendices. The necessary background in physics (thermodynamics and statistical physics), chemistry and fluid mechanics (subsonic and supersonic flows) is recalled in Part III. Part II is for theoreticians. Detailed analytical studies are presented here on the basis of the physical insights presented in the first part. Conversely, these calculations provide the solid foundations for the physical analyses of Part I.

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[2] Markstein G., 1964, *Nonsteady flame propagation*. New York: Pergamon.
[3] Williams F., 1985, *Combustion theory*. Menlo Park, Calif.: Benjamin/Cummings, 2nd ed.
[4] Zeldovich Y., et al., 1985, *The mathematical theory of combustion and explosions*. New York: Plenum.
[5] Borghi R., Champion M., 2000, *Modélisation et théorie des flammes*. Édition Technip.
[6] Kuo K., 2005, *Principles of Combustion*. Hoboken, N.J.: John Wiley and Sons, 2nd ed.
[7] Law C., 2006, *Combustion physics*. Cambridge University Press.

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Flames, Shocks, Detonations, Ablation Fronts and Explosion of Stars
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Excerpt
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Part One

Physical Insights

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1

General Considerations

Nomenclature

Dimensional Quantities

	Description	**S.I. Units**
a	Mean molecular velocity. Sound speed	m s^{-1}
c_p	Specific heat at constant pressure	J K^{-1} kg^{-1}
c_v	Specific heat at constant volume	J K^{-1} kg^{-1}
d_L	Scale of laminar flame thickness	m
$\mathcal{D}$	Normal propagation velocity	m s^{-1}
D	Molecular diffusivity	m^2 s^{-1}
e	Energy	J $\equiv$ kg $(m/s)^2$
E	Activation energy	J $mole^{-1}$
E_G	Gamow energy	J
k_B	Boltzmann's constant	J K^{-1}
ℓ	Molecular mean free path	m
L	Length of tube, burner or space scale	m
m	Mass flux	kg $m^{-2}s^{-1}$
$M_\odot$	Mass of the sun	kg
n	Number density	m^{-3}
p	Pressure	Pa
q_m	Heat of combustion per unit mass	J kg^{-1} $\equiv$ $(m/s)^2$
R	Radius	m
s	Entropy	J K^{-1} kg^{-1}
S	Surface area	m^2
t	Time	s
T	Temperature	K
T^*	Cutoff temperature	K
U_L	Laminar flame speed	m s^{-1}
U_b	Laminar flame speed w.r.t. burnt gas	m s^{-1}
v	Impact velocity	m s^{-1}

ρ	Density	$\mathrm{kg\,m^{-3}}$
σ_o	Collision cross section	$\mathrm{m^2}$
σ_{nr}	Collision cross section for nuclear reaction	$\mathrm{m^2}$
τ	A characteristic time	s

Nondimensional Quantities and Abbreviations

cst.	Constant	
M	Mach number	U/a
Z	Mixture fraction	
γ	Ratio of specific heats	c_p/c_v
ϑ	Stoichiometric coefficient	
ϕ	Equivalence ratio	
CJ	Chapman–Jouget	
ICF	Inertial confinement fusion	
DDT	Deflagration-to-detonation transition	
D-T	Deuterium-tritium	
SNI	Supernovae type I	
SNII	Supernovae type II	
ZND	Zeldovich–von Neumann–Döring	

Superscripts, Subscripts and Math Accents

a^*	Critical value
a_b	Burnt gas
a_{coll}	Collisions
a_{CJ}	Chapman–Jouget conditions
a_{diff}	Diffusion
a_e	Elecron
a_{nr}	Nuclear reaction
a_N	Neumann state (behind a shock)
a_r	Reaction
a_u	Unburnt gas

1.1 Introductory Remarks

In this introductory chapter we briefly introduce the physical background and the context of the phenomena that are studied in this book. The discussion is limited to orders of magnitude and dimensional analysis.

As first demonstrated by the experiments of Lavoisier at the end of the eighteenth century, combustion is an exothermic chemical reaction between a fuel, such as hydrogen or a hydrocarbon, and an oxidant, generally the oxygen of ambient air. The reaction rate is a strongly increasing function of temperature, leading to thermal self-acceleration. Due to the