CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

1

General Considerations

Nomenclature

Dimensional Quantities

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

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

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

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

thermal sensitivity, combustion occurs almost exclusively in thermal fronts. The concept of a well-stirred (homogeneous) reactor, widely used by chemists, is of only limited interest in practical combustion. Self-propagating exothermic reaction waves, flames (subsonic waves called also deflagrations) and detonations (supersonic waves) were identified in the nineteenth century. Self-consistent theoretical analyses of the dynamics of such waves and of the instabilities of their fronts started in the mid-twentieth century and are still in progress. The kinetics of heat release in combustion is complex; it involves hundreds of elementary reactions and tens of species. Examples are given in Chapter 5, while the basic elements of chemistry are recalled in Chapter 14. Hopefully most of the phenomena can be described using ultra-simplified chemistry schemes.

The dynamics of combustion waves is a key issue in different areas of physics. For example the deflagration-to-detonation transition, which is not yet fully understood, concerns not only the safety of power plants but also the explosion of stars in astrophysics.

With the development of nuclear physics during the twentieth century, astrophysicists explained how stars can maintain a quasi-stationary state of high temperature thanks to the energy released by nuclear fusion reactions, compensating the losses by radiation. These reactive phenomena have some analogies with ordinary combustion, but have also differences, arising mainly from the extreme conditions of temperature and density at which thermonuclear reactions occur. A short introduction to thermonuclear fusion is given in Section 1.3.1. In contrast to combustion on earth, the dynamics of reactive fronts in such extreme conditions is not yet a mature field, and a detailed presentation is outside the scope of this book. The explosion of stars during the gravitational collapse at the end of their lifetime, the famous supernovae that are typically 10^9–10^{10} times brighter than the sun, are fascinating phenomena that are not fully explained. Shock formation and/or the deflagration-to-detonation transition are expected to play essential roles in the outbursts of supernovae. In this book, which is mainly concerned with combustion on earth, these phenomena will be discussed in simple physical terms with the objective of extracting the basic mechanisms without entering into the details of nuclear physics.

Ablation fronts, which arise in inertial confinement fusion (ICF), will be discussed in the same spirit. The concept of this method of energy production, whose feasibility is not yet proved, is to burn a few milligrammes of nuclear fuel by imploding a spherical shell using high-power laser radiation. The ignition of a nuclear reaction at the central hot spot, compressed to more than 1000 times the density of liquids, depends critically on the control of hydrodynamic instabilities of the ablation front during the implosion. The similarities and differences with gaseous flames open new perspectives in the study of the dynamics of such thermal fronts.

1.2 Combustion Waves on Earth

1.2.1 Combustion Modes

Two different modes of combustion are identified according to whether the fuel and the oxidant are initially mixed at the molecular level or spatially separated. The former is called premixed combustion and the latter non-premixed.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

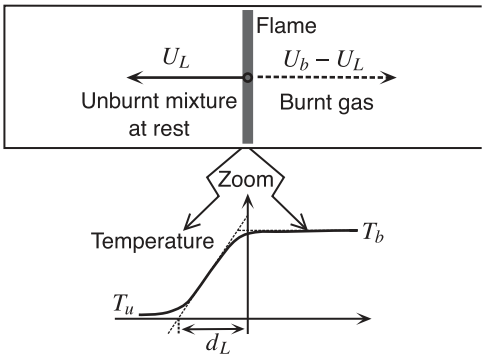

Figure 1.1 Planar flame propagating from the open to the closed end of a tube. The unburnt gas is at rest, and the flame propagates at a speed U_L with respect to the tube. The hot burnt gas flows out of the tube with velocity $U_L(T_b - T_u)/T_u$; see (2.1.2).

Propagating Waves

In premixed combustion (gaseous, liquid or solid), the reaction generally propagates through the initial mixture as a reaction wave, transforming reactants into combustion products. There are two very distinct types of propagating combustion waves, depending on the conditions of ignition:

- *Premixed flames* are very subsonic and quasi-isobaric since their propagation is governed by thermal conduction, and the term *deflagration* referred usually to fast flames essentially in turbulent flows.
- *Detonations* are supersonic waves composed of a shock wave with a strong pressure pulse, followed by a reaction zone.

These waves are thin, of a few tenths of a millimetre thick for flames and a few millimetres to centimetres for gaseous detonations in ordinary conditions. They are thus often assimilated to infinitely thin fronts whose instantaneous position is well defined. They transform fresh gas at temperature $T_u \approx 300\,\mathrm{K}$ into burnt gas at temperature $T_b \approx 1200$–$3000\,\mathrm{K}$.

For the case of a curved flame front propagating in a nonhomogeneous and/or nonstationary flow, the propagation speed is defined as the speed of the local normal to the front with respect to the initial reactive mixture just ahead of the front. This notion is well defined if the spatial and temporal scale of velocity variations in the upstream flow are much larger than the thickness of the flame and the transit time of a fluid particle across the flame, respectively. This is often the case. The propagation speed of a planar deflagration front in a quiescent reactive mixture, called the laminar flame speed and designated by U_L in the rest of this book, is defined without ambiguity; see Fig. 1.1.

In automobile petrol engines, a flame is ignited by a spark plug and propagates as a wrinkled premixed flame through the turbulent gas mixture confined in the cylinder. In a Bunsen flame such as that of Fig. 1.2, the conical premixed flame is stationary in the frame

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

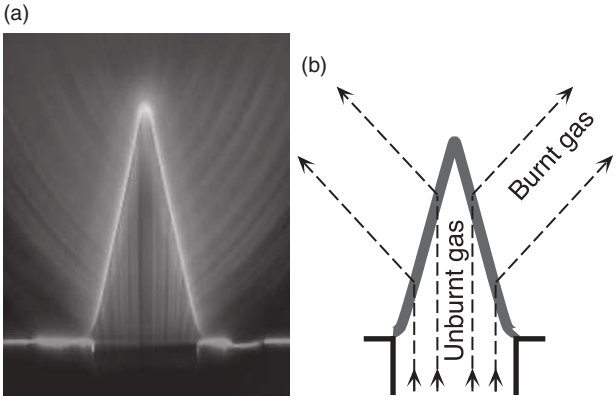

Figure 1.2 Bunsen flame. (a) Tomographic cut through a Bunsen flame. The unburnt gas is seeded with microscopic refractory solid particles, which diffuse the laser light sheet used to visualise the flow (courtesy of J.Quinard, IRPHE Marseilles). (b) The flow lines are strongly deflected through the flame front; see also Fig. 2.6.

of the burner. The unburnt reactive mixture flows out of the orifice in a laminar flow with a velocity greater than flame speed, U_L, and the inclination of the flame spontaneously adjusts itself so that the component of the gas flow normal to the flame front is equal to U_L. Increasing the flow rate will decrease the angle of the summit and increase the height of the cone.

For a planar flame, the product of the initial density of the unburnt gas and the laminar flame speed, $\rho_u U_L$, defines the mass of reactive mixture transformed into burnt products per unit time and per unit surface of a planar flame, $m = \rho_u U_L$. When the internal structure of the flame is not significantly modified by wrinkling of the front, the mass flow rate remains close to $\rho_u U_L$ and the total mass of gas burnt per unit time is given by $\rho_u U_L S$, where S is the total flame surface area. This is true when the wavelength of wrinkling is much greater than the thickness of the flame. However, at the tip of a Bunsen cone the curvature is very high and a particular study is required.

Non-Premixed Combustion

In non-premixed combustion, the fuel and the oxidant are separated by the reaction front, fed by diffusive fluxes, and the flame is called a diffusion flame; see Fig. 1.3. This mode of combustion does not propagate in the preceding sense, but propagation along the wall of a solid combustible is possible. It is the type of flame found in a candle or a cigarette lighter. In industrial gas-fired burners (furnace, boilers, ovens, etc.) the chemical reaction develops in the mixing layer between the jet of fuel gas and the ambient air (oxidant); see Fig. 1.4. In this book attention is focused on premixed systems, and diffusion flames will not be covered. For more detail, readers are referred to classical books.[1,2,3] A brief outline

[1] Williams F., 1985, *Combustion theory*. Menlo Park, Calif.: Benjamin/Cummings, 2nd ed.
[2] Turns S., 2000, *An introduction to combustion*. McGraw-Hill, 2nd ed.
[3] Law C., 2006, *Combustion physics*. Cambridge University Press.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

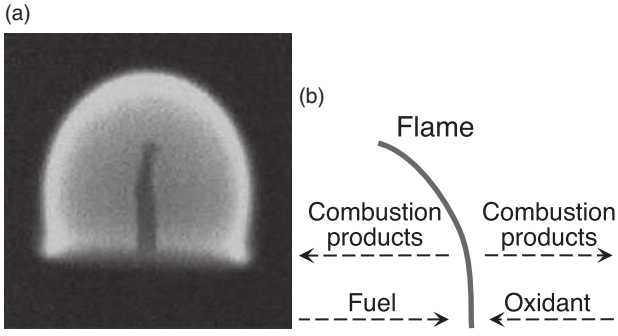

Figure 1.3 Photo of a candle flame in micro-gravity. In the absence of gravity-induced convection, the reaction zone is blue and the flame is hemispheric. (b) Diffusive fluxes in the region of the flame. The heat is evacuated in the same direction as the combustion products. Photo from nasa.gov website with thanks.

Figure 1.4 Diffusion flame in a sheared mixing layer. The black arrows represent the flow of fuel and oxidant separated by a wall, at the end of which the diffusion flame is anchored. Between pairs of roll-ups, stagnation points appear similar to that shown in Fig. 1.7, where the flame is locally stretched.

is presented in Section 1.2.4. The two types of flame (premixed and diffusion) can coexist in highly turbulent combustion chambers, when fuel and oxidant are injected separately.

1.2.2 Premixed Combustion

In this section we recall the basic concepts in the theory of premixed combustion.[1]

Combustion Temperature and Equivalence Ratio

The energy liberated by ordinary combustion comes from the change in binding energy between the atoms forming the molecules. The binding is due to interactions of the electrons in the external layers of the atomic structure. The order of magnitude of this energy is a few electron-volts (eV) per molecule, leading to a temperature increase of few thousand Kelvin; see Section 14.1.1.

The temperature of combustion of premixed gases results from a chemical equilibrium; see Section 14.2. This temperature varies with the composition of the mixture. It reaches a maximum when the proportion of fuel and oxidant is near stoichiometry, defined as the

[1] Clavin P., 1994, *Ann. Rev. Fluid Mech.*, **26**, 321–352.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

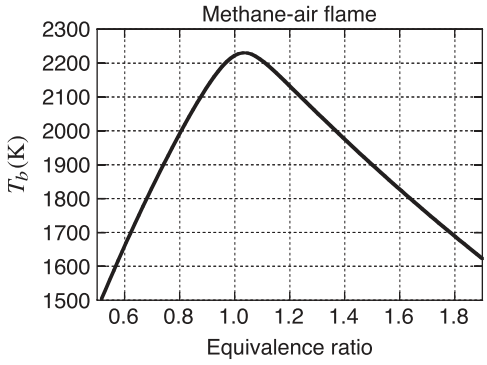

Figure 1.5 Calculated burnt gas temperature of methane–air flames as a function of equivalence ratio.

composition for which both are totally consumed, for example two moles of hydrogen mixed with one mole of oxygen, $2H_2+O_2 \rightarrow 2H_2O$. More generally, if ϑ_F^+ moles of fuel F fully react with ϑ_O^+ moles of oxidant O to form combustion products P: $\vartheta_F^+ F + \vartheta_o^+ O \rightleftharpoons P$, then a fresh mixture containing N_F moles of fuel and N_O moles of oxidant is said to have a stoichiometric composition if $N_F/N_O = \vartheta_F^+/\vartheta_O^+$.

The equivalence ratio ϕ of the mixture is defined by

$$\phi = \frac{N_F/N_O}{\vartheta_F^+/\vartheta_O^+}. \tag{1.2.1}$$

A stoichiometric mixture is characterised by $\phi = 1$. In a rich mixture, $\phi > 1$, the fuel is in excess and the combustion is limited by the oxidant. For lean mixtures, $\phi < 1$, the oxidant is in excess. An example of the evolution of the combustion temperature of methane–air flames with equivalence ratio is shown in Fig. 1.5.

Chemical Kinetics

The chemical kinetics controlling the reaction rate of the combustion of hydrogen and common hydrocarbon fuels is complex. Nevertheless the system has overall global properties that can be reasonably well approximated by simple kinetic models, described in Chapter 5. The overall chemical heat release rate increases very strongly with temperature, and the combustion rate undergoes a thermal runaway, which stops only when the minority reactant has been completely consumed. The energy release rate is significant only for temperatures typically above 1000 K. At room temperature a reactive mixture can be conserved indefinitely: the composition of the mixture is totally frozen far from thermo-chemical equilibrium. However, at high temperature, the characteristic reaction time (time to reach thermo-chemical equilibrium) is short, of the order of a few microseconds at the temperature produced by the exothermic reaction, typically 2000 K.

The thermal runaway in combustible mixtures can be described in macroscopic terms, as a function of the temperature and pressure. It is not necessary to invoke Boltzmann's equation. This is because the frequency of inelastic collisions, which liberate chemical

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

energy, is much lower than the frequency of the elastic collisions, which maintain the (Maxwell–Boltzmann) equilibrium distribution of velocity. In other words, a reactive molecule undergoes many elastic collisions before being transformed. The liberation of energy thus proceeds on a time scale that is long compared with the time needed to reach local equilibrium, and the temperature remains locally and globally a well-defined quantity during the chemical reaction.

Thermal Sensitivity and the Arrhenius Law

The characteristic reaction time, τ_r, of a first-order elementary reaction between two reactive species, $R_1 + R_2 \rightarrow P_1 + P_2$, is defined in a homogeneous medium by the evolution equation $\mathrm{d}n_1/\mathrm{d}t = -n_1/\tau_r$, where $n_1 = N_1/V$ is the number density of the limiting reactive species R_1. Usually, the reaction time τ_r is a function of the temperature, T, and proportional to the density n_2 of the species R_2. To simplify the presentation, we will limit the discussion in this section to the situation where the species R_2 is in great excess, such that the relative quantity consumed by the reaction is very small. The change of concentration is negligible in the expression for τ_r, which is then only a function of the temperature, T. For most gaseous combustible mixtures, far from the flammability limits, and over a wide range of temperature, the reaction rate is described by the Arrhenius law,

$$1/\tau_r \approx \mathrm{e}^{-E/k_BT}/\tau_{coll} \quad \text{with} \quad E/k_BT \gg 1, \tag{1.2.2}$$

where τ_{coll} is the mean time between elastic collisions of species R_1 with R_2, and E is an activation energy that is systematically greater than the mean energy of thermal agitation, k_BT, typically by an order of magnitude. The activation energy E can be interpreted as the energy that must be brought by the molecules into a collision in order to open bonds and initiate the chemical reaction. The exponential factor in the Arrhenius law comes from the Maxwell–Boltzmann distribution of velocities. It represents the fraction of the number of collisions (per unit time) in which the relative energy carried by the two molecules is greater than E. According to (1.2.2), the thermal sensitivity of the reaction rate increases as the ratio of activation energy to mean thermal energy, E/k_BT, increases: $\delta\tau_r/\tau_r \approx \delta\tau_{coll}/\tau_{coll} - (E/k_BT)\delta T/T$, where, according to (1.2.3), the sensitivity of the collision rate, $1/\tau_{coll}$, to temperature at constant pressure is only $T^{1/2}$, $\delta\tau_{coll}/\tau_{coll} \approx -(1/2)\delta T/T$, and can be neglected,

$$\delta\tau_r/\tau_r \approx -(E/k_BT)\delta T/T,$$

since, typically, $E/k_BT_b \sim 8$–12, where T_b is the maximum temperature in the flame, $T_b \sim 1200$–$3000\,\mathrm{K}$. The collision frequency can easily be evaluated by the elementary kinetic theory of gases as follows. The distance travelled by a molecule during a lapse of time δt is $a\delta t$ where $a \propto \sqrt{k_BT/\mathrm{m}_R}$ is the mean velocity of the molecules (of the order of the speed of sound), a few hundred metres per second for normal conditions, and m_R is the mass of a molecule. The volume swept, $a\sigma_o\delta t$, is expressed in terms of the collision cross section $\sigma_o = 4\pi r_o^2$ where r_o is the range of action of inter-molecular forces (a few angstroms, $10^{-10}\,\mathrm{m}$). Introducing n, the number density of particles, the number of

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

collisions experienced by the test particle is $na\sigma_o\delta t$, and the number of collisions per unit time is $na\sigma_o$. The mean free path ℓ, namely the mean distance travelled by a molecule between two collisions, is obtained by the ratio of the distance travelled to the number of collisions,

$$\ell = 1/(n\sigma_o), \qquad 1/\tau_{coll} = na\sigma_o; \tag{1.2.3}$$

see Section 13.3. This leads to a temperature dependence of τ_{coll} as $T^{-1/2}$ at constant pressure, $p = nk_BT$.

The Arrhenius law (1.2.2) then describes a strong variation of the reaction rate with temperature. For example, taking a typical value for $E/k_BT_b = 8$, the Arrhenius factor at the temperature of the burnt gas is $\mathrm{e}^{-E/k_BT_b} \approx 3 \times 10^{-4}$. So, for a typical mean time between elastic collisions of one nanosecond, $\tau_{coll} \approx 10^{-9}$ s, the characteristic reaction time in the burnt gas is of the order of 1 s, $\tau_r(T_b) \approx \tau_{coll}\,\mathrm{e}^{E/k_BT_b} \approx 3\times 10^{-6}$ s. However, at room temperature T_u, $T_b/T_u \approx 8$, $E/k_BT_u = 64$, the characteristic reaction time $\tau_r(T_u) \approx \tau_{coll}\,\mathrm{e}^{E/k_BT_u}$ is of the order of 6×10^{18} s, which is longer than the estimated age of the universe $\approx 4 \times 10^{17}$ s, or 13×10^9 years! The reaction rate given by the Arrhenius law is thus completely negligible at room temperature. The high sensitivity of the reaction rate to temperature makes premixed flames very different from the reaction–diffusion waves encountered in other fields, as for example in biophysics; see Section 8.3.

Cut-Off Temperature, Flammability Limits

The Arrhenius law (1.2.2) is a drastic simplification that is nevertheless useful to analyse the thermal propagation of flames and detonations. However, certain details of chemical kinetics also play an essential role, as explained in Chapter 5. This is the case, for example, when the limits of flammability or detonability are approached. These limits correspond to brutal transitions in the energy release rate. The behaviour of flames at these limits can be qualitatively represented in a simple but discontinuous model by introducing a cut-off temperature $T^* \approx 1000$ K; see (9.1.1) and (9.1.2). The reaction rate is given by (1.2.2) for temperatures above cut-off, $T > T^*$, but drops to zero below T^*, corresponding to the crossover of chain-branching and chain-breaking reactions; see Section 5.2.2.

Cool Flames

The chemical reaction never stops suddenly below T^*, but the nature of the oxidation reaction changes completely. The combustion is incomplete; the initial reactants are not transformed into stable species such as water vapour and carbon dioxide, which are the major species produced at thermo-chemical equilibrium. Instead, the initial reactive species are degraded to form relatively stable intermediate species, or more exactly metastable species, such as peroxides, or aldehydes, such as formaldehyde. Only a small part of the available chemical energy is released, and the characteristic reaction time increases rapidly as the combustion temperature drops below T^*. For common hydrocarbon molecules, the cut-off temperature is in the range 900–1300 K. The chemical reactions that take place at low temperature, $T < T^*$, play no significant role in the propagation of normal flames.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-09868-8 — Combustion Waves and Fronts in Flows
Paul Clavin , Geoff Searby
Excerpt
More Information

Nevertheless, chemical waves, and even successions of waves (called 'cool flames' since they release little energy) can propagate below T^*. They can be produced in special laboratory conditions.[1] The analytical study of such reaction–diffusion waves[2] show that they have nothing to do with ordinary flames, and they will not be treated in this book.

Dimensional Analysis

Several mechanisms participate in the propagation of laminar combustion fronts: the amount and rate of heat release, the transport of heat and mass, and also compressible phenomena characterised by the speed of sound. In usual gaseous flames and detonations, the radiative transfer of heat is weak and can be neglected compared with diffusive transport. The physical mechanisms can then be characterised by the following quantities:

- The amount of chemical energy, q_m, released per unit mass of the mixture. This energy is of the order of the square of the sound speed in the burnt gas, a_b^2, which is typically four to ten times larger than in the fresh mixture, $(a_b/a_u)^2 \approx T_b/T_u$.
- The exothermic reaction rate, $1/\tau_r$, which is a strongly increasing function of the temperature of the gas.
- The molecular and thermal diffusion coefficients, D, which all have the same order of magnitude in a gas.

Using dimensional analysis, it is possible to construct different velocities from these parameters. It will be seen that the orders of magnitude for the propagation velocity of laminar flames are $\sqrt{D/\tau_r(T_b)}$, and $\sqrt{q_m}$ for detonations.

1.2.3 Flames in Premixed Gas

In ordinary premixed combustion, the initial thermodynamic state of the reactants can be gaseous, liquid (such as nitromethane or nitroglycerin[1]) or solid, such as the propellants used in missiles and rocket engines. The temperature of the combustion products T_b is determined by the heat of reaction (the chemical energy that is released) and is generally in the range 1200–3000 K for air-based combustion. Since the exothermic reaction can proceed only if the temperature is sufficiently high, typically above 1000 K, the reaction zone is almost systematically located in the gas phase.[2] In the rest of this book we will consider gaseous mixtures.

[1] To be exact, nitromethane and nitroglycerin are not mixtures of reactants, but *monopropellants*, i.e. metastable molecules, which decompose under the action of heat to release heat and combustion products.
[2] One notable exception is the oxidation of solid carbon (charcoal).

[1] Lewis B., von Elbe G., 1961, *Combustion flames and explosions of gases*. Academic Press.
[2] Nicoli C., et al., 1990, In P. Gray, G. Nicolis, F. Barras, P. Borkmans, S. Scott, eds., *Spatial inhomogeneities and transient behavior in chemical kinetics*, 317–334, Manchester University Press.

© in this web service Cambridge University Press www.cambridge.org