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Structure and Dynamics of Combustion Waves in Premixed Gases

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*Theoretical analyses (analytical studies of simplified models)
+ laboratory experiments*



Contents

- Lecture 1: Orders of magnitude
- Lecture 2: Governing equations
- Lecture 3: Thermal propagation of flames
- Lecture 4: Hydrodynamic instability of flames
- Lecture 5: Thermo diffusive phenomena
- Lecture 6: Thermal quenching and flammability limits
- Lecture 7: Flame kernels and quasi-isobaric ignition
- Lecture 8: Thermo-acoustic instabilities. Vibratory flames
- Lecture 9: Turbulent flames
- Lecture 10: Supersonic waves
- Lecture 11: Initiation of detonations
- Lecture 12: Galloping detonations
- Lecture 13: Stability analysis of shock waves
- Lecture 14: Nonlinear dynamics of shock waves. Mach stem formation
- Lecture 15: Cellular detonations

Combustion is a fascinating phenomenon coupling complex chemistry to transport mechanisms and nonlinear fluid dynamics. This book provides an up-to-date and comprehensive presentation of the nonlinear dynamics of combustion waves and other non-equilibrium energetic systems. The major advances in this field have resulted from analytical studies of simplified models performed in close relation with carefully controlled laboratory experiments. The key to understanding the complex phenomena is a systematic reduction of the complexity of the basic equations.

Focusing on this fundamental approach, the book is split into three parts. Part I provides physical insights for physics-oriented readers, part II presents detailed technical analysis using perturbation methods for theoreticians, and part III recalls the necessary background knowledge in physics, chemistry and fluid dynamics. This structure makes the content accessible to newcomers to the physics of unstable fronts in flows, whilst also offering advanced material for scientists who wish to improve their knowledge.

Paul Clavin is Professor Emeritus at Aix-Marseille Université and is an honorary member of the Institut Universitaire de France (Chair of Mécanique Physique 1993-2004). In 1995 he founded a renowned research institute, the Institut de Recherche sur les Phénomènes Hors Équilibre (IRPHE) and has received major awards from the Société Française de Physique (Plumey 1988), French Academy of Sciences (Grand Prix 1995) and from the Combustion Institute (Zeldovich Gold medal, San Francisco, August 2014).

Geoff Searby is retired Director of Research at the Institut de Recherche sur les Phénomènes Hors Équilibre (IRPHE). He is a renowned specialist of the physics of thermo-acoustic instabilities in combustion chambers and rocket motors, and his experiments have made major contributions to the understanding of the dynamics of flame fronts. In 2004 he obtained a major award from the French Academy of Sciences.

Cover illustration: TBC

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Clavin and Searby

Combustion Waves and Fronts in Flows

CAMBRIDGE

Combustion Waves and Fronts in Flows

Flames, Shocks, Detonations, Ablation Fronts
and Explosion of Stars

Paul Clavin and Geoff Searby



Lecture 1: Orders of magnitude

1-1: Overall combustion chemistry

1-2: Combustion waves in gaseous mixtures

1-3: Arrhenius law

1-4: Hydrocarbon/air flames

1-5: Instabilities of flames

I – 1) Overall combustion chemistry

reactants → products + heat release

Lavoisier 1777



binding energy of small molecules \approx a few eV

$$1\text{eV/molecule} \approx 23 \text{ kcal/mole} \Rightarrow T_b - T_u \approx 2000 \text{ K} \\ (C_p \approx 10 \text{ cal/mole/K})$$

reaction time $\tau_r(T)$ extremely sensitive to temperature:

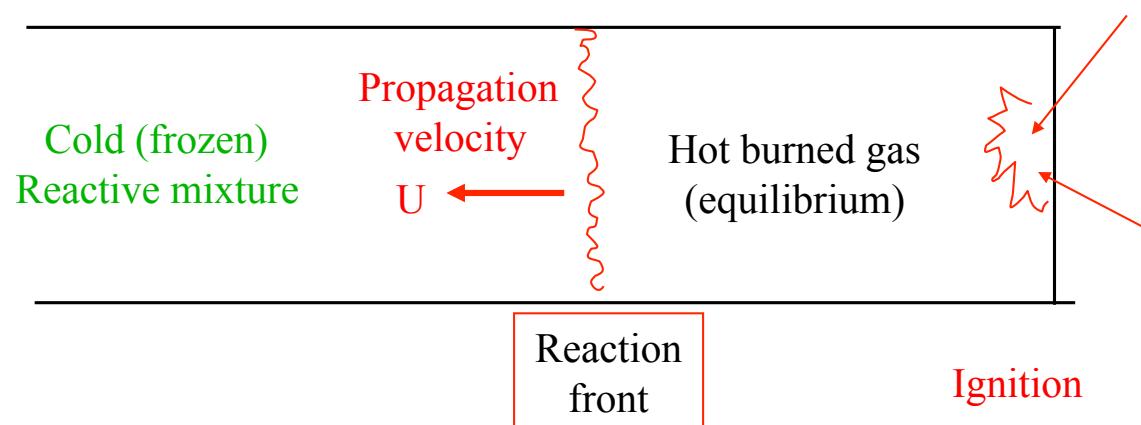
$T < 500K : \tau_r(T) \approx \infty$ (frozen mixture of reactants)

$T \approx 2500K : \tau_r(T) \approx 10^{-6}s.$

Euler 1738



thermal feedback \Rightarrow combustion waves



Davy 1830



I – 2) Combustion waves in premixed gaseous mixtures

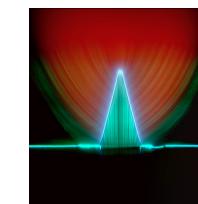
Flames : $10 \text{ cm/s} - 10 \text{ m/s}$, $\Delta p/p \approx -10^{-5}$

acetylyen/oxygen

Laminar propagation



E.Mallard
H.L. Chatelier
Mallard, Le Chatelier 1883



Laser Tomography
L.Boyer 1980

Bec Bunsen
J. Quinard 2000

Fast deflagrations : $\approx 100 \text{ m/s}$, $\Delta p/p \approx -10^{-1}$

Turbulent propagation



John H.S. Lee 1990

Detonations : $\approx 2000 \text{ m/s}$, $\Delta p/p \approx +30$

Cellular structure



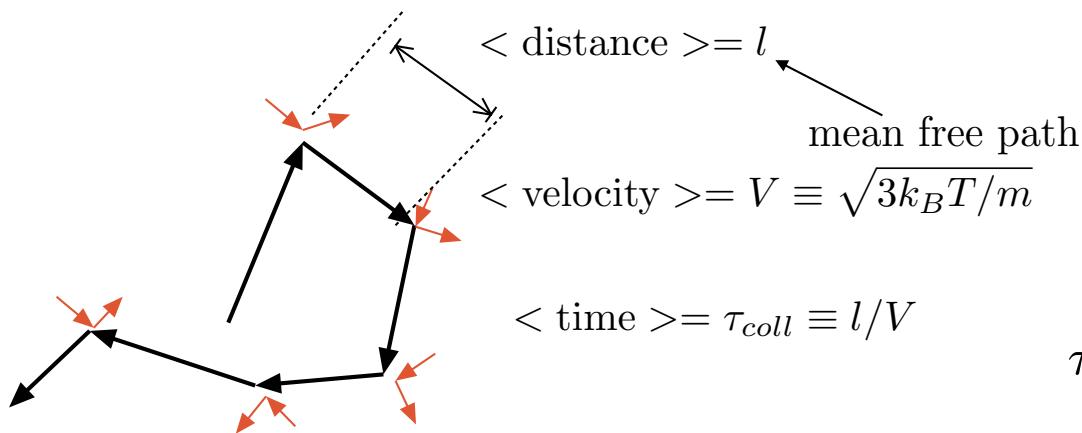
Berthelot, Vielle 1884



Shchelkin 1960

Back to the kinetic theory of gases

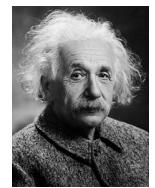
Binary collisions of molecules



Maxwell 1867



Boltzmann 1877



Einstein 1905

speed of sound: $a \approx V$

τ_{coll} : collision time \approx relaxation time

Equilibrium state. The Maxwell-Boltzmann distribution

m : mass of molecules, n : number density, T : temperature, k_B : Boltzmann cst.

$$f^{(eq)}(\mathbf{v}, n, T) d^3\mathbf{v} d^3\mathbf{r} = n \frac{m^{3/2}}{(2\pi k_B T)^{3/2}} e^{-m|\mathbf{v}|^2/(2k_B T)} d^3\mathbf{v} d^3\mathbf{r}$$

velocity of molecules element of volume

Molecular diffusion \equiv Random Walk

spreading :

$$\frac{1}{(4\pi D t)^{3/2}} e^{-r^2/4Dt}$$

$$D = lV = l^2/\tau_{\text{coll}} \approx a^2\tau_{\text{coll}}$$

Diffusion coefficient

Dimensional parameters

chemical energy/unit mass $q_m \Rightarrow T_b/T_u = 5 - 10$

sound speed, $a_b/a_u = \sqrt{T_b/T_u}$

reaction rate $1/\tau_r(T_b)$

molecular and thermal diffusion coefficients $D \approx D_T$

Dimensional analysis

$$[q_m] = (\text{velocity})^2$$

propagation velocity

$$[D] = (\text{velocity})^2 \times \text{time}$$

$$D \approx 10^{-3} \text{ m}^2/\text{s}$$

detonation: $\mathcal{D} \approx \sqrt{q_m} \approx a_b$

supersonic $\mathcal{D}/a_u > 1$

supersonic $\mathcal{D}/a_u > 1$

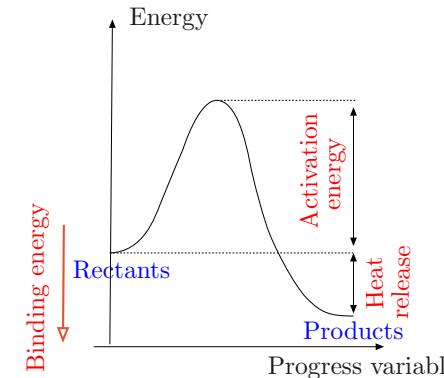
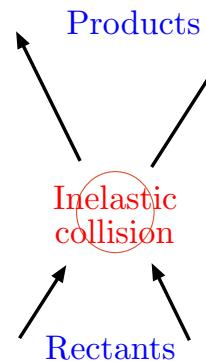
laminar flames: $U_L \approx \sqrt{D/\tau_r(T_b)}$

subsonic $U_L/a_u < 1$

subsonic $U_L/a_u < 1$

I – 3) Overall reaction rate. Arrhenius factor

Collision in gases



$$\frac{E}{k_B T_b} \approx 8$$

$$e^{-E/k_B T_b} \approx 3 \times 10^{-4}$$

$$T_b/T_u = 8 \Rightarrow e^{-E/k_B T_u} \approx 1.6 \times 10^{-28}$$

Kinetic theory of gases \Rightarrow Arrehnius law

$$\text{MB distribution } \propto e^{-\frac{1}{2} \frac{mv^2}{k_B T}} \Rightarrow \frac{1}{\tau_r(T)} = \frac{1}{\tau_{coll}} e^{-E/k_B T}$$

Arrhenius factor

elastic collision rate $1/\tau_{coll} \approx 10^9 \text{ s}^{-1}$

$$\Rightarrow 1/\tau_r(T_b) \approx 3 \times 10^5 \text{ s}^{-1}$$

$$T_b/T_u = 8 \Rightarrow \tau_r(T_u) \approx 10^{10} \text{ years !!}$$

Kinetic theory of gases \Rightarrow Flame properties
sound speed

$$D \approx a^2 \tau_{coll} \approx l^2 / \tau_{coll}$$

men free path

$$U_L \approx \sqrt{D_T / \tau_r}$$

laminar flame velocity

subsonic

sound speed

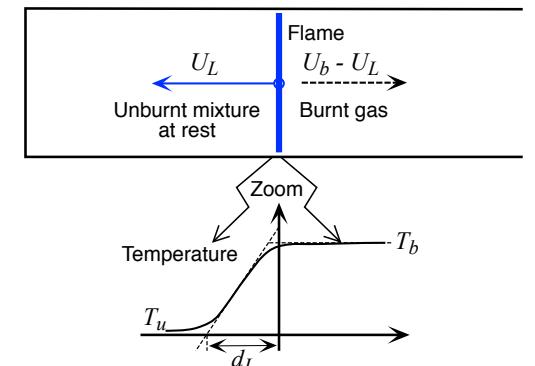
$$d_L \approx D_T / U_L$$

macroscopic structure

flame thickness

$$d_L \approx l \sqrt{e^{E/k_B T_b}} \gg l$$

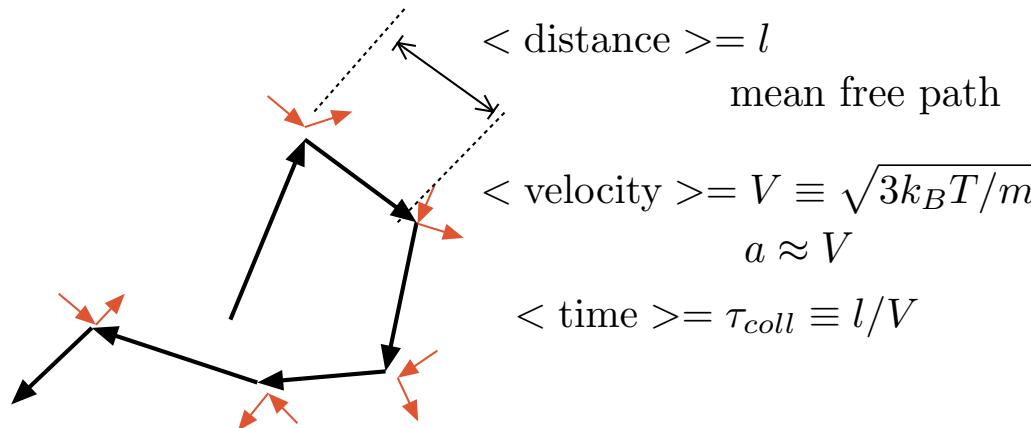
mean free path



Molecular diffusion \equiv Random Walk



Maxwell 1867 Boltzmann 1877 Einstein 1905



spreading :
$$\frac{1}{(4\pi Dt)^{3/2}} e^{-r^2/4Dt}$$

$$D = lV = l^2/\tau_{coll} \approx a^2\tau_{coll}$$

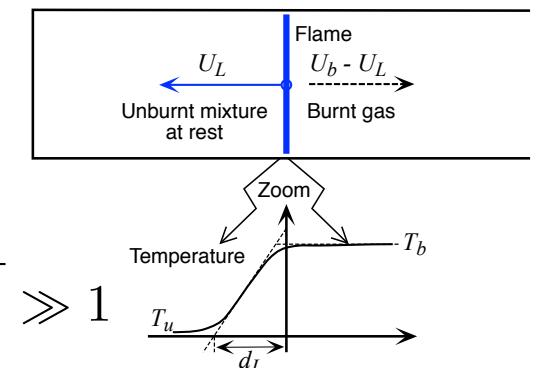
Flame structure

$$U_L \approx \sqrt{D/\tau_r(T_b)}$$

$$\frac{1}{\tau_r(T_b)} = \frac{1}{\tau_{coll}} e^{-E/k_B T_b}$$

$$U_L/a \approx \sqrt{e^{-E/k_B T_b}} \ll 1$$

$$d_L/l \approx U_L \tau_r / l \approx \sqrt{D \tau_r} / l \approx \sqrt{e^{E/k_B T_b}} \gg 1$$



Limitations of the dimensional analysis

$$\left. \begin{array}{l} e^{-E/k_B T_b} \approx 3 \times 10^{-4} \\ a \approx 500 \text{ m/s} \\ l \approx 10^{-7} \text{ m} \end{array} \right\} \Rightarrow$$

$$U_L \approx 8.6 \text{ m/s}$$

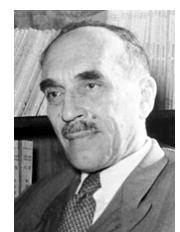
$$d_L \approx 0.6 \times 10^{-5} \text{ m}$$

!!

too large

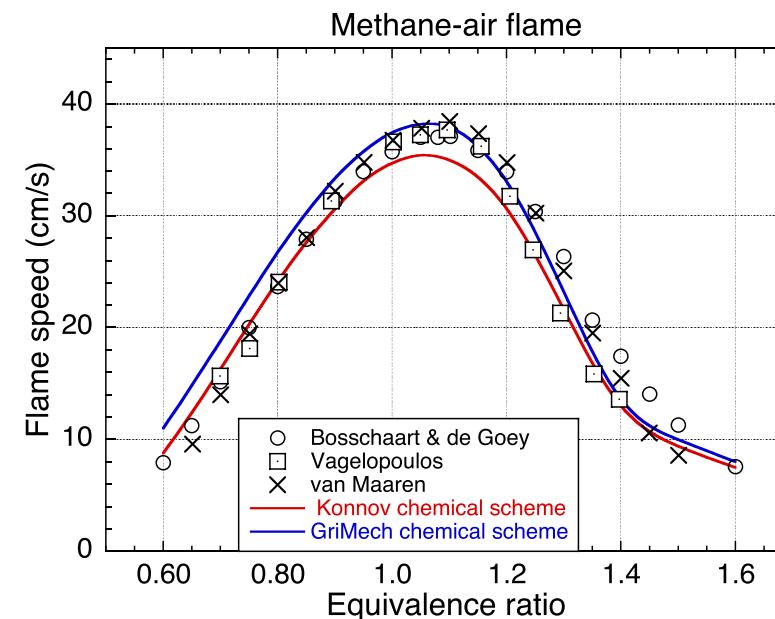
too small

10 – 50 cm/s
hydrocarbon/air
 $1 - 10^{-1}$ mm



I – 4) Hydrocarbon/air flames

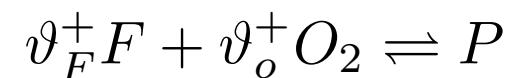
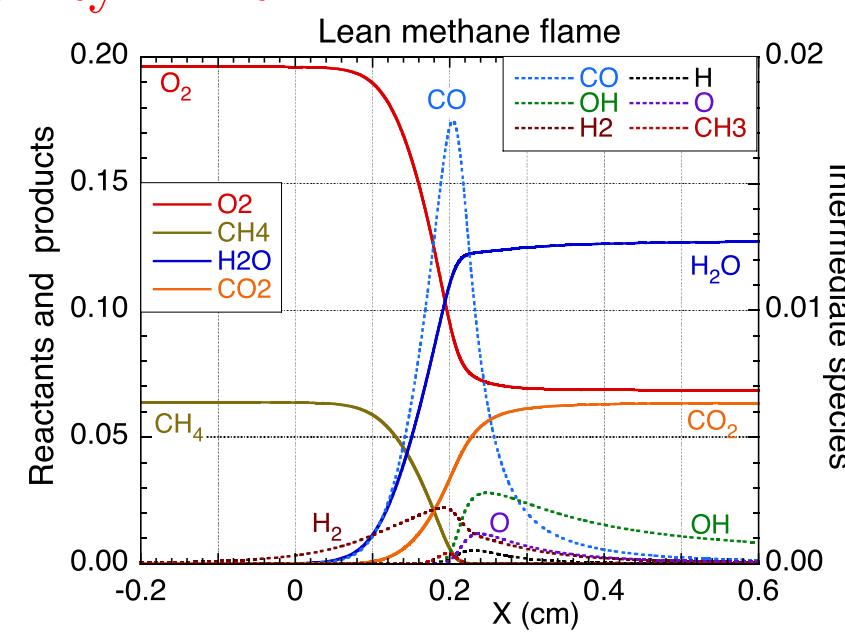
Methane-air flame



near to the flammability limit

$$\phi = 0.65$$

”thicker flame”



Equivalence ratio

$$\phi = \frac{N_F / N_{O_2}}{\vartheta_F^+ / \vartheta_{O_2}^+}$$

$\phi = 1$: stoichiometry

$\phi > 1$: fuel rich

$\phi < 1$: fuel lean

$$d_L \approx U_L \tau_r(T_b)$$

$$\approx \sqrt{D_T \tau_r(T_b)}$$

$$\approx D_T \sqrt{\tau_r(T_b) / D_T}$$

$$\approx D_T / U_L$$

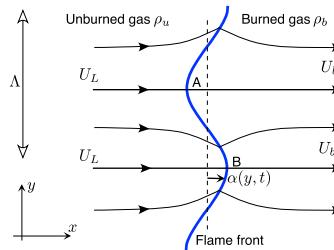
$$U_L \searrow \quad d_L \nearrow$$

I – 5) Instabilities of flames

Intrinsic instabilities

Planar flames are linearly unstable:

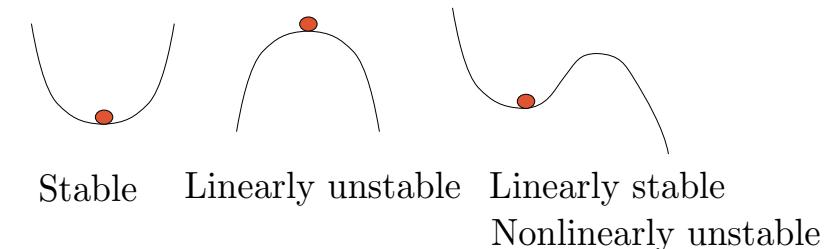
- hydrodynamic instability of the flame front



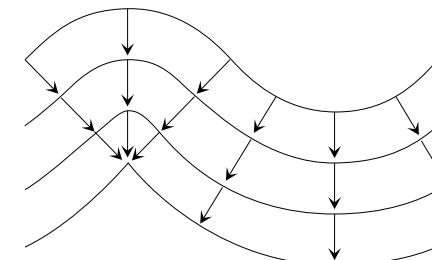
induced flow



Propane lean flame

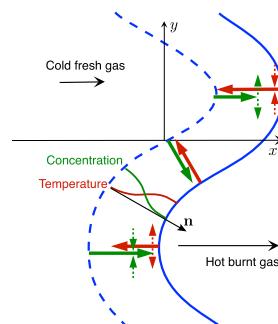


$$\rho_u > \rho_b$$



Cusp formation
Huygens construction

- diffusional-thermal instability of the inner flame structure



Unstable inner structure



Propane rich flame

$$D_T < D$$

System instability (combustion in a cavity)

The coupling of flames with acoustics can be unstable

Thermo-acoustic instabilities (Rayleigh criterion)



Lord Rayleigh 1878

Combustion chambers

Rocket engine

Gas turbines

Vibratory instability of flames in tubes

Lean methane-air flame

$$\phi = 0.73 \quad U_L = 23 \text{ cm/s}$$

$$\phi = 0.8 \quad U_L = 30 \text{ cm/s}$$

Acoustic instability in Premixed Flames

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G. Searby

G. Searby IRPHE 2006

Tomography cut: L. Boyer 1980

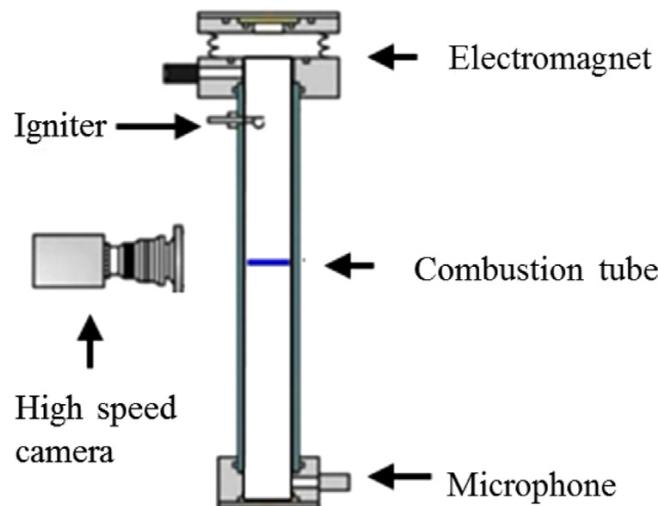
Last symposium on combustion (2018)

Effect of geometrical parameters on thermo-acoustic instability
of downward propagating flames in tubes

Ajit Kumar Dubey, Yoichiro Koyama, Nozomu Hashimoto, Osamu Fujita

Division of Mechanical and Space Engineering, Hokkaido University, Kita 13 Nishi 8 Kita-ku, Sapporo, Hokkaido, 930-8555, Japan

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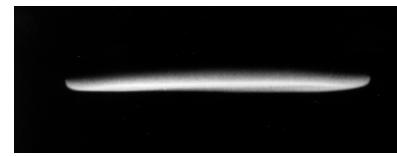


Effect of acceleration

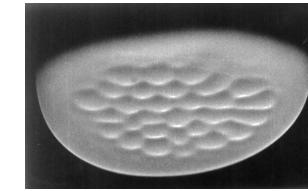
Gravity



Propane flame propagating upwards

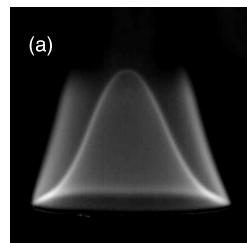


Slow downwards propagating flame

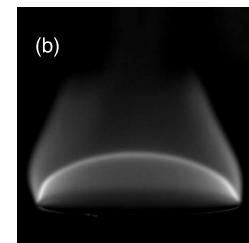


slightly faster

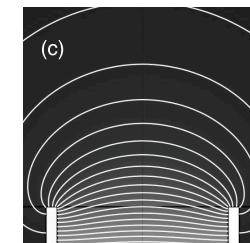
Effect of an acoustic field on a Bunsen flame



Methane rich Bunsen flame
 $\phi = 1.5$



in the presence of
an axial acoustic field



equipotential surface
in the absence of flame