Tsinghua-Princeton-CI Summer School
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Lectures on Dynamics of Combustion Waves in Premixed Gases

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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

Lecture 2: Governing equations

2-1. Conserved extensive quantities

2-2. Continuity

2-3. Fick's law. Diffusion equation

2-4. Conservation of momentum

2-5. Conservation of total energy

Thermal equation

Inviscid flows in reactive gases

Conservative forms

One-dimensional inviscid and compressible flow

2.6. Entropy production

Lecture 3: Thermal propagation

3-1. Quasi-isobaric approximation (Low Mach number)

3-2. One-step irreversible reaction

3-3. Unity Lewis number and large activation energy

3-4. Zeldovich & Frank-Kamenetskii asymptotic analysis

Preheated zone

Inner reaction layer

Matched asymptotic solution

3-5. Reaction diffusion waves

Phase space

Selected solution in an unstable medium

Lecture 4 : Hydrodynamic instability of flames

4-1. Jump across an hydrodynamic discontinuity

4-2. Linearized Euler equations of an incompressible fluid

4-3. Conditions at the front

4-4. Dynamics of passive interfaces

4-5. Darrieus-Landau instability

4-6. Curvature effect: a simplified approach

Lecture 5: Thermo-diffusive phenomena

5-1. Flame stretch and Markstein numbers

Passive interfaces

One-step flame model

The second Markstein number

5-2. Thermo-diffusive instabilities

Planar flames for Le $\neq 1$

Jump conditions across the reaction layer

Linear equations and linear analysis

Cellular instability (Le < 1)

Oscillatory instability (Le > 1)

Lecture 6: Thermal quenching and flammability limits

6-1. Extinction through thermal loss

6-2. Basic concepts in chemical kinetics

Combustion of hydrogen

Two-step model. Crossover temperature

One-step model with temperature cutoff

6-3. Flame speed near flammability limits

Lecture 7: Flame kernels and quasi-isobaric ignition

Lecture 8: Thermo-acoustic instabilities

Lecture 8-1. Rayleigh criterion

Acoustic waves in a reactive medium
Sound emission by a localized heat source
Linear growth rate

Lecture 8-2. Admittance & transfer function

Flame propagating in a tube
Pressure coupling
Velocity and acceleration coupling

Lecture 8-3. Vibratory instability of flames

Acoustic re-stabilisation and parametric instability (Mathieu's equation)
Flame propagating downward (sensitivity to the Markestein number)
Bunsen flame in an acoustic field

Lecture 9 : Turbulent flames

9-1. Introduction

9-2. Turbulent diffusion

Einstein-Taylor's diffusion coefficient

Rough model of turbulent transport

Well-stirred flame regime

9-3. Strongly corrugated flammelets regime

Kolmogorov's cascade

Gibson's scale

Elements of fractal geometry

Self similarity of strongly corrugated flames

Co-variant laws

9-4. Turbulent combustion noise

Monopolar sound emission

Sound generated by a turbulent flame

Blow torch noise

Lecture 10 : Supersonic waves

10-1. Background

Model of hyperbolic equations for the formation of discontinuity

Riemann invariants

Rankine-Hugoniot conditions for shock waves

Mikhelson (Chapman-Jouguet) conditions for detonations

10-2. Inner structure of a weak shock wave

Formulation

Dimensional analysis

Analysis

10-3. ZND structure of detonations

10-4. Selection mechanism of the CJ wave

Lecture 11: Initiation of detonation

11-1. Direct initiation

Flow of burnt gas in spherical CJ detonations
Point blast explosions
Zeldovich criterion
Critical energy

11-2. Spontaneous initiation and quenching

Initiation at high temperature
Spontaneous quenching

11-3. Deflagration-to-detonation transition

Basic ingredients
Experiments
Runaway phenomenon
Mechanisms of DDT

Lecture 12 : Galloping detonations

12-1. Physical mechanisms

Instability mechanism

Two limiting cases

12-2. General formulation

Constitutive equations

Strong shock in the Newtonian approximation

12-3. Strongly overdriven regimes in the limit $(\gamma - 1) \ll 1$

Distinguished limit

Integral-differential equation for the dynamics

Oscillatory instability

12-4. CJ detonations for small heat release

Reactive Euler equations in 1-D geometry

Near CJ regimes for small heat release. Transonic reacting flows

Slow time scale

Asymptotic model for CJ or near CJ regimes

Results for simplified chemical kinetics

Lecture 13 : Stability analysis of shock waves

13-1. Acoustic waves and entropy-vorticity wave

Linearized Euler equations

Linearized flow field

13-2. Analyses

Dispersion relation for general materials

Classification of normal modes

Spontaneous emission of sound and instability

Stability of shocks in ideal gases

Stability of reacting shocks

Lecture 14: Nonlinear dynamics of shock waves Mach stem formation

14-1. Experimental and DNS results

What is a Mach stem ?

Mach stems and cellular detonations

Spontaneous formation of Mach stems

14-2. Multidimensional dynamics of shock fronts

Linear dynamics

Weakly nonlinear analysis

14-3. Shock-vortex interaction

Formulation

Analysis of the crossover

14-4. Shock-turbulence interaction

Composite solution

Model equation

Comparison with DNS

Lecture 15 : Cellular detonations

15-1. Cellular detonations at strong overdrive

Order of magnitude. Scaling

Formulation

Outer flow in the burnt gas

Inner structure

Matching

Linear growth rate

Weakly nonlinear analysis

15-2. Cellular instability near the CJ condition

Formulation

Scaling

Model for CJ or near CJ regimes

Multidimensional stability analysis