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WORKSHOP ON SPACE PHYSICS:
"Materials in Micorgravity"
27 February - 17 March 1989

"Combustion"

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WORKSHOP ON SPACE PHYSICS :
MATERIALS IN MICROGRAVITY.

LECTURES ON COMBUSTION
by
I. GÖKALP
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OUTLINE

1. GENERAL INTRODUCTION
2. TURBULENT COMBUSTION
3. DROPLET AND SPRAY COMBUSTION
4. MICRO-GRAVITY COMBUSTION

COMBUSTION

Required Text:

1. Williams, F. A., Combustion Theory, 2nd Edn, Benjamin/Cummings Publishing Co., Menlo Park, CA, 1985.

Recommended Text:

2. Kuo, K. K., Principles of Combustion, Wiley, 1986.

Other Texts:

3. Rosner, D. E., Transport Processes in Chemically Reacting Flow Systems, Butterworths, 1986.

4. Lewis, B., and von Elbe, G., Combustion, Flames and Explosions of Gases, 3rd Edn, Academic Press, 1987.

5. Spalding, D. B., Combustion and Mass Transfer, Pergamon, 1979.

6. Glassman, I., Combustion, Second Edition, Academic Press, 1987.

7. Kanury, A. M., Introduction to Combustion Phenomena, Gordon and Breach, 1975.

8. Chigier, N. A., Energy, Combustion and Environment, McGraw-Hill, 1981.

9. Strehlow, R. A., Combustion Fundamentals, McGraw-Hill, 1984, International Textbook Co.

Scientific Monographs:

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11. Eckbreth, A. C., Laser Diagnostics for Combustion Temperature and Species, Abacus Press, Tunbridge Wells, UK, 1988.

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19. Mulcahy, M. F. R., Gas Kinetics, Thomas Nelson, 1973.

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21. Kollmann, W. (Editor), Prediction Methods for Turbulent Flows, Hemisphere, Washington, 1980.

22. Bradley, J. N., Flame and Combustion Phenomena, Methuen, 1969.

23. Putman, A. A., Combustion Drive Oscillations in Industry, Elsevier, 1971.

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30. Oppenheim, A. K., Introduction to Gasdynamics of Explosions, CISM, Udine, Italy and Springer-Verlag, 1972.

Applications and Technology:

31. Drysdale, D., Fire Dynamics, Wiley, 1985.

32. Lefebvre, A. H., Gas Turbine Combustion, Hemisphere/McGraw-Hill, 1983.

33. Heywood, J. B., Internal Combustion Engines Fundamentals, McGraw-Hill, 1988.

34. Ferguson, C. J., Internal Combustion Engines, Wiley, 1986.

35. Khalil, E. E., Modelling of Furnaces and Combustors, Abacus Press, Tunbridge Wells, UK, 1982.

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Serials

1. Symposia (International) on Combustion, The Combustion Institute, Pittsburgh, PA.

2. Combustion and Flame, Elsevier.

3. Combustion Science and Technology, Gordon and Breach.

4. Progress in Energy and Combustion Science, Pergamon.

5. Institute of Energy, Journal, London (formerly Institute of Fuel, Journal).

GENERAL OBJECTIVES OF REDUCED GRAVITY COMBUSTION RESEARCH

- TO HELP TO UNDERSTAND AND ANALYZE EARTH-BASED COMBUSTION PHENOMENA BY ELIMINATING SEVERAL COMPLEX COUPLINGS BETWEEN BUOYANT, INERTIAL AND VISCOUS FORCES

Examples :

- Counter gradient diffusion in turbulent premixed flames
- The role of buoyancy in the balance of turbulent kinetic energy in turbulent flames
- The role of buoyancy in the stability of laminar flames

- TO HELP TO UNDERSTAND AND ANALYZE SPACE-BASED COMBUSTION PHENOMENA

Example :

- Flame spread along solid surfaces under reduced gravity conditions (fire safety considerations on board a spacecraft)

THE RELATIVE IMPORTANCE OF BUOYANCY CAN BE REPRESENTED BY THE GRASHOFF NUMBER

$$Gr = g L^3 \frac{\Delta T}{T \nu^2}$$

g : ACCELERATION OF THE GRAVITY

L : CHARACTERISTIC LENGTH SCALE

ΔT : CHARACTERISTIC TEMP. CHANGE

T : TEMP. OF THE MEDIUM

ν : KINEMATIC VISCOSITY OF THE GASEOUS MEDIUM

TAKING $Gr \simeq 1$ AS THE UPPER LIMIT OF CONDITI WHERE BUOYANCY EFFECTS CAN BE NEGLECTED, AN NOTING THAT $\Delta T / T \simeq 1$ FOR COMBUSTION PROCES.

⇓

$L \sim 100\ \mu m$ AT ATMOSPHERIC PRESSURE

UNFORTUNATELY, EXPERIMENTS ON SUCH SCALES CANNOT BE RESOLVED BY EXISTING OR ANTICIPATED COMBUSTION INSTRUMENTATION.

1. GENERAL INTRODUCTION

1. WHAT IS COMBUSTION

1.1. A: CONTROLLED BURNING S.
1.1. B: UNCONTROLLED BURNING S.

1.1 A: EXAMPLES

- BURNING OF FUELS IN FURNACES TO
  - RAISE STEAM
  - HEAT AIR
  - CARRY OUT PYROMETALLURGICAL PROCESSES

- BURNING OF FUELS IN ENGINES TO
  - PRODUCE POWER
  - THRUST

- BURNING IN INCINERATORS TO
  - CONTROL WASTES

1. B. EXAMPLES

- BURNING OF COMBUSTIBLE MATERIALS IN
  - GASEOUS EXPLOSIONS
  - DUST EXPLOSIONS

- FIRES IN
  - FOREST
  - STRUCTURAL ELEMENTS
  - LIQUID POOLS

1. 2. WHAT IS A COMBUSTIBLE MATERIAL?

WOOD	METHANOL
CHARCOAL	NATURAL GAS
COAL	COAL GAS
WASTES	COKE OVENS GAS
PETROL	LIQUEFIED PETROLEUM GAS (LPG)
KEROSENE	WHEAT DUST
FUEL OIL	GRASS
	TREES
	CELLULOSIC AND ORGANIC POLYMERIC BUILDING AND FURNISHING MATERIAL
	ETC.

YOU NEED ALSO AN OXYDANT!

AIR
ENRICHED AIR
OXYGEN
ETC

1.3. THE DIFFERENT PHENOMENA CONTRIBUTING TO COMBUSTION

- THE KINETICS OF THE CHEMICAL REACTION
- THE FLUID FLOW ASSOCIATED WITH THE FUEL, OXYDANT AND/OR THE COMBUSTION PRODUCTS
- HEAT TRANSFER
- EMISSION OF LIGHT, RADIATION.

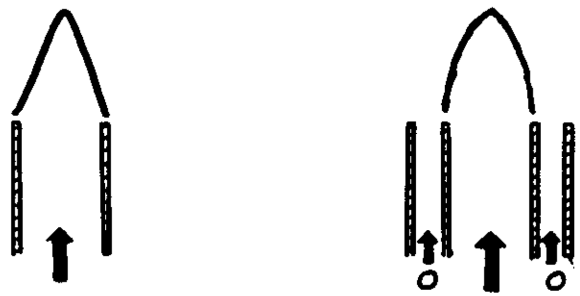
THESE FEATURES DISTINGUISH COMBUSTION PROCESSES FROM OTHER CHEMICAL REACTIONS

SLIDE 1 – LAMINAR COMBUSTION ZONE
SLIDE 2 – TURBULENT COMBUSTION ZONE) FLAMES

Propriétés générales des flammes

o réaction chimique très exothermique
T élevée → espèces excitées → front lumineux

o réactifs : { combustible (hydrocarbure, alcool ...)
comburant (oxygène)
+ eventuellement un diluant (N_2, Ar...)

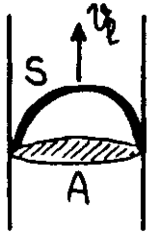


F+O — prémélange — chalumeau, moteur

F — diffusion — bougie, chaudière, matériaux solides (incendi

Propriétés générales des flammes

vitesse de propagation



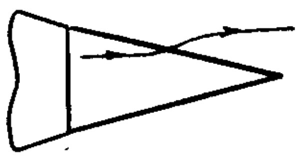
$V_f = v_\ell \cdot \frac{A}{S}$

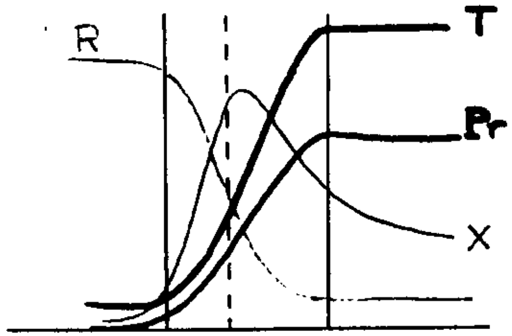
flamme stabilisée $\quad V_f = \frac{\text{débit}}{\text{surface}} \quad v_{gaz} = V_f$

flamme laminaire — transports moléculaires

flamme turbulente — transports turbulents

Structure d'une flamme





Propriétés générales des flammes

grandeurs caractéristiques

- T : 2000 K
- V_f : 40 cm/s (hydrocarbures)
- e : 99 1/10 mm à P = 1 atm
- t_s : 99 ms

paramètres importants

- nature du combustible
- richesse
- Pression
- type de flamme
- régime d'écoulement

CHEMICAL KINETICS OF COMBUSTION REACTIONS

COMBUSTION IS AN ENSEMBLE OF ESSENTIALLY EXOTHERMAL CHEMICAL REACTIONS. GLOBALLY ONE MAY WRITE

$$K + O \rightarrow P + \vec{Q}$$

- K — Combustible
- O — Oxydant
- P — Reaction Products
- Q — Heat Release

$$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$$

$$CH_4 + 2O_2 + N_2 \rightarrow CO_2 + 2H_2O + N_2$$

ARE EXAMPLES OF STOICHIOMETRIC REACTIONS, WHICH PRODUCE THE MAXIMUM POSSIBLE OF COMBUSTION PRODUCTS.

THE STOICHIOMETRIC RATIO IS THE (MOLE / MASS) RATIO OF THE COMBUSTIBLE OVER THE OXYDANT CORRESPONDING TO THAT REACTION. FOR EXAMPLE

$$C_2H_2 + \frac{5}{2} O_2 \rightarrow 2CO_2 + H_2O$$

THE S.R IS 1/2.5

THE EQUIVALENCE RATIO $\Phi = \dfrac{(C/O)}{(C/O)_{ST}}$

$\Phi < 1 \rightarrow$ LEAN

$\Phi > 1 \rightarrow$ RICH

MIXTURE

FOR A GIVEN ELEMENTARY REACTION

$$k_R = k \exp\left(-\frac{E_A}{RT}\right)$$

- k_R — reaction constant
- k — pre-exponential factor
- E_A — Activation energy

or $T_A = \dfrac{E_A}{R}$ Activation temperature

$5000K < T_A < 25000K$

ONE-STEP GLOBAL REACTION SCHEME:

$$C_nH_m + \left(n + \frac{m}{4}\right) O_2 \rightarrow n\,CO_2 + \frac{m}{2} H_2O$$

THE GLOBAL REACTION RATE IS

$$W_R = A T^{\alpha} C_{C_nH_m}^{a} C_{O_2}^{b} \exp\left(-\frac{E}{RT}\right)$$

THE DIMENSION OF W_R IS $(\text{MOLES})\, L^{-3} T^{-1}$ or $(\text{MASS})\, L^{-3} T^{-1}$

A, α, a, b, E ARE DETERMINED FROM EXPERIMENT

TWO-STEPS REACTION SCHEME

1. INITIATION PHASE: PRODUCTION OF H_2 and CO
2. OXYDATION OF CO and H_2: PRODUCTION OF CO_2 and H_2O

$$C_nH_m + \left(\frac{n}{2} + \frac{m}{4}\right)O_2 \rightarrow n\,CO + \frac{m}{2} H_2O \qquad (R1)$$

$$CO + \frac{1}{2} O_2 \rightarrow CO_2 \qquad (R2)$$

$$W_1 = A_1\, C_{C_nH_m}^{a_1}\, C_{O_2}^{b_1}\, \exp\left(-\frac{E_1}{RT}\right)$$

$$W_2 = A_2\, C_{CO}^{a_2}\, C_{O_2}^{b_2}\, C_{H_2O}^{c_2}\, \exp\left(-\frac{E_2}{RT}\right)$$

1.5. LAMINAR PREMIXED FLAME

THEY ARE ESSENTIALLY CHARACTERIZED BY TWO PARAMETERS:

* THE LAMINAR PROPAGATION VELOCITY (U_L) or ($S_L^\dagger$)
* THE LAMINAR FLAME THICKNESS (δ_L)

BY ASSUMING THAT THE TWO DOMINANT PHENOMENA IN A LAMINAR FLAME ARE

* CHEMISTRY
* MOLECULAR DIFFUSION (OF HEAT AND SPECIES)

DIMENSIONAL CONSIDERATIONS GIVE

$$U_L \sim \left(\frac{a}{\tau_c}\right)^{1/2} ; \quad \delta_L \sim (a\,\tau_c)^{1/2}$$

WHERE $a \equiv \lambda/\rho C_p$ THERMAL DIFFUSION COEF.
or $a \equiv D$ MASS DIFFUSION COEF

$\tau_c \equiv$ A GLOBAL CHEMICAL TIME SCALE (CHARACTERISTIC TIME)

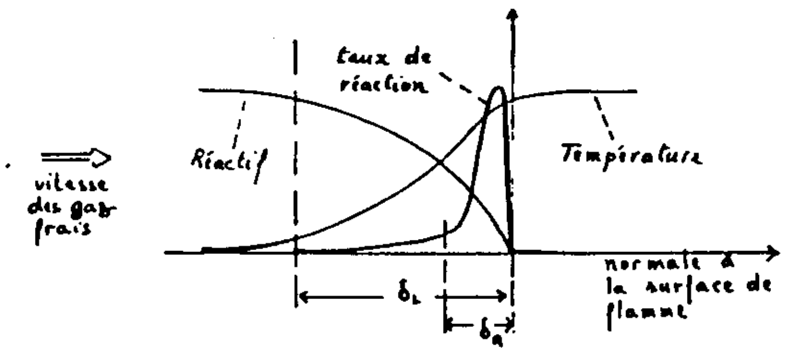


Figure 3-2

u_L : IS THE VELOCITY OF THE REACTANTS WITH RESPECT TO THE FLAME

SO, THE CONSERVATION OF MASS ACROSS A UNIT SURFACE OF FLAME GIVES

$$\rho_R u_L = \rho_P u_P$$

ρ_R : DENSITY OF REACTANTS

ρ_P : DENSITY OF PRODUCTS

u_P : VELOCITY OF PRODUCTS WITH RESPECT TO THE FLAME

AS $\rho_P < \rho_R$ BECAUSE $T_P > T_R$

AND $P_P \simeq P_R$ (THIS IS AN EXPERIMENTAL OBSERVATION)

$$u_P > u_L$$

HOW TO STABILIZE (OR ANCHOR) A PREMIXED LAMINAR FLAME

FLAMMABILITY LIMITS

p
T
Φ
Dilution.
Da

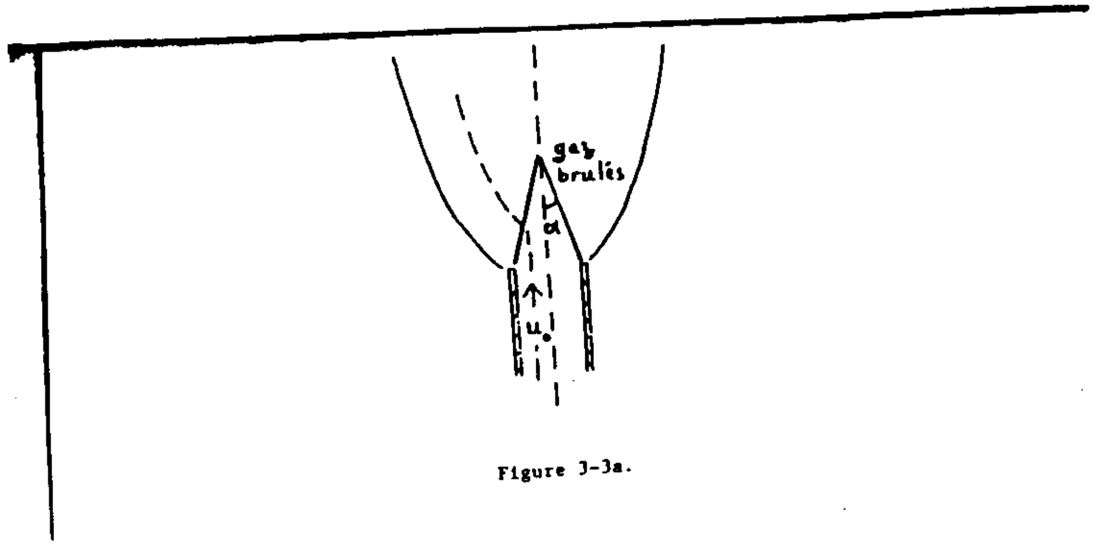


Figure 3-3a.

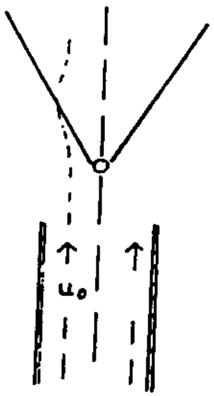


Figure 3-3b.

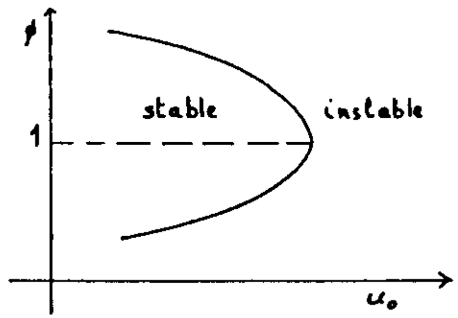


Figure 3-5.

6. LAMINAR DIFFUSION (OR NON-PREMIXED) FLAME.

* PROFILES OF TEMPERATURE AND CONCENTRATION ARE DIFFERENT IN DIFFERENT REGIONS

* THE FLAME ZONE IS THICKER

* THE FLAME ZONE IS GENERALLY YELLOW DUE TO RADIATION FROM SOOT PARTICLES

* CONVECTIVE PHENOMENA ARE MORE IMPORTANT

* THE STATE OF THE MIXTURE IS ONLY LOCALLY DEFINED

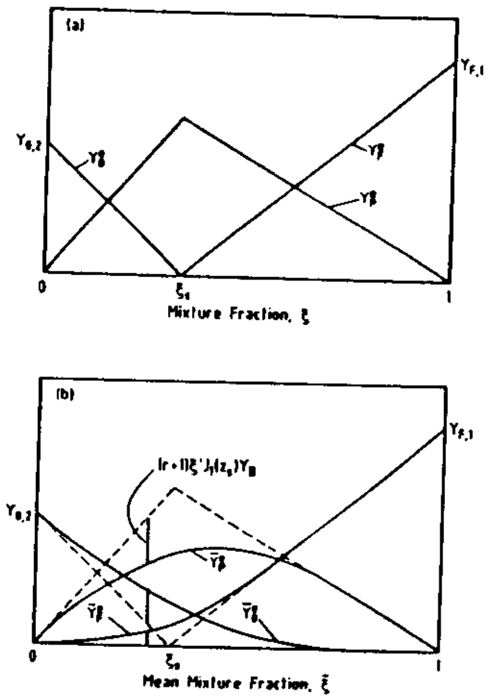
* THE DEFINITION OF A FLAME PROPAGATION VELOCITY AND A CONSTANT LAMINAR FLAME THICKNESS IS MEANINGLESS.

* AN ALTERNATIVE SCALE IS THE FLAME HEIGHT WHICH CAN BE DETERMINED BY MAKING THE "THIN FLAME HYPOTHESIS"

$$\tau_c < \frac{d_0}{U_0} < \frac{d_0^2}{a}$$

$$\frac{L_F}{d_0} = K \frac{U_0 d_0}{a} \quad \text{and} \quad K = K\left(\frac{g d_0}{U_0^2}, \frac{\rho_0}{\rho_{air}}\right)$$

106 BILGER



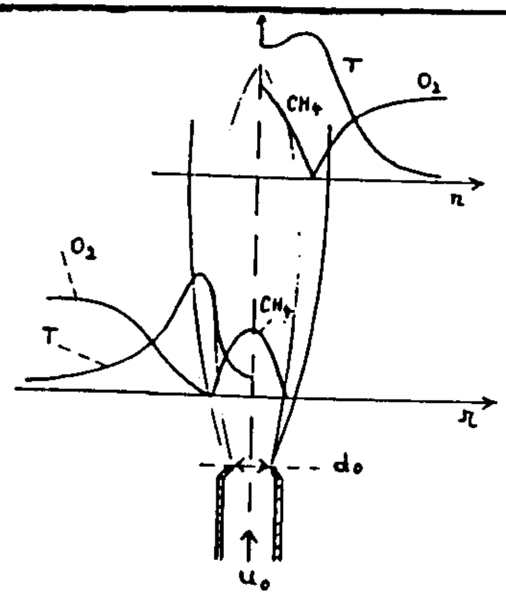
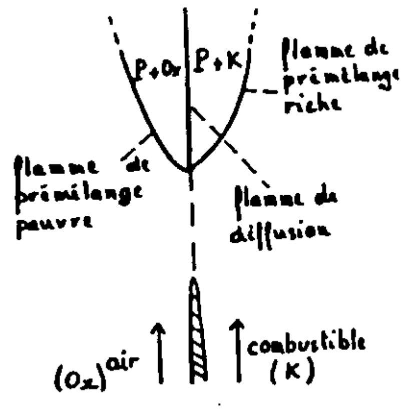

T
O_2
CH_4
r
O_2
T
CH_4
r
d_0
u_0

Figure 3-6.


P+Ox
P+K
flamme de prémélange riche
flamme de prémélange pauvre
flamme de diffusion
$(Ox)^{air}$
combustible (K)

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1.7. COMBUSTION MODELLING.

WE NEED TO SOLVE A SERIES OF COUPLED EQUATIONS :

- CONSERVATION OF MASS

  WHICH INTRODUCES THE KINETICS OF COMBUSTION

- CONSERVATION OF MOMENTUM

  WHICH INTRODUCES THE NATURE OF THE FLOW FIELD (LAMINAR OR TURBULENT)

- CONSERVATION OF ENERGY

  WHICH INTRODUCES THE VARIOUS EXCHANGES BETWEEN THE FLAME AND ITS SURROUNDINGS.