FLAME PHENOMENA IN PREMIXED COMBUSTIBLE GAS

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DEFINITION OF FLAME

Flame can be described as a reaction zone that move with respect to the gas supporting it or a propagation at local combustion zone that can defend by itself at speed below the speed of sound

Flame have a local characteristic, so there only covered a little part of mixture that can burn at that time.

CHARACTERISTIC OF FLAME

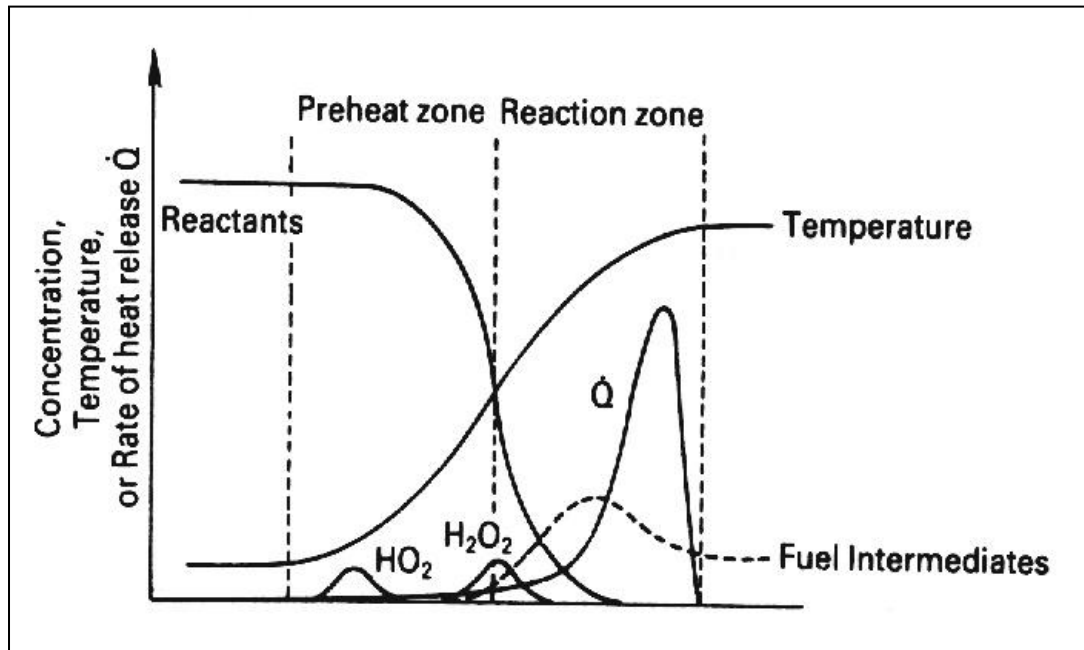**FLAME THICKNESS**

LAMINAR FLAME SPEED

TEMPERATURE OF FLAME

VISIBLE RADIATION

STRUCTURE AND ZONE OF FLAME

- The structure of Laminar Premixed Flame

- Zone of Flame

✓ Preheat zone

A small amount of heat is released

✓ Reaction zone

Mainly of chemical energy are released

FLAME TEMPERATURE

This is the temperature of the gases when they leave the reaction zone, Tb. In a premixed flame, a well-defined mixture composition enters the flame at a fixed temperature and pressure. Therefore it is, possible to calculate the adiabatic flame temperature from the thermodynamical properties of the original mixture.
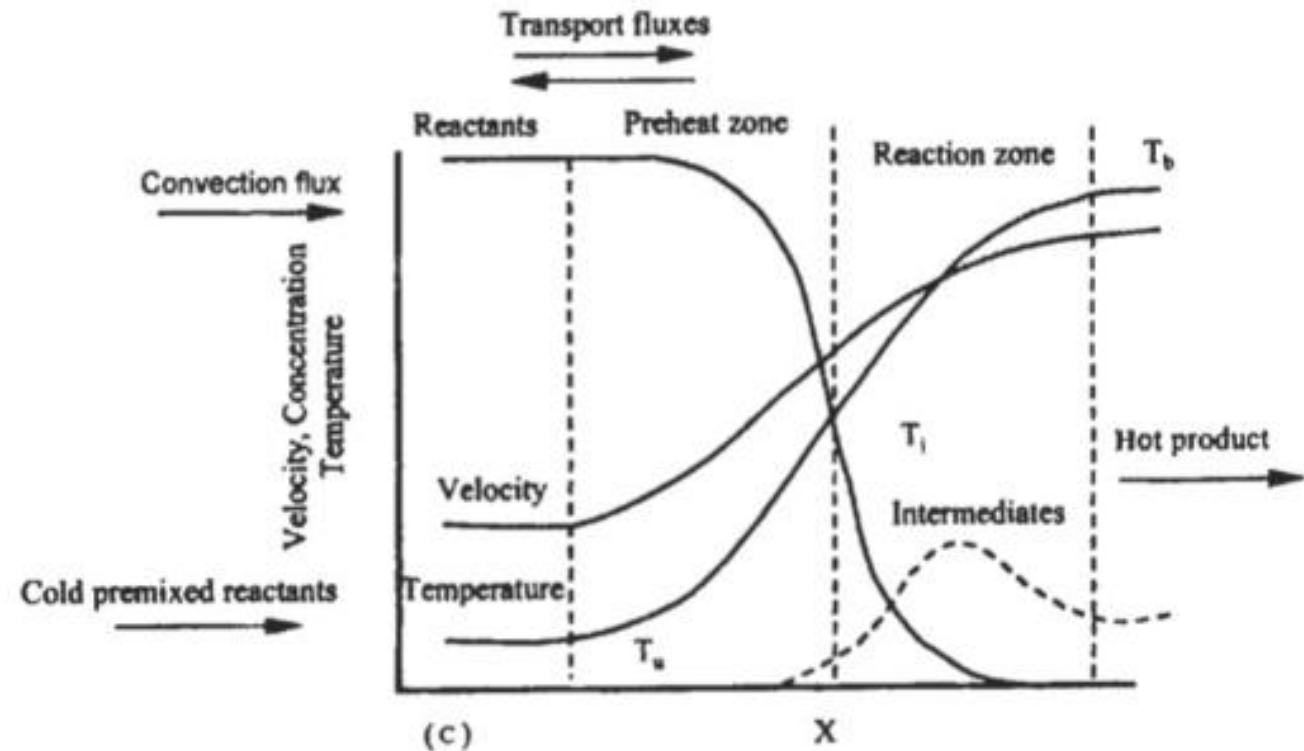
The temperature, concentration and velocity profiles through an idealized one-dimensional stationary premixed flame

FLAME THICKNESS

- At the atmospheric pressure, the flame thickness is very thin (in ordo of mm)

- Temperature gradient and species concentration are huge

- The huge gradients that give a source of propulsion which make flame defend by themselves are heat diffusion and radical species from reaction zone to preheat zone

FLAME THICKNESS ANALYSIS

$$\delta = \left[\frac{-2\rho_u \alpha}{(\nu + 1)\bar{\dot{m}}'''_{bb}} \right]^{1/2} = \frac{2\alpha}{S_L}$$

where ;

α = thermal diffusivity (m2/s)

ν = ratio mass of oxidizer-fuel (kg/kg)

ρ_u = mix density of unburned gas (kg/m3)

$\bar{\dot{m}}'''_{bb}$ = volumetric mass production rate of fuel

Note:

$\bar{\dot{m}}'''_{bb}$ = (+) for production

(-) for consumption

LAMINAR FLAME SPEED

- The major difference between premixed flame and non-premixed flame is a flame speed, S_L

- Defined as the velocity at which unburned gases move through the combustion wave in the direction normal to the wave surface

- The initial theoretical analyses for the determination of the laminar flame speed fell into three categories; thermal theories, diffusion theories, and comprehensive theories.

LAMINAR FLAME SPEED

- Density of products is getting lower than density of reactants, because the flame is used to heating the product of combustion.

- Law of Continuity : velocity of burned gas is faster than velocity of unburned gas

- There is an acceleration of gas flow when crossing the flame

$$\rho_u S_L A = \rho_u v_u A = \rho_b v_b A$$

S_L

Unburned gas

v_u

ρ_u

Burned gas

v_b

ρ_b

stationary flame
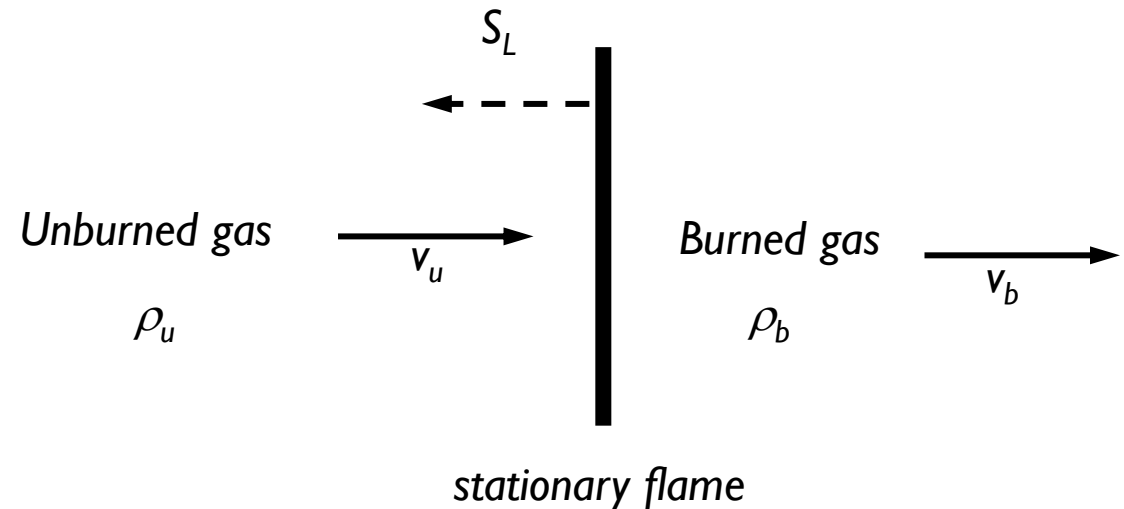
BURNING VELOCITY OF A PREMIXED FLAME

Burning velocity, UI, is defined as the relative linear velocity with which a planar flame front in a one-dimensional flow system moves normal to its surface through the adjacent unburned gas.
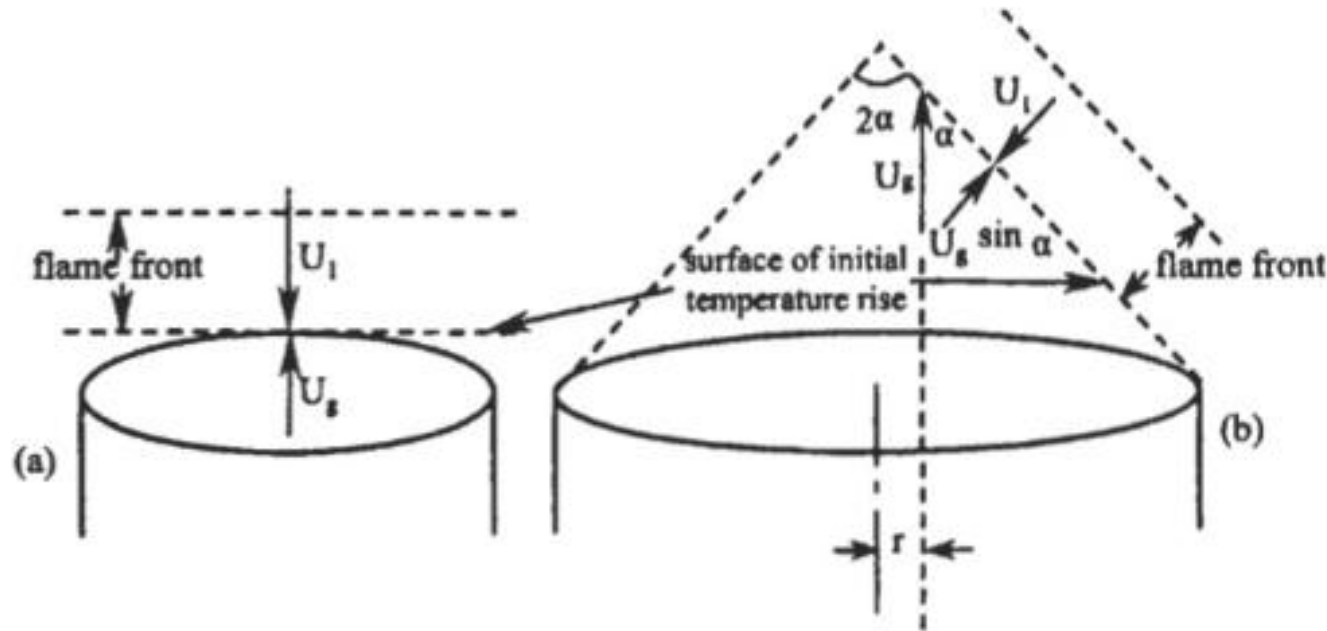
Burning velocity and flow velocity for (a) flat flame and (b) conical flame

BUNSEN BURNER FLAME

- A Bunsen flame, provides an illustration of both type of flames, premixed flame and non-premixed flame as shown in fig 0.3.1

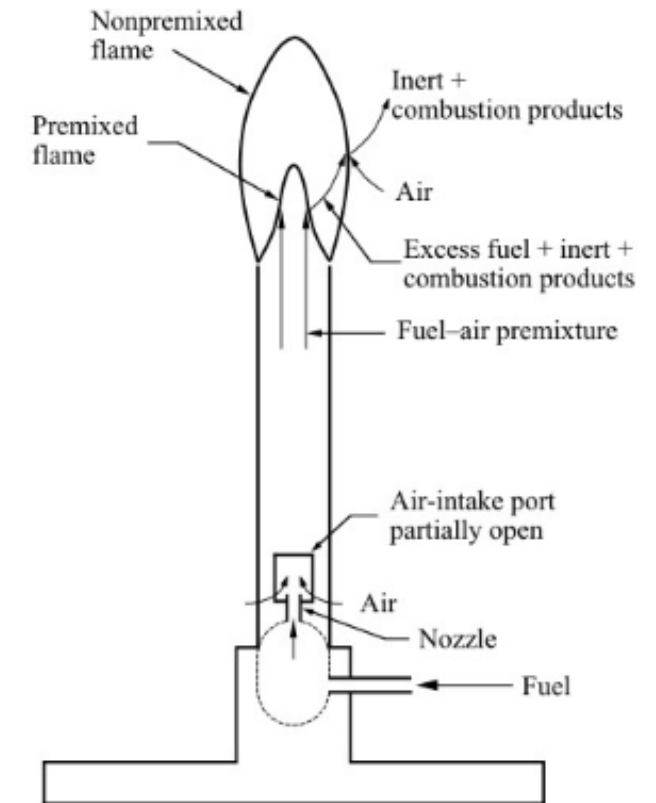- The shape of flame is depending on combination of velocity profile and heat losses at the pipe wall
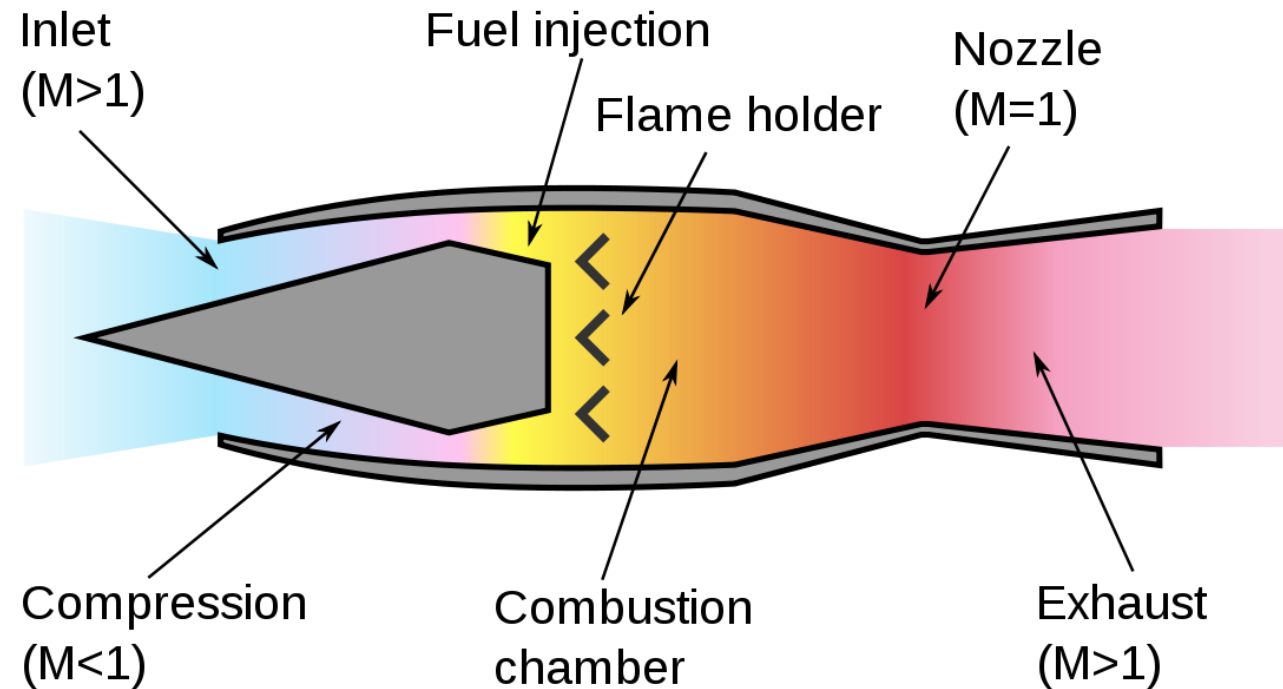

Figure 0.3.1. Schematic of the Bunsen flame.

LAMINAR FLAME STABILIZATION

- To make a laminar flame stabilization we need to attach the flame to a flame-holder or burner, which locally interacts with the flow and combustion processes to provide a stabilizing zone.

Inlet (M>1)

Fuel injection

Flame holder

Nozzle (M=1)

Compression (M<1)

Combustion chamber

Exhaust (M>1)

ANALYSIS OF LAMINAR PREMIXED FLAME

- Spalding (1979); the basic formula for flame speed

Assumptions;

- Steady flow, constant area, and one-dimensional

- Negligible kinetic and potential energy, viscous sheer stress, and thermal radiation

- Constant pressure

- Heat diffusion follow the law of Fourier and Fick, assumed as binary diffusion

- Lewis number, $Le = \dfrac{\alpha}{D} = \dfrac{K}{\rho c_p D}$, that state as ratio of thermal diffusivities with mass diffusivities is equal to one

ANALYSIS OF LAMINAR PREMIXED FLAME

- Each mix heat specific are same and constant

- Fuel and oxidizer form product through reaction in one stage of exothermic

- Oxidizer supplied based on stochiometric or excess condition, so the whole of fuel is used as flame

CONT'D

ANALYSIS OF LAMINAR PREMIXED FLAME SPEED

$$S_L = \left[-2\alpha(\nu + 1) \frac{\bar{\dot{m}}'''_{bb}}{\rho_u} \right]^{1/2}$$

where ;

α = thermal diffusivity (m2/s)

ν = ratio mass of oxidizer-fuel (kg/kg)

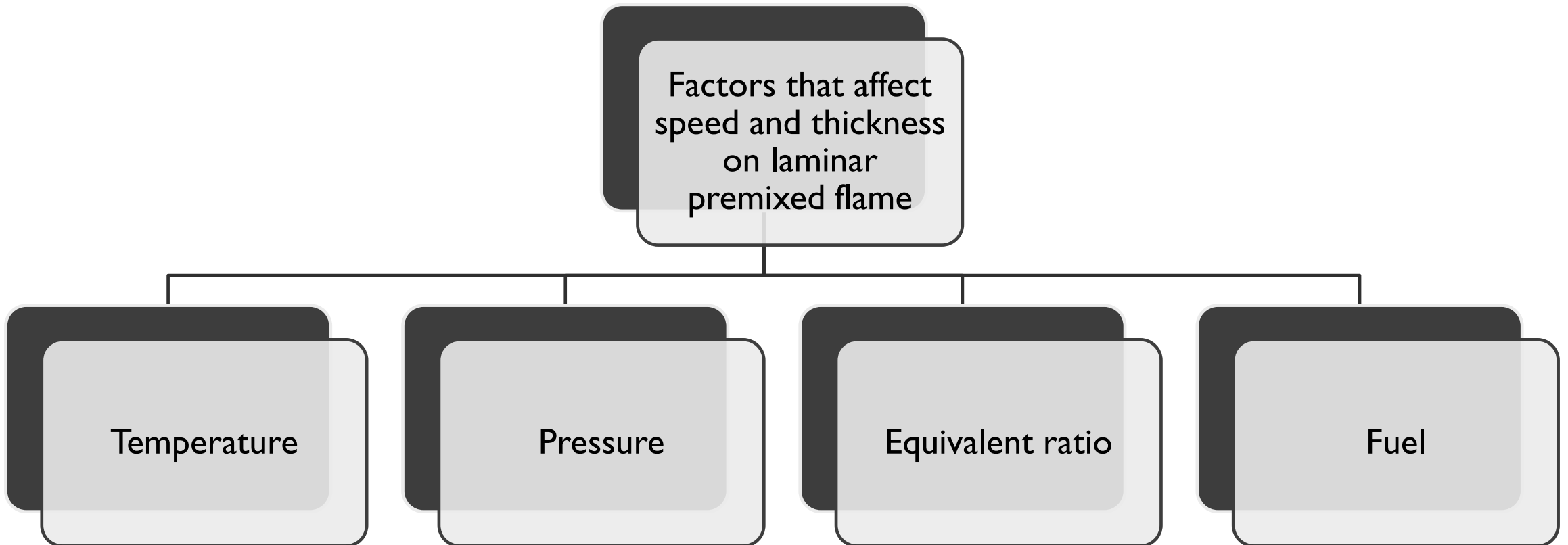ρ_u = mix density of unburned gas (kg/m3)

$\bar{\dot{m}}'''_{bb}$ = volumetric mass production rate of fuel
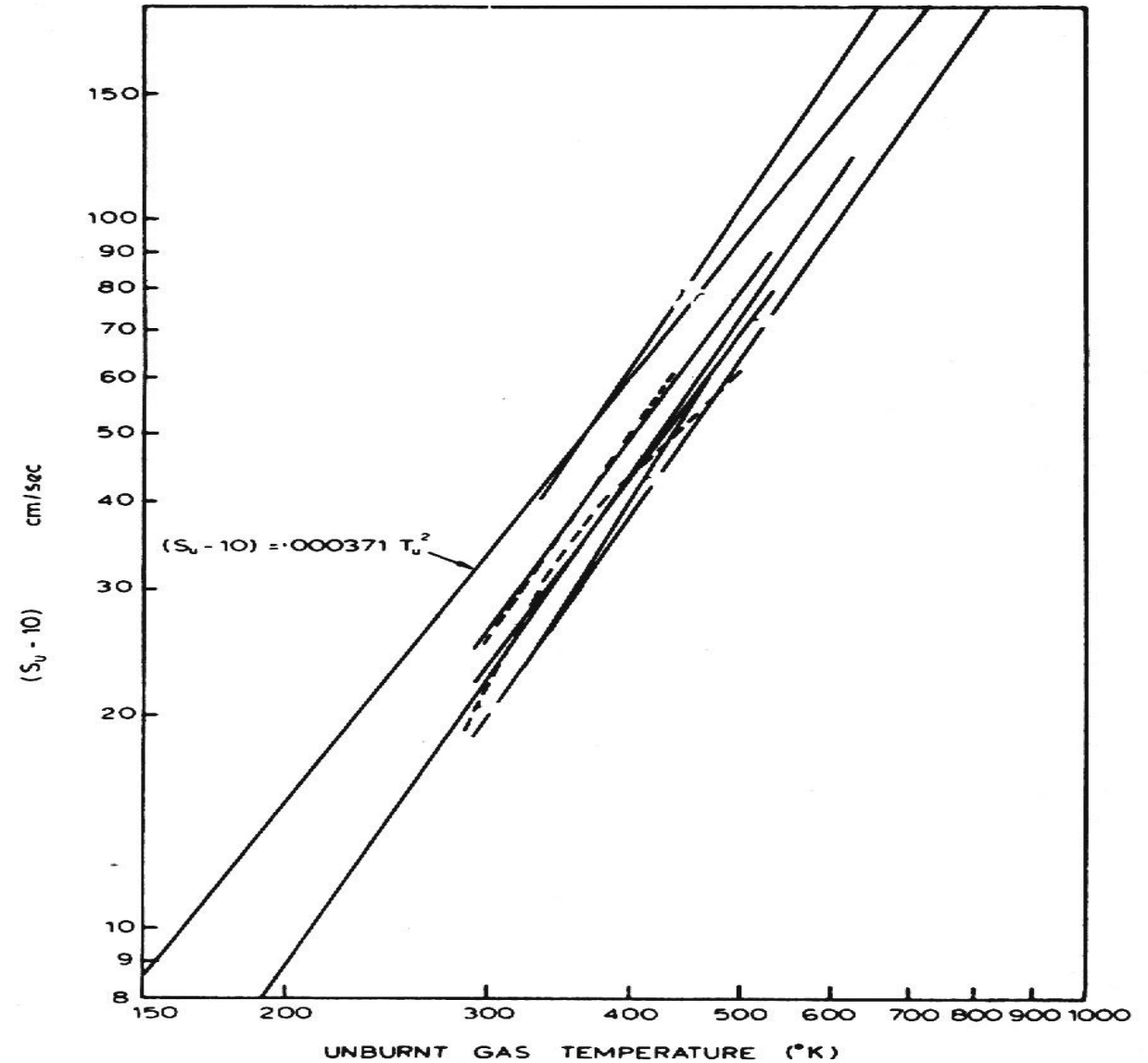
Note:

$\bar{\dot{m}}'''_{bb}$ = (+) for production

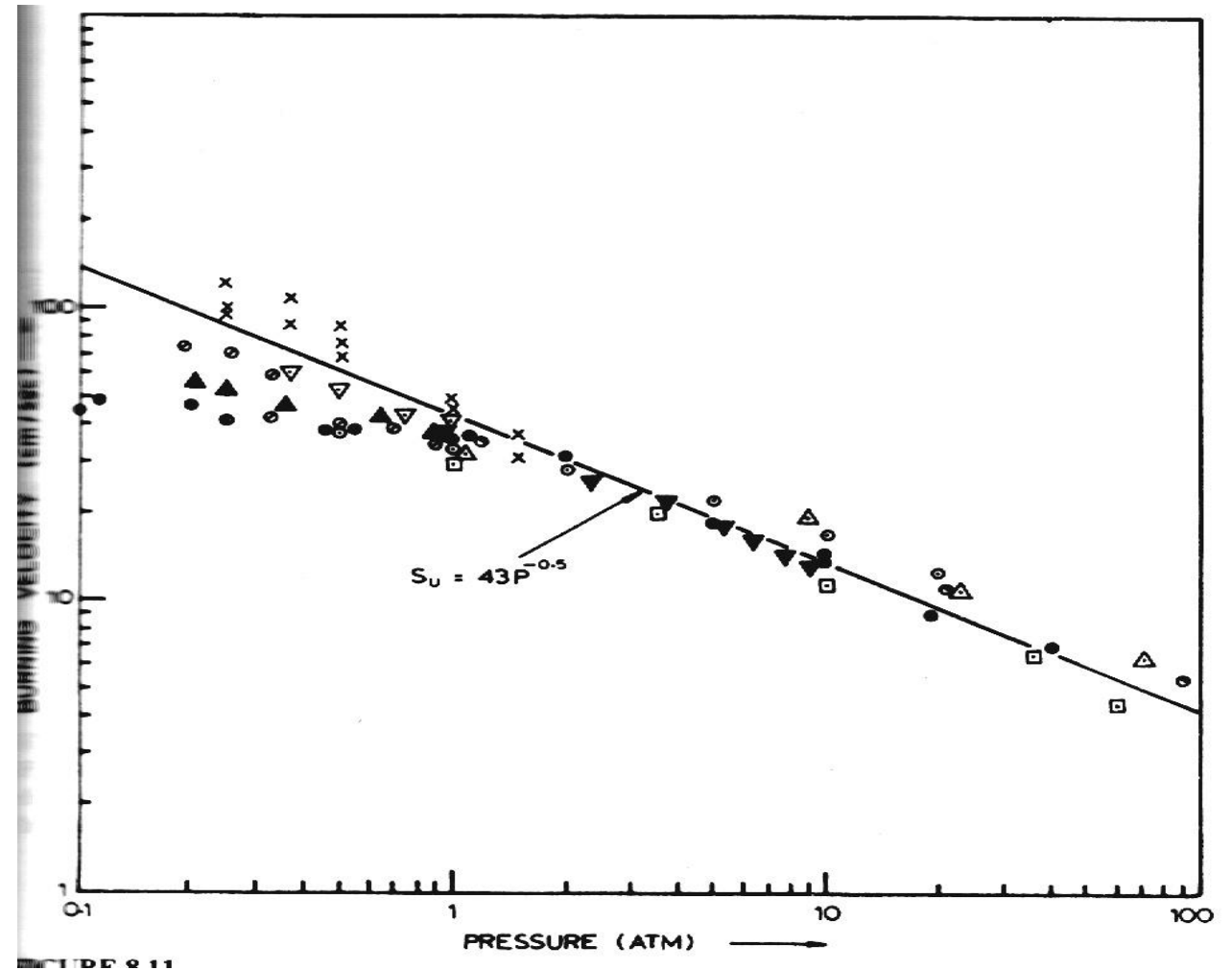(-) for consumption

FACTORS THAT AFFECT FLAME

Factors that affect speed and thickness on laminar premixed flame

Temperature

Pressure

Equivalent ratio

Fuel

FACTORS THAT AFFECT FLAME

TEMPERATURE

FACTORS THAT AFFECT FLAME

PRESSURE

$S_U = 43P^{-0.5}$

FACTORS THAT AFFECT FLAME
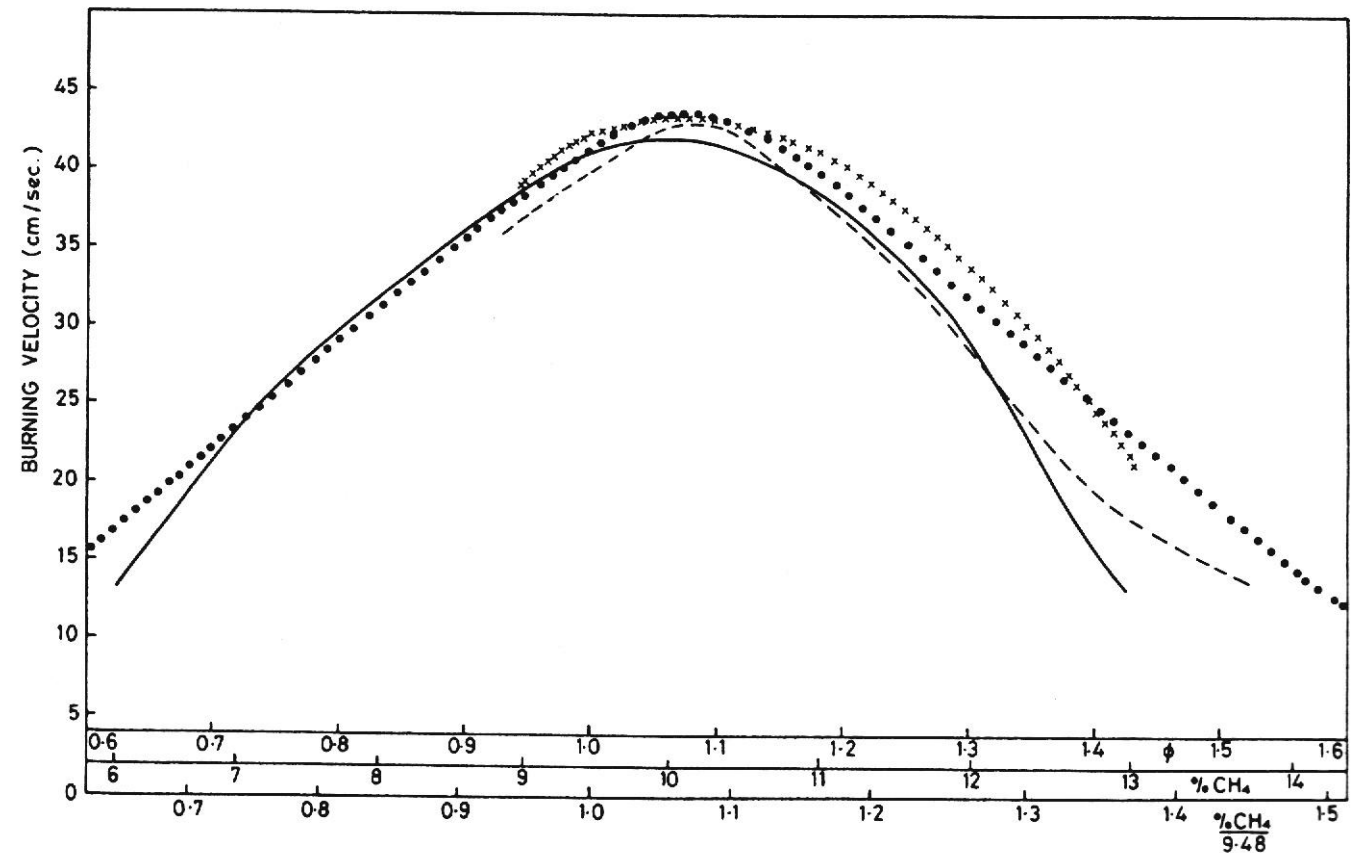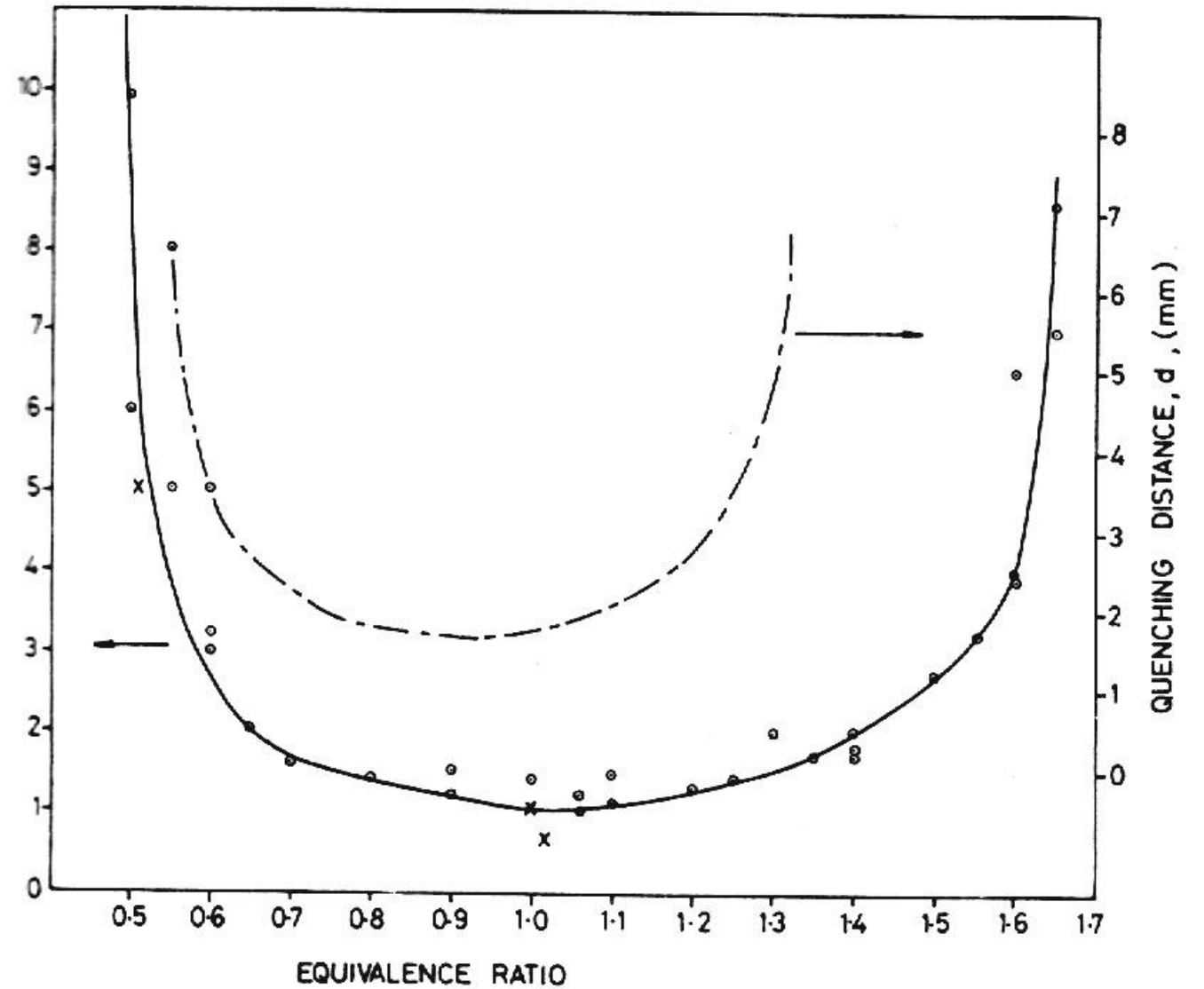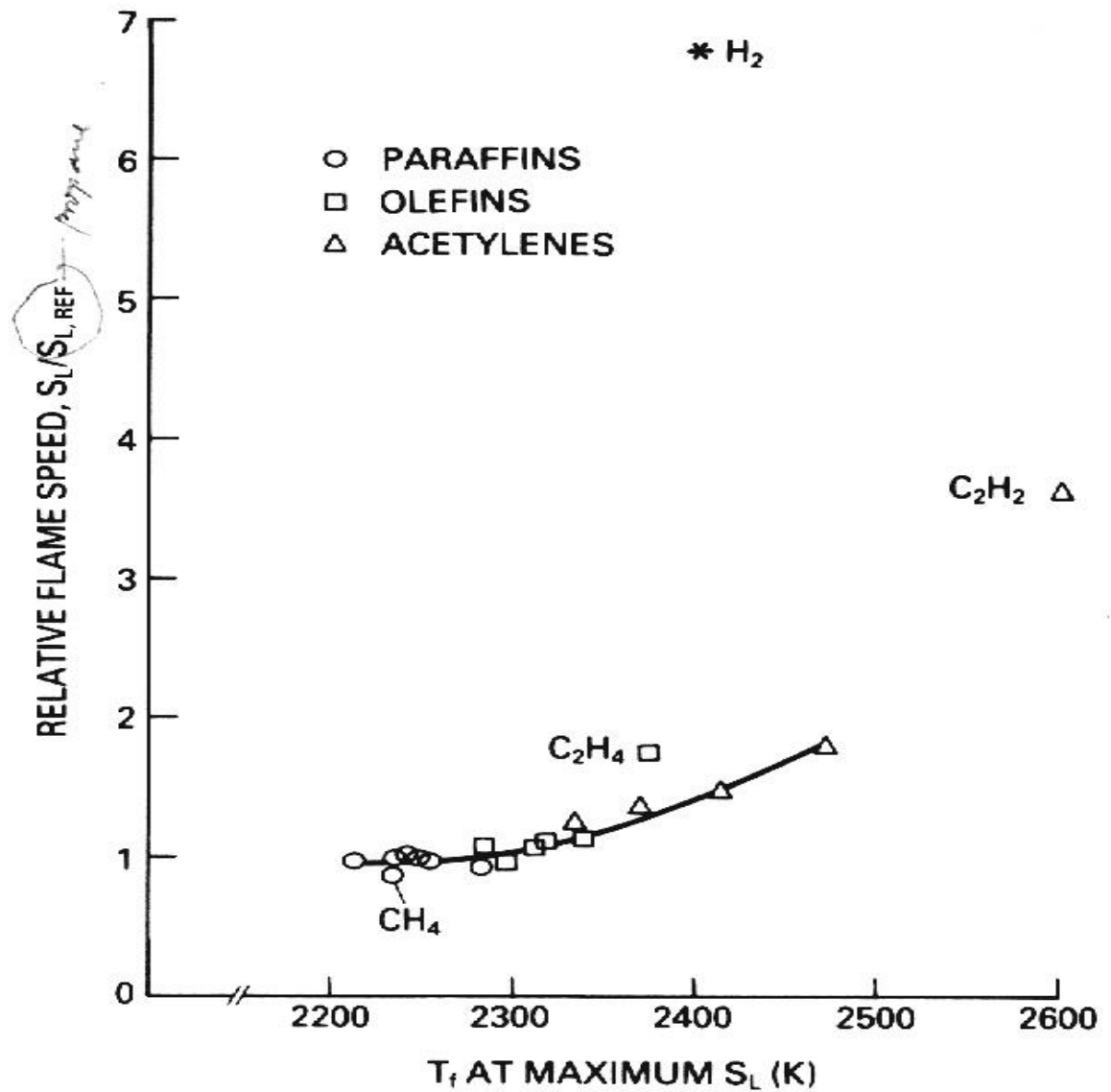
EQUIVALENT RATIO

FIGURE 8.12

FACTORS THAT AFFECT FLAME

EQUIVALENT RATIO TO THICKNESS

FACTORS THAT AFFECT FLAME

FUEL

CORRELATION OF FLAME SPEED

Correlation laminar premixed flame for kinds of fuel.

Meghalchi dan Keck (1982):

$$S_L = S_{L,ref} \left(\frac{T_u}{T_{u,ref}}\right)^{\gamma} \left(\frac{p}{p_{ref}}\right)^{\beta} (1 - 2{,}1 Y_{diluent})$$

Where;
$$T_{u,ref} = 298 \text{ K}$$
$$p_{ref} = 1 \text{ atm}$$
$$S_{L,ref} = B_M + B_2(\Phi - \Phi_M)^2$$
$$\gamma = 2{,}18 - 0{,}8(\Phi - 1)$$
$$\beta = -0{,}16 + 0{,}22(\Phi - 1)$$

TABLE 8.3
Values for B_M, B_2, and Φ_M used with Eqn. 8.28 [13]

Fuel	Φ_M	B_M(cm/s)	B_2(cm/s)
Methanol	1.11	36.92	−140.51
Propane	1.08	34.22	−138.65
Isooctane	1.13	26.32	−84.72
RMFD-303	1.13	27.58	−78.34

Note:
B_M, B_2 dan Φ_M depend on the fuel (Table 8.3)

FLAMMABILITY LIMITS

Lower flammable limit or lean limit,

The percentage of fuel gas when small amount of combustible fuel gas or vapor added gradually to air, until reach at a point that the mixture just becomes flammable.

Upper flammable limit or rich limit,

The percentage of fuel gas when more fuel gas is added, and another point will eventually be reached at which the mixture will no longer burn

TABLE 4.3 Flammability Limits of Some Fuels in Air[a]

	Lower (lean)	Upper (rich)	Stoichiometric
Methane	5	15	9.47
Heptane	1	6.7	1.87
Hydrogen	4	75	29.2
Carbon monoxide	12.5	74.2	29.5
Acetaldehyde	4.0	60	7.7
Acetylene	2.5	100	7.7
Carbon disulfide	1.3	50	7.7
Ethylene oxide	3.6	100	7.7

[a]Volume percent.

TABLE 4.4 Comparison of Oxygen and Air Flammability Limits[a]

	Lean		Rich
	Air	O_2	Air
H_2	4	4	75
CO	12	16	74
NH_3	15	15	28
CH_4	5	5	15
C_3H_8	2	2	10

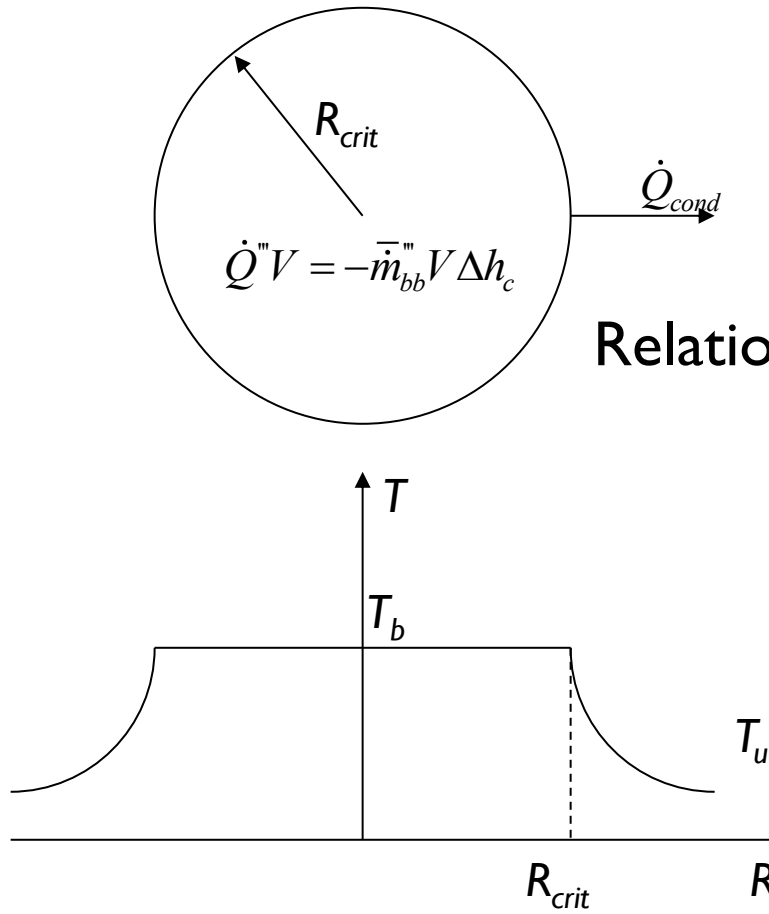[a]Fuel volume percent.

FLAMMABILITY LIMITS

IGNITION

Homogenous ignition, in which ignition occurs simultaneously throughout the reactant volume

Auto ignition or self-ignition, when the temperature of a vessel containing a homogeneous mixture of reactants is raised, a point is reached at which ignition occurs

ANALYSIS OF IGNITION

$$\dot{Q}'''V = -\bar{\dot{m}}'''_{bb}V\Delta h_c = \dot{Q}_{cond,total}$$

$$(-\bar{\dot{m}}'''_{bb}\Delta h_c)\left(\frac{4\pi R^3_{crit}}{3}\right) = k\left(4\pi R^2_{crit}\right)\frac{T_b - T_u}{R_{crit}}$$

$$R^2_{crit} = \frac{3k(T_b - T_u)}{-\bar{\dot{m}}'''_{bb}\Delta h_c}$$

Relation $: \Delta h_c = (v + 1)cp(Tb - Tu)$

$$\delta = \left[\frac{-2\rho_u\alpha}{(v + 1)\bar{\dot{m}}'''_{bb}}\right]^{1/2} = \frac{2\alpha}{S_L}$$

$$R_{crit} = \sqrt{6}\frac{\alpha}{S_L} = \sqrt{6}\frac{\delta}{2}$$

Minimum Energy of Ignition:

$$E_{ign} = m_{crit}c_p(T_b - T_u)$$

$$= 61{,}6p\left(\frac{c_p}{R_b}\right)\left(\frac{T_b - T_u}{T_b}\right)\left(\frac{\alpha}{S_L}\right)^3$$