



Laminar Premixed Flames

Part (1)

SIMPLIFIED ANALYSIS

Turns (2000) proposes simplified laminar flame speed and thickness on one-dimensional flame.

Assumptions used:

- **One-dimensional, constant-area**, steady flow. One-dimensional flat flame is shown in Figure 8.5.
- Kinetic and potential energies, viscous shear work, and thermal radiation are all neglected.
- The small pressure difference across the flame is neglected; thus, **pressure is constant**.

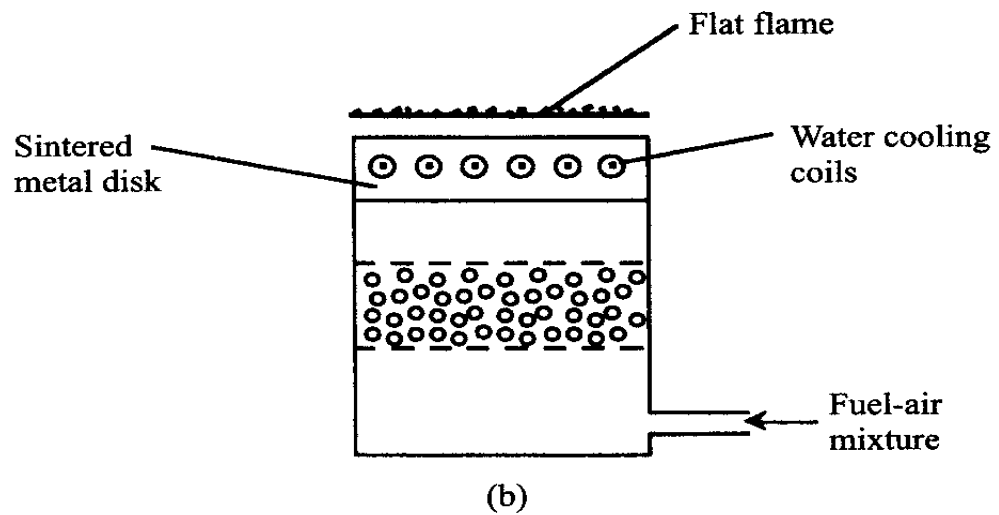
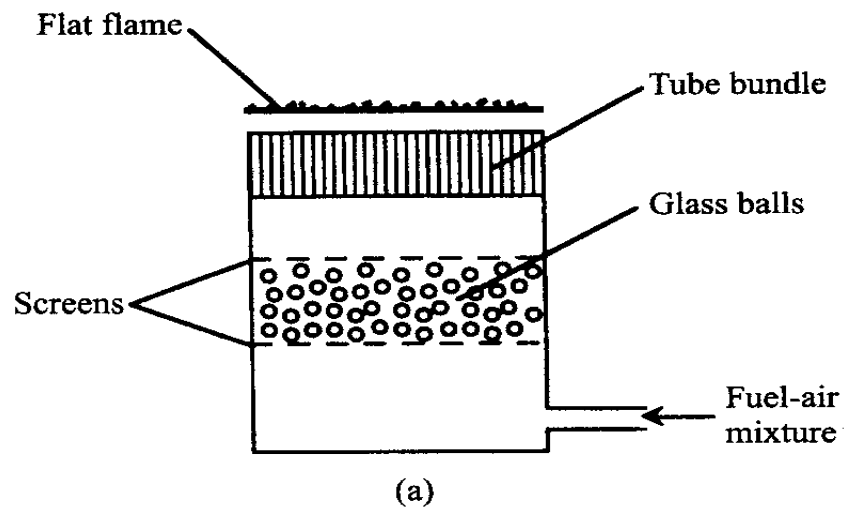


Figure 8.5 (a) Adiabatic flat-flame burner. (b) Nonadiabatic flat-flame burner.

- The diffusion of heat and mass are governed by **Fourier's and Fick's laws** respectively (**laminar flow**).
- Binary diffusion is assumed.
 - The Lewis number, Le , which expresses the ratio of thermal diffusivity, α , to mass diffusivity, D , i.e., **is unity**,

$$Le = \frac{\alpha}{D} = \frac{k}{\rho C_p D}$$

$$\alpha = \frac{k}{\rho_u C_p}$$

- The C_p mixture $\neq f(\text{temperature, composition})$. This is equivalent to assuming that individual species specific heats are all equal and constant.
- Fuel and oxidizer form products in a single-step exothermic reaction. Reaction is
$$1 \text{ kg fuel} + \nu \text{ kg oxidiser} \rightarrow (\nu + 1) \text{ kg products}$$
- The oxidizer is present in stoichiometric or excess proportions; thus **fuel is completely consumed at the flame.**

■ For this simplified system, S_L and δ found are

■
$$S_L = \left[-2\alpha(\nu + 1) \frac{\bar{\dot{m}}_F'''}{\rho_u} \right]^{1/2} \quad (8.20)$$

■ and

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

■ or

$$\delta = \frac{2\alpha}{S_L}$$

(8.21)

where is $\bar{\dot{m}}_F'''$ **volumetric mass rate** of fuel and α is thermal diffusivity. Temperature profile is assumed **linear from T_u to T_b** over the small distance, as shown in Fig. 8.9.

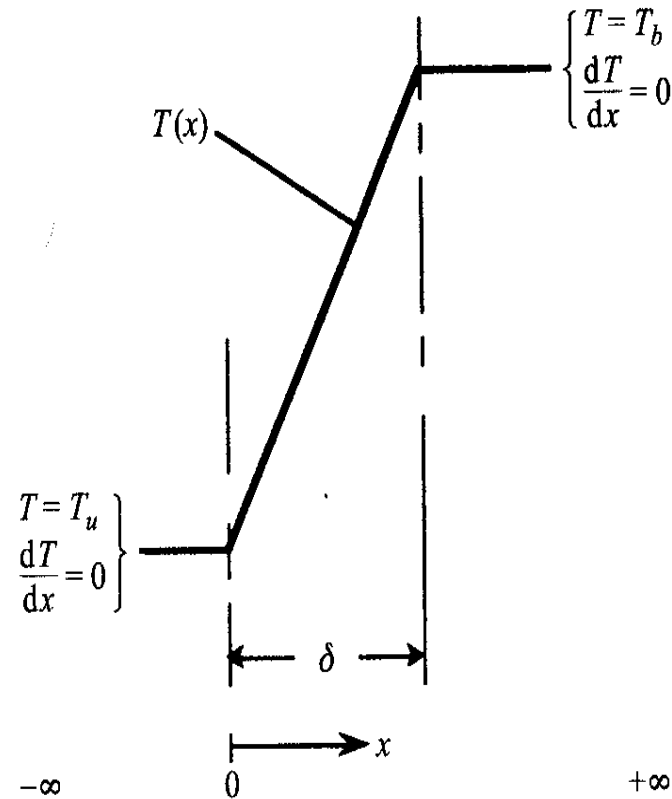


Figure 8.9 Assumed temperature profile for laminar premixed flame analysis.

the energy release rate is by means of the heat of combustion per unit mass of oxygen ... Is the energy that remains within the control volume of the flame.

FACTORS INFLUENCING FLAME SPEED (S_L) AND FLAME THICKNESS (δ)

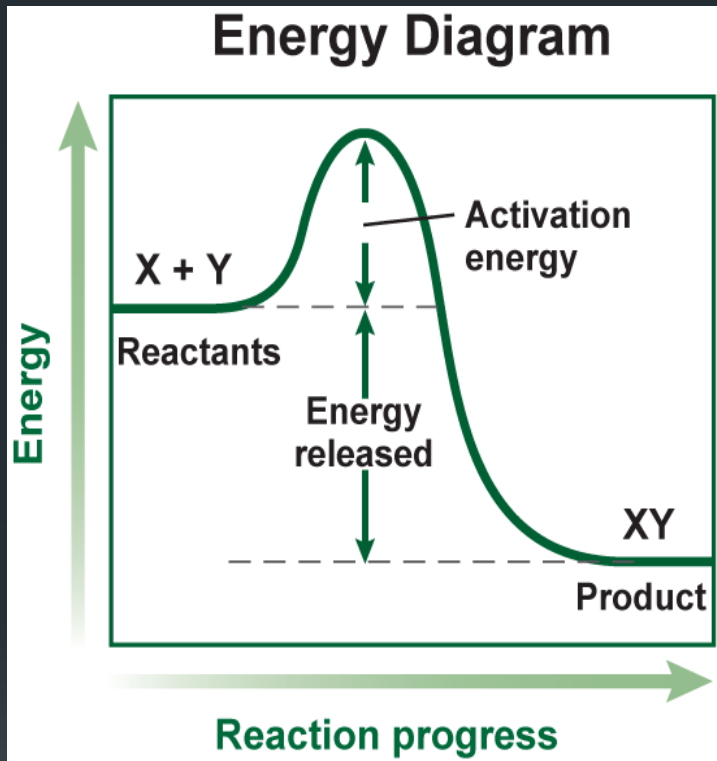
1. Temperature (T_u and T_b)

- Temperature dependencies of S_L and δ can be inferred from Eqns 8.20 and 8.21. Explicit dependencies is proposed by **Turns** as follows

- $\alpha \propto \frac{k(\bar{T})}{\rho_u C_p(\bar{T})} \propto \bar{T}^{0.75} T_u P^{-1}$ (8.27)

- where α is thermal diffusivity, T_u is unburned gas temperature, $\bar{T} \equiv 0.5(T_b + T_u)$, T_b is burned gas temperature.

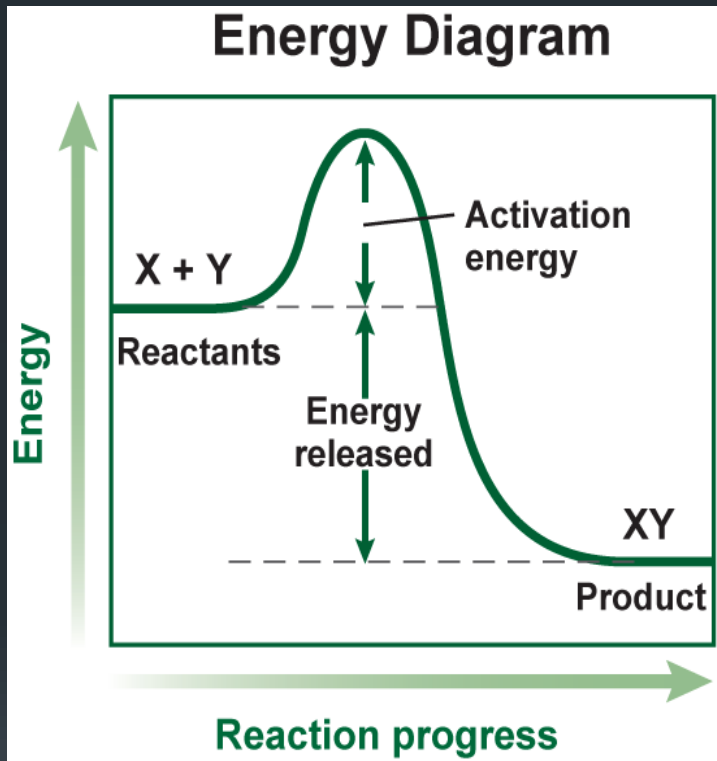
6.2 Chemical Reactions



Energy of Reactions

- **Activation energy:** the minimum amount of energy needed for reactants to form products in a chemical reaction.

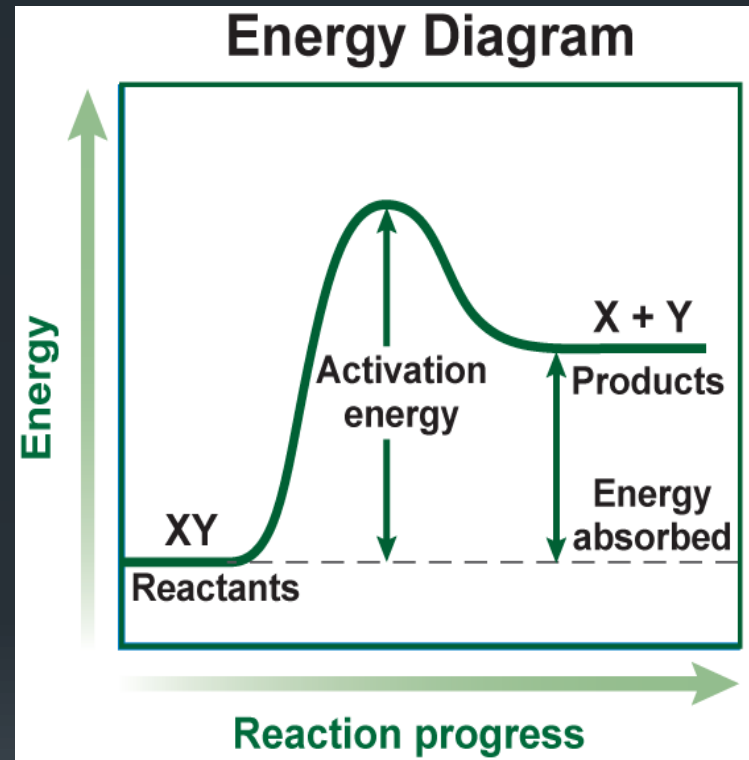
6.2 Chemical Reactions



- This reaction is **exothermic** and released heat energy.
- The energy of the product is lower than the energy of the reactants.

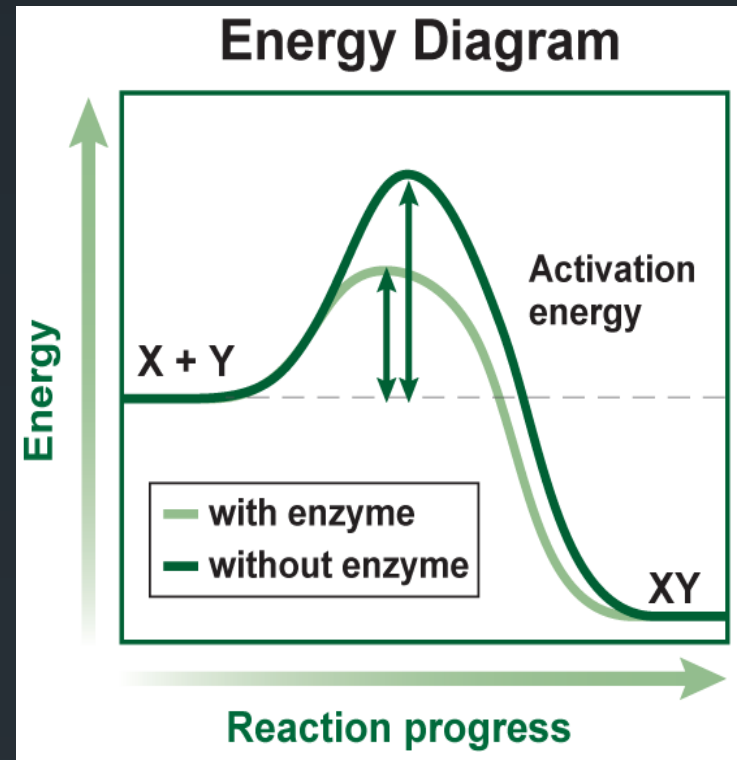
6.2 Chemical Reactions


- This reaction is **endothermic** and absorbed heat energy.
- The energy of the products is higher than the energy of the reactants.
- Ex: photosynthesis



Enzymes

- A **catalyst** is a substance that lowers the activation energy and speeds up a reaction.
- It does not increase how much product is made and it can be re-used over and over again.
- **Enzymes** are biological catalysts.





where the exponent n is the overall reaction order, $R_u =$ universal gas constant (J/kmol-K), $E_A =$ activation energy (J/kmol)

- Combining above scalings yields and applying Eqs 8.20 and 8.21

- $S_L \propto \bar{T}^{0.375} T_u T_b^{-n/2} \exp\left(\frac{-E_A}{2R_u T_b}\right) P^{(n-2)/2}$ (8.29)

- $\delta \propto \bar{T}^{0.375} T_b^{n/2} \exp\left(\frac{E_A}{2R_u T_b}\right) P^{-n/2}$ (8.30)

- For hydrocarbons, $n \approx 2$ and $E_A \approx 1.67 \cdot 10^8$ J/kmol (40 kcal/gmol). Eqn 8.29 predicts S_L to increase by factor of 3.64 when T_u is increased from 300 to 600K. Table 8.1 shows comparisons of S_L and δ
- The empirical S_L correlation of **Andrews and Bradley** [19] for stoichiometric methane-air flames,
$$S_L \text{ (cm/s)} = 10 + 3.71 \cdot 10^{-4} [T_u \text{ (K)}]^2 \quad (8.31)$$
which is shown in Fig. 8.13, along with data from several experimenters.
- Using Eqn. 8.31, an increase in T_u from 300 K to 600 K results in S_L increasing by a factor of 3.3, which compares quite favourably with our estimate of 3.64 (Table 8.1).

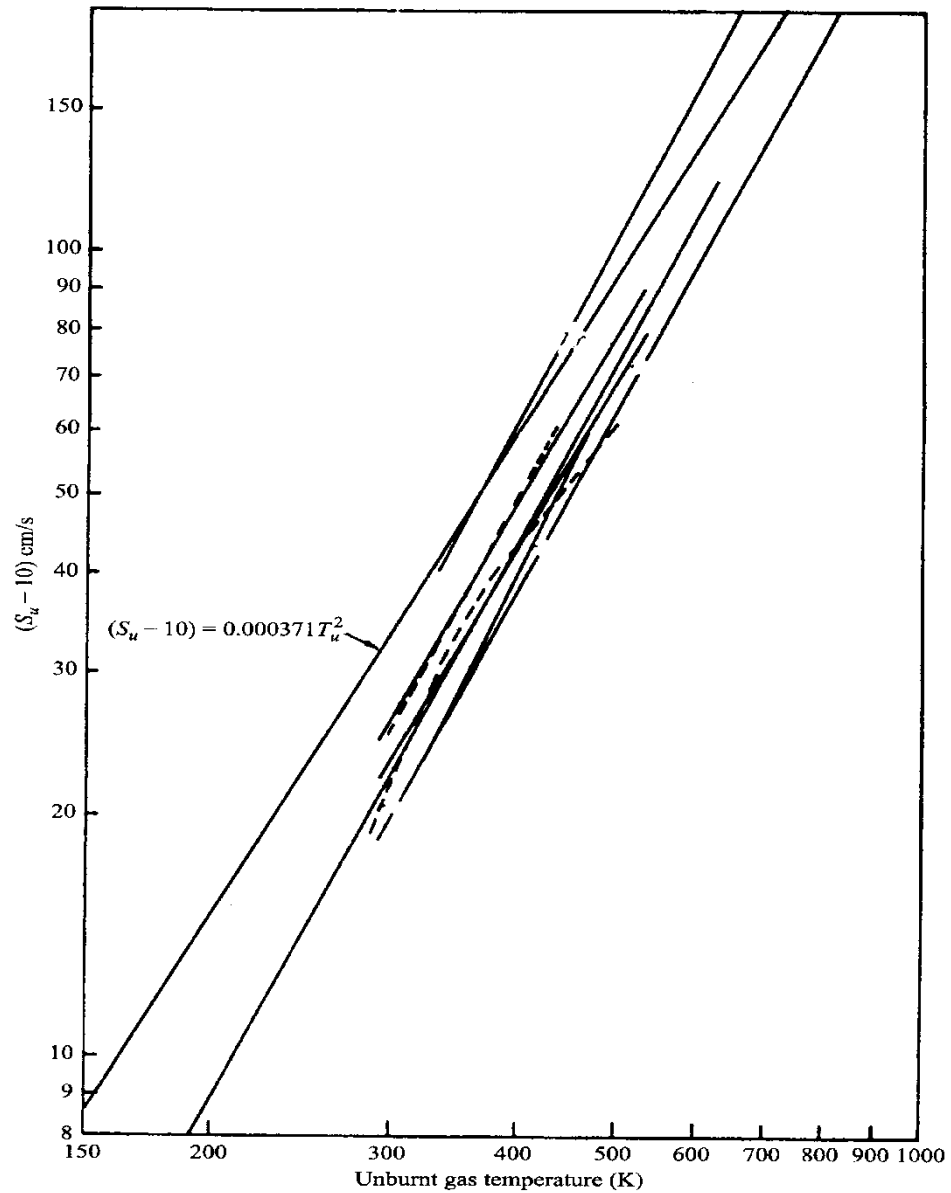


Figure 8.13 Effect of unburnt gas temperature on laminar flame speeds of stoichiometric methane-air mixtures at 1 atm. Various lines are data from various investigators.
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- **Table 8.1** Estimate of effects of T_u and T_b on S_L and δ using Eq 8.29 and 8.30

Case	A (ref)	B	C
T_u (K)	300	600	300
T_b (K)	2,000	2,300	1,700
$S_L/S_{L,A}$	1	3.64	0.46
δ/δ_A	1	0.65	1.95

- Case A: reference
- Case C: T_b changes due to heat transfer or changing equivalent ratio, either lean or rich.
- Case B: T_u changes due to preheating fuel

2- Pressure (P)

- From Eq. 8.29, if, again, $n \approx 2$, $S_L \neq f(P)$.
- Experimental measurements generally show a negative dependence of pressure. Andrews and Bradley [19] found that

$$S_L \text{ (cm/s)} = 43[P \text{ (atm)}]^{-0.5} \quad (8.32)$$

fits their data for $P > 5$ atm for methane-air flames (Fig. 8.14).

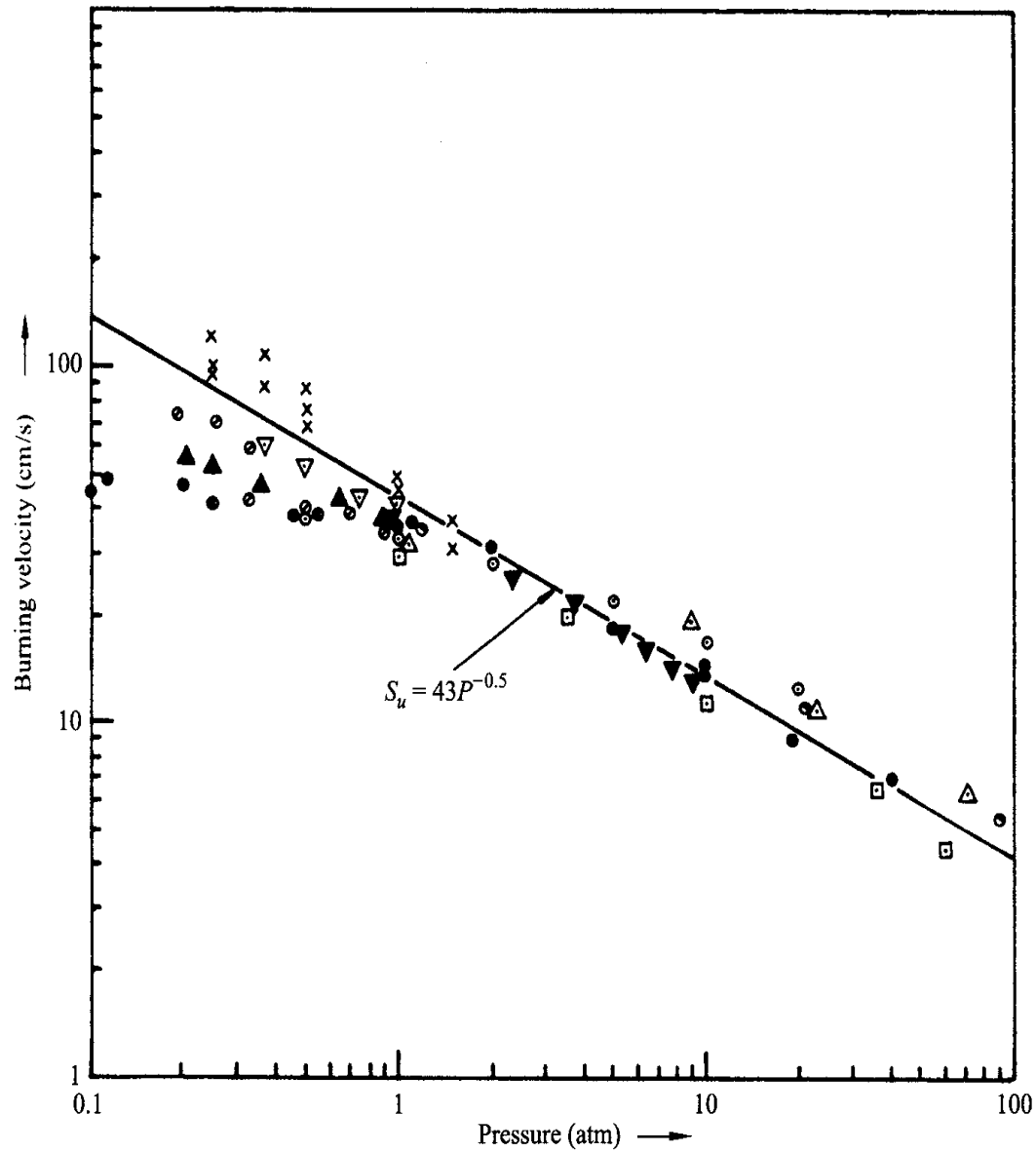


Figure 8.14 Effect of pressure on laminar flame speeds of stoichiometric methane-air mixtures for $T_u = 16\text{--}27^\circ\text{C}$.

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3- Equivalent Ratio (Φ)

- Except for very rich mixtures, the primary effect of Φ on S_L for similar fuels is **a result of how this parameter affects flame temperatures**; thus, we would expect $S_{L,max}$ at a slightly rich mixture and fall off on either side as shown in Fig. 8.15 for behaviour of methane.
- Flame thickness (δ) shows the inverse trend, **having a minimum near stoichiometric** (Fig. 8.16).

4- Fuel Type

- Fig. 8.17 shows S_L for C_1 - C_6 paraffins (single bonds), olefins (double bonds), and acetylenes (triple bonds). Also shown is H_2 . S_L of C_3H_8 is used as a reference.
- Roughly speaking the C_3 - C_6 hydrocarbons all follow the same trend as a function of flame temperature. C_2H_4 and C_2H_2 ' $S_L >$ the C_3 - C_6 group, while CH_4 ' S_L lies somewhat below.

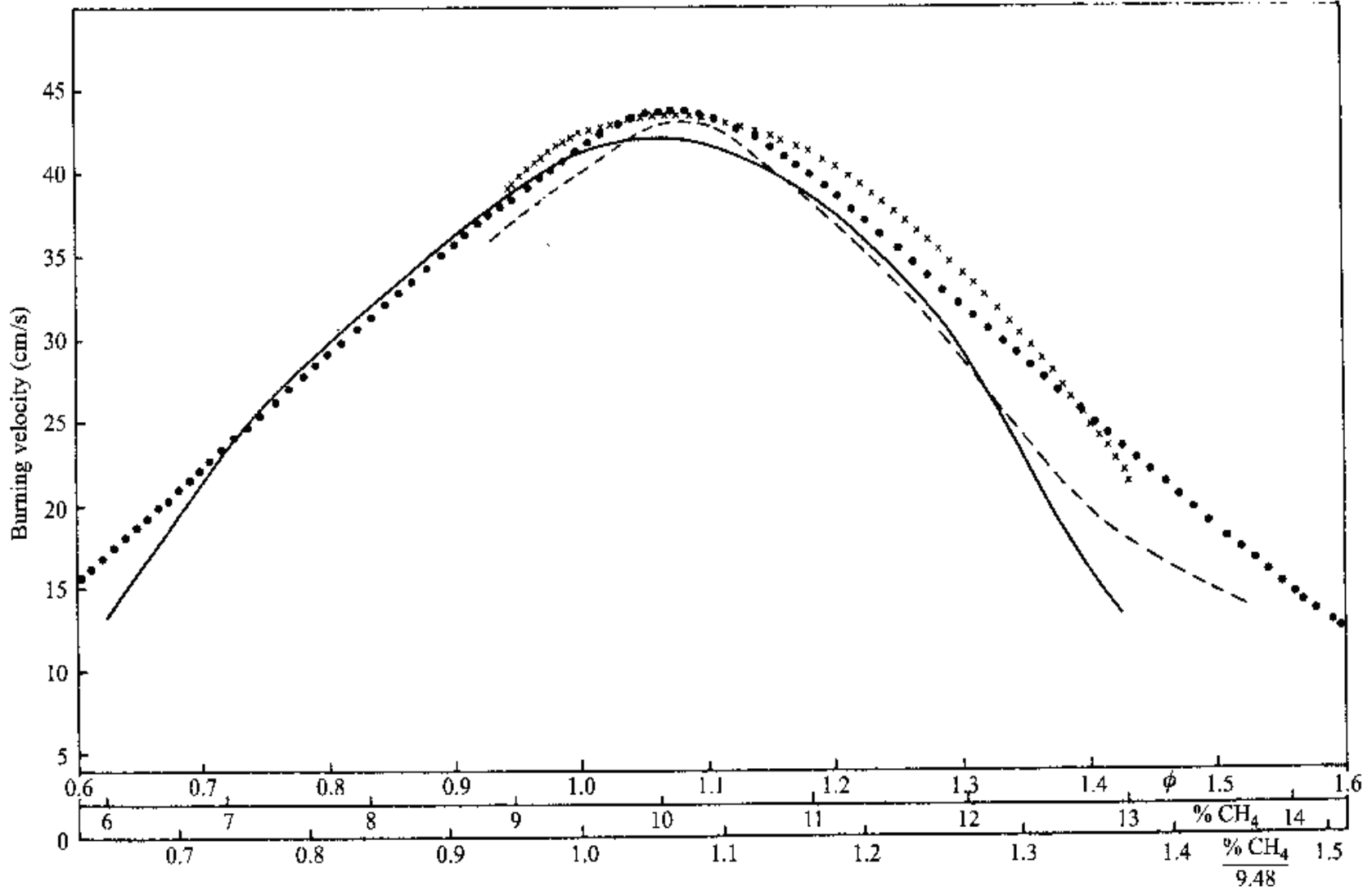


Figure 8.15 Effect of equivalence ratio on the laminar flame speed of methane-air mixtures at atmospheric pressure.

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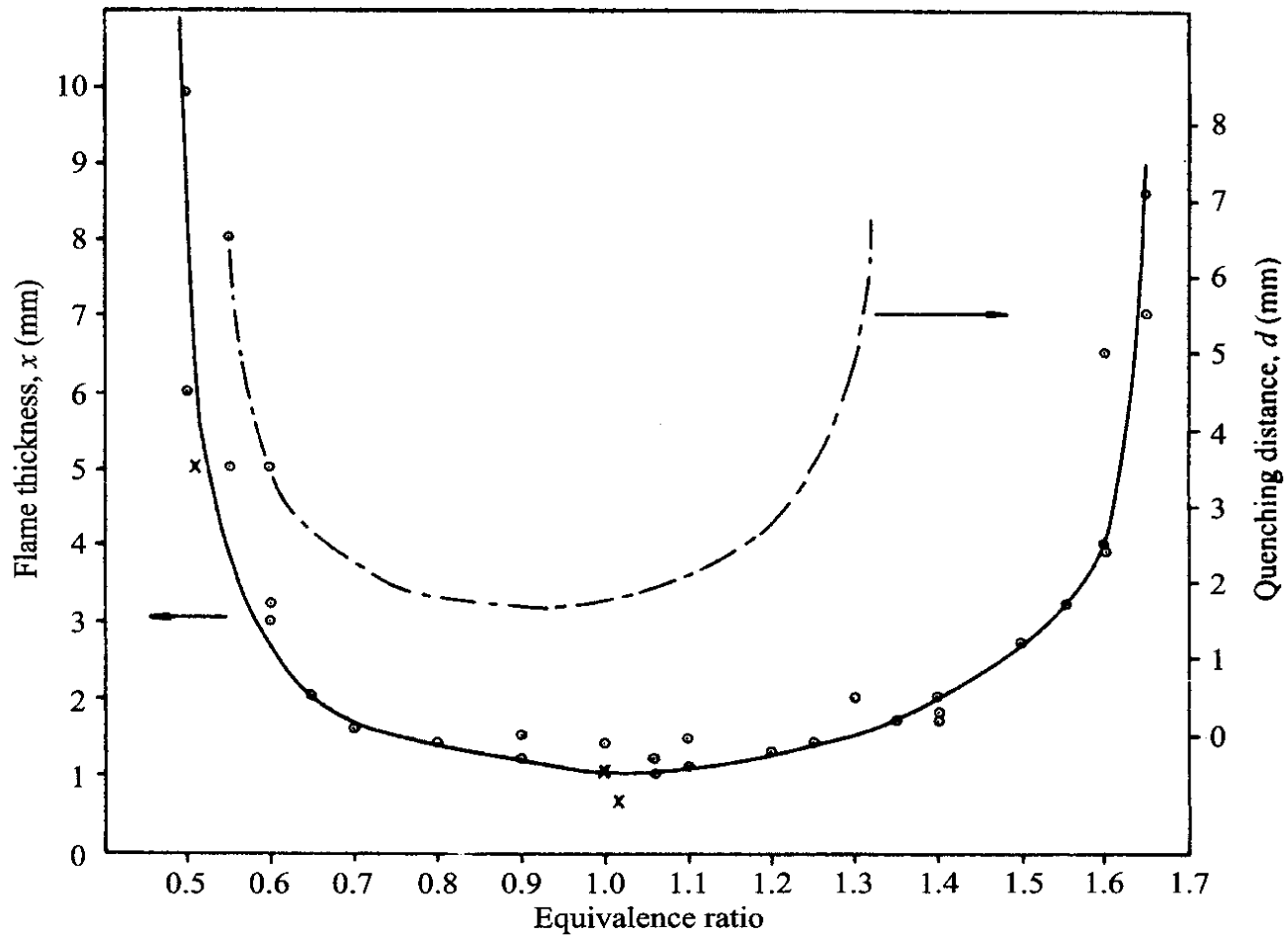


Figure 8.16 Flame thickness for laminar methane-air flames at atmospheric pressure. Also shown is the quenching distance.

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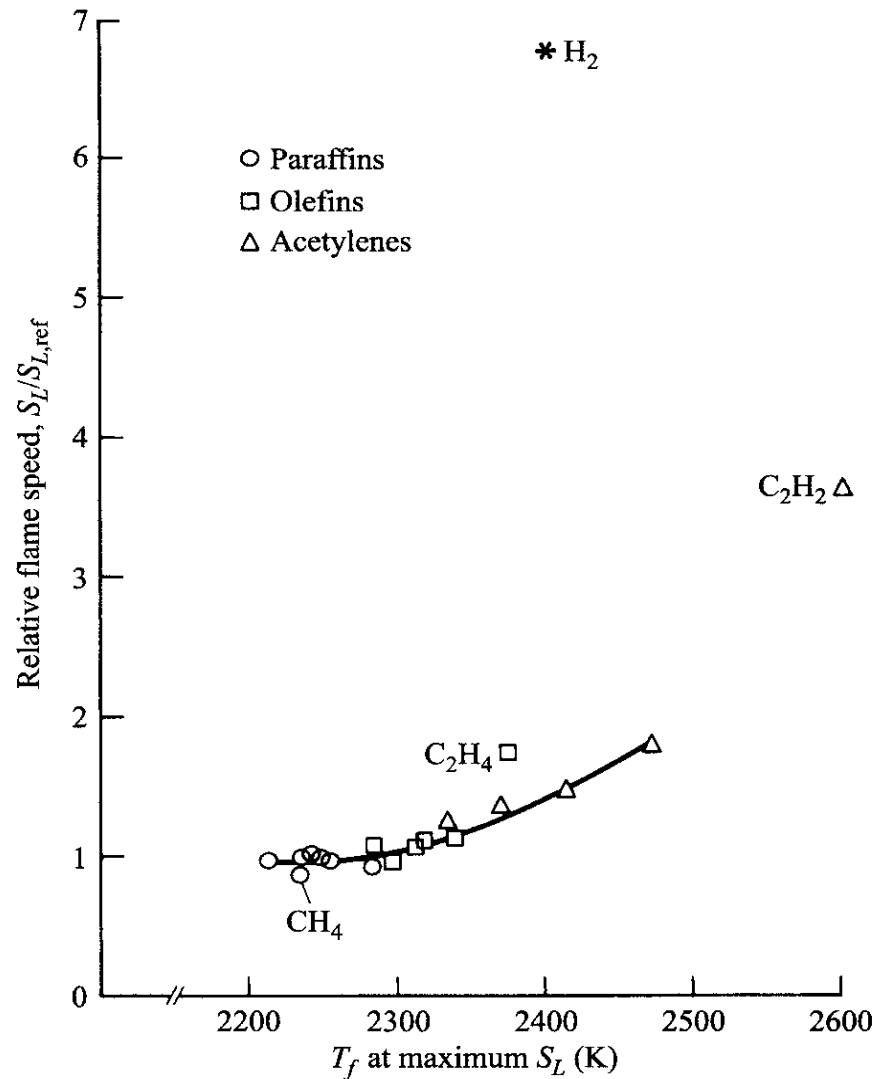


Figure 8.17 Relative flame speeds for C_1 - C_6 hydrocarbon fuels. The reference flame speed is based on propane using the tube method [21].



- H_2 's $S_{L,max}$ is many times $>$ that of C_3H_8 . Several factors combine to give H_2 its high flame speed:
 - i. the thermal diffusivity (α) of pure H_2 is many times $>$ the hydrocarbon fuels;
 - ii. the mass diffusivity (D) of H_2 likewise is much $>$ the hydrocarbons;
 - iii. the reaction kinetics for H_2 are very rapid since the relatively slow $CO \rightarrow CO_2$ step that is a major factor in hydrocarbon combustion is absent.

- **Law [20]** presents a compilation of laminar flame-speed data for various pure fuels and mixtures shown in Table 8.2.
- **Table 8.2** S_L for various pure fuels burning in air for $\Phi = 1.0$ and at 1 atm

Fuel	S_L (cm/s)
CH_4	40
C_2H_2	136
C_2H_4	67
C_2H_6	43
C_3H_8	44
H_2	210

FLAME SPEED CORRELATIONS FOR SELECTED FUELS

- Metghalchi and Keck [11] experimentally determined S_L for various fuel-air mixtures over a range of temperatures and pressures typical of conditions associated with reciprocating internal combustion engines and gas turbine combustors.
- Eqn 8.33 similar to Eqn. 8.29 is proposed

$$S_L = S_{L,ref} \left(\frac{T_u}{T_{u,ref}} \right)^\gamma \left(\frac{P}{P_{ref}} \right)^\beta (1 - 2.1Y_{dil}) \quad (8.33)$$

for $T_u > \approx 350$ K.