

## *Lecture 3*

### *Non-premixed flames*

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# Background

- Develop understanding of how soot is formed in diffusion flame.
- Add partial air in fuel stream to provide non-sooting operation.
- Pollutant emission ( $\text{NO}_2$  and  $\text{CO}$ )
- Flame geometry ( short flames are desired)
- Effects of fuel type

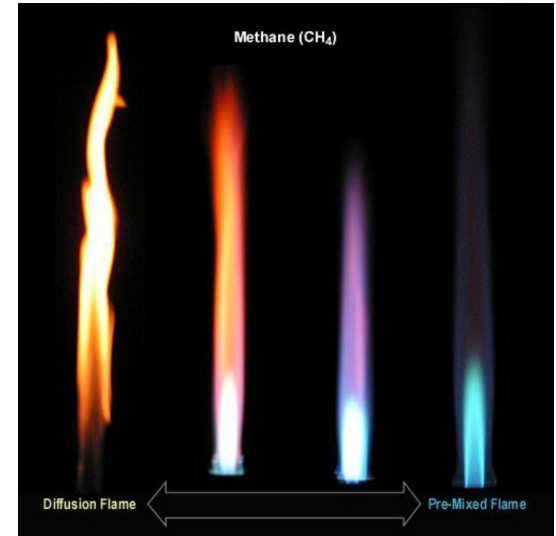
# Non-premixed Flames

**Non-premixed flames are commonly termed as diffusion flames, where the oxidizer and fuel are not mixed prior to reaching the flame front**

- By definition, a diffusion flame in combustion is a flame in which oxidizer combines with the fuel through diffusion. Consequently, the flame speed of a non-premixed flame is limited by the rate of diffusion
- Non-premixed flames generally tend to burn slower and to produce more soot, in comparison to premixed flames, due to the possibility in having insufficient amounts of oxidizer for a complete reaction.

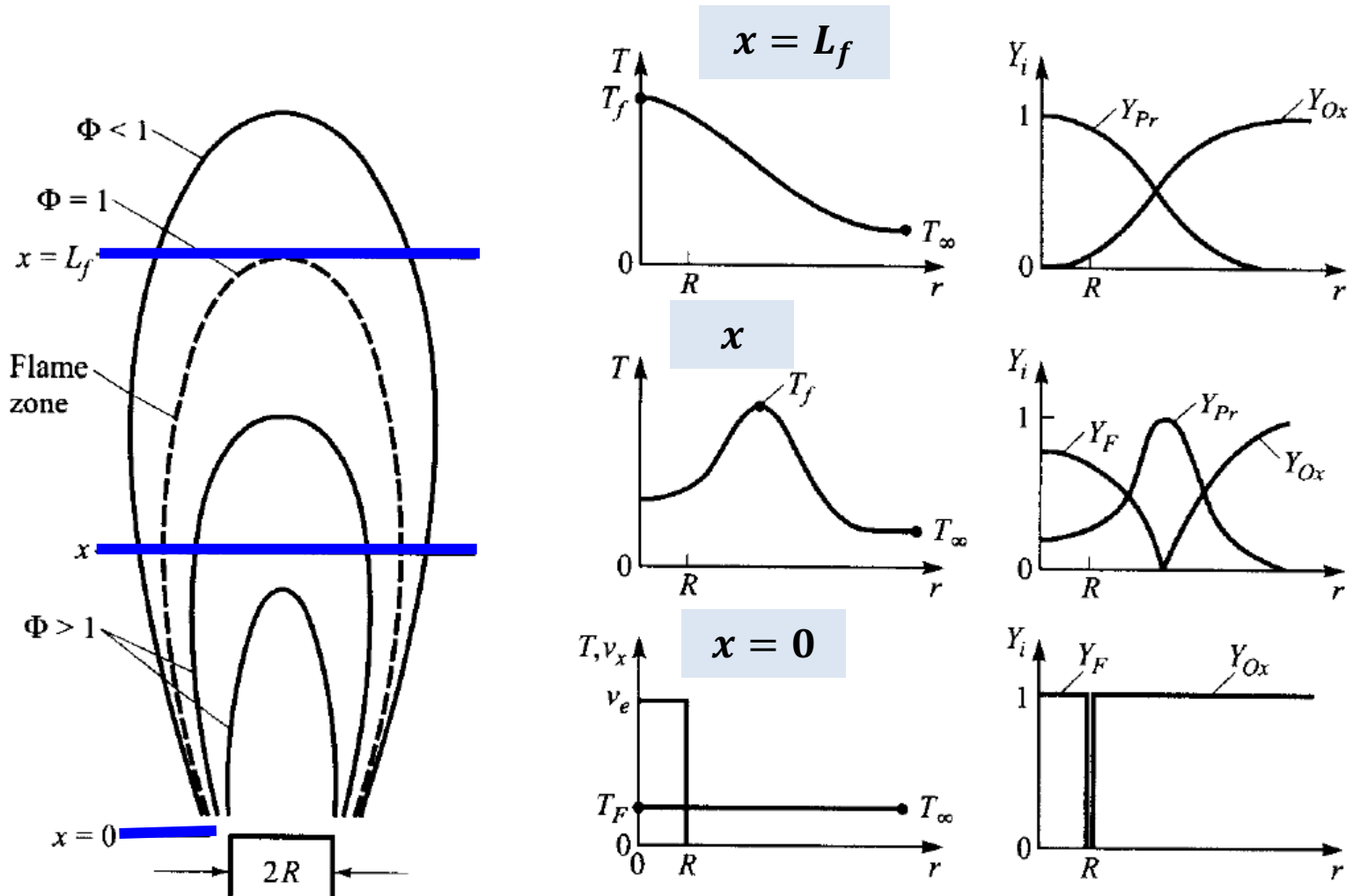
# Diffusion methane flame

The picture depicts some different flames of the combustion of methane ( $\text{CH}_4$ ), ranging from non-premixed (diffusion) flames to premixed flames



- ❑ In non-premixed flames it is entirely the rate of molecular diffusion but not the chemical kinetics that sustains the combustion process. The **mass fraction gradients** resulting from the consumption of fuel and oxidizer at the reaction zone drive the diffusion transport of fuel and oxidizer toward the flame where they mix and react.
- ❑ The pure fuel migrates towards the combustion zone nevertheless due to the lack of oxygen the fuel is pyrolyzed and broken down into smaller molecules and radicals. This is the cause of soot formation which gives the distinctive bright yellow colour to these flames.
- ❑ As the products of pyrolysis approach the combustion zone they will find adequate oxygen to perform the stoichiometric oxidation reactions. The resulting flame zone is substantially thicker than premixed flames. As a consequence, the flame will always position itself such that the mass fluxes of fuel and oxidizer entering the reaction zone are at stoichiometric conditions.

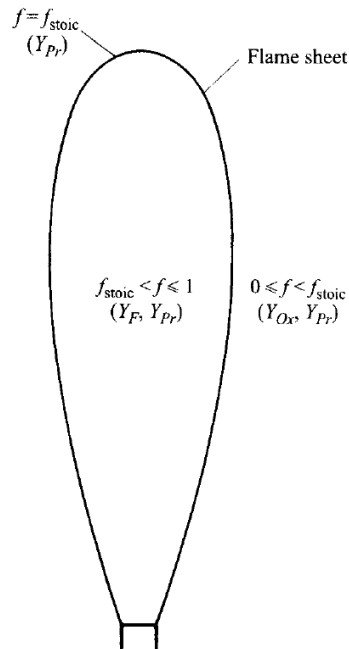
# Laminar diffusion flame structure



$T_f$  flame temperature;  $Y_i$  mass fraction;  $p_r$  products;  $O_x$  oxidizer;  $F$  fuel;

# Mixture Fraction

$$\text{mixture fraction } f \equiv \frac{\text{Mass of material having its origin in the fuel stream}}{\text{Mass of mixture}} = Y_F + \left( \frac{1}{1+\nu} \right) Y_{Pr}$$



**Inside the flame** ( $f_{stoic} < f \leq 1$ )

$$Y_F = \frac{f - f_{stoic}}{1 - f_{stoic}} \quad Y_{Ox} = 0 \quad Y_{Pr} = \frac{1 - f}{1 - f_{stoic}}$$

**At the flame** ( $f_{stoic} = f$ )

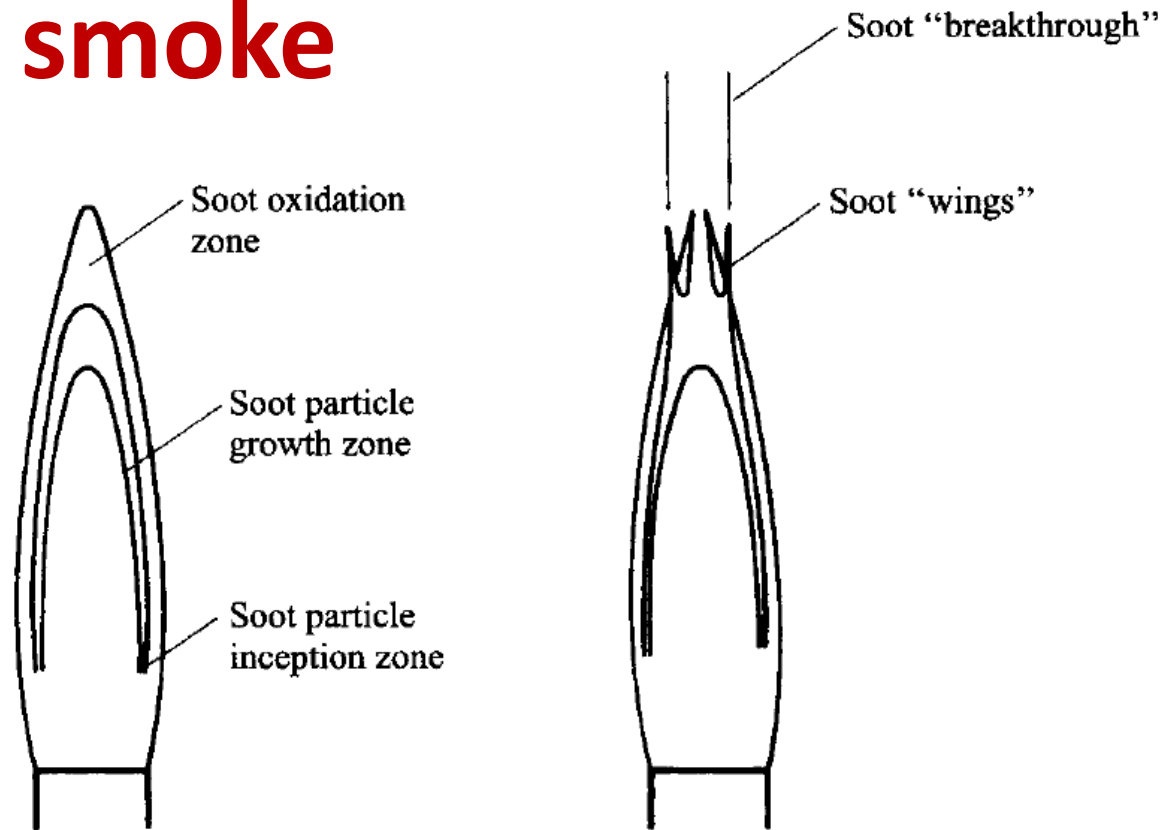
$$Y_F = 0 \quad Y_{Ox} = 0 \quad Y_{Pr} = 1$$

**Outside the flame** ( $0 \leq f < f_{stoic}$ )

$$Y_F = 0 \quad Y_{Ox} = 1 - \frac{f}{f_{stoic}} \quad Y_{Pr} = \frac{f}{f_{stoic}}$$

The mixture fraction is particularly useful in dealing with diffusion flames where the fuel and oxidizer streams are initially segregated. For premixed combustion, the mixture fraction is everywhere uniform, assuming all species have the same diffusivities; hence, a conservation equation for 'f' provides no new information.

# Soot and smoke

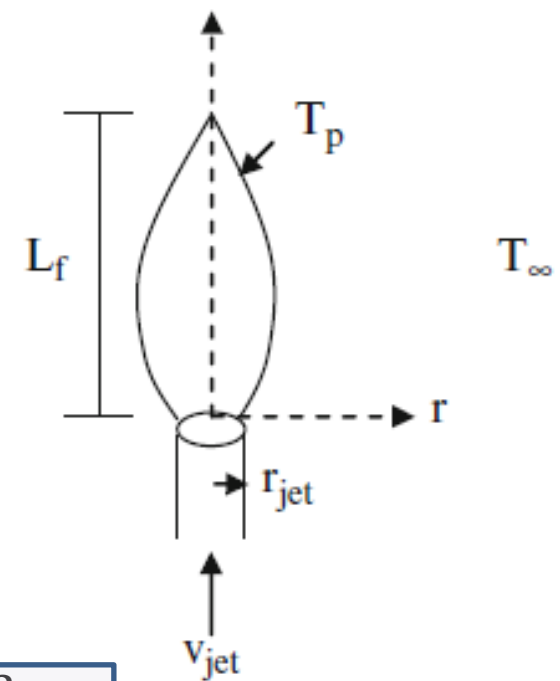


Depending on the **fuel type** and **flame residence time**, not all of the soot that is formed may be oxidized on its journey through high-temp oxidizing regions. In this case, soot 'wings' may appear, with the soot breaking through the flame. This soot that breaks through is generally referred to as **smoke**.

# Laminar jet flame height

The length, or height, of a non-premixed flame is an important property indicating the size of a flame.

$$L_f \propto \frac{\dot{Q}_{fuel}}{D \cdot Y_{F,stoic}} \propto \frac{V_{jet} r_{jet}^2}{D \cdot Y_{F,stoic}} \quad (\text{for circular-port flames})$$



diffusion time

$$\tau_{diffusion} \approx \frac{r_{jet}^2}{D}$$

convective time

$$\tau_{convective} \approx \frac{L_f}{V_{jet}}$$

chemistry time

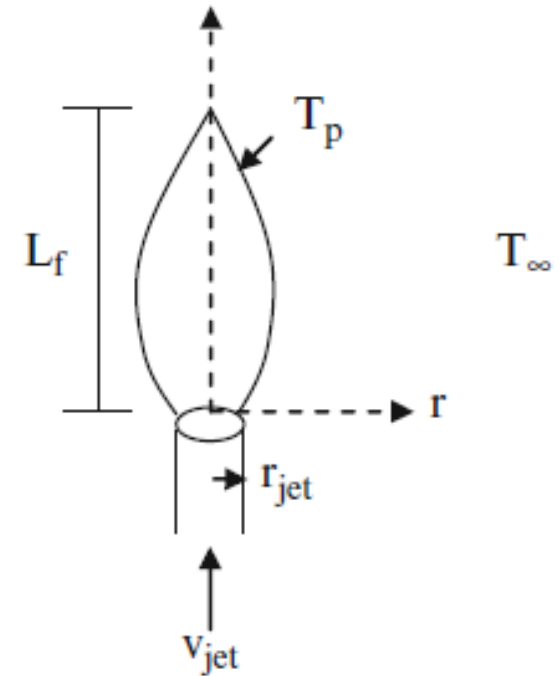
$$\tau_{chem} \approx \frac{[Fuel]}{\dot{r}_{fuel}}$$



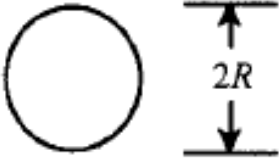

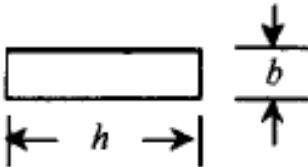
# Simplified theoretical descriptions

## Assumptions:

- 1) The flow is laminar, steady and axisymmetric, produced by a jet of fuel emerging from a circular nozzle, which burns in a infinite reservoir of oxidizer.
- 2) Only three species: fuel, oxidizer and products.
- 3) Fuel and oxidizer react in stoichiometric proportions at the flame.
- 4) Species molecular transport is by simple binary diffusion governed by Fick's Law.
- 5) Thermal energy and species diffusivities are equal. Thus the Lewis number ( $Le = \alpha/D$ ) is unity.
- 6) Radiation heat transfer is negligible.
- 7) Axial diffusion is neglected.
- 8) Flame axis is oriented vertically upwards.



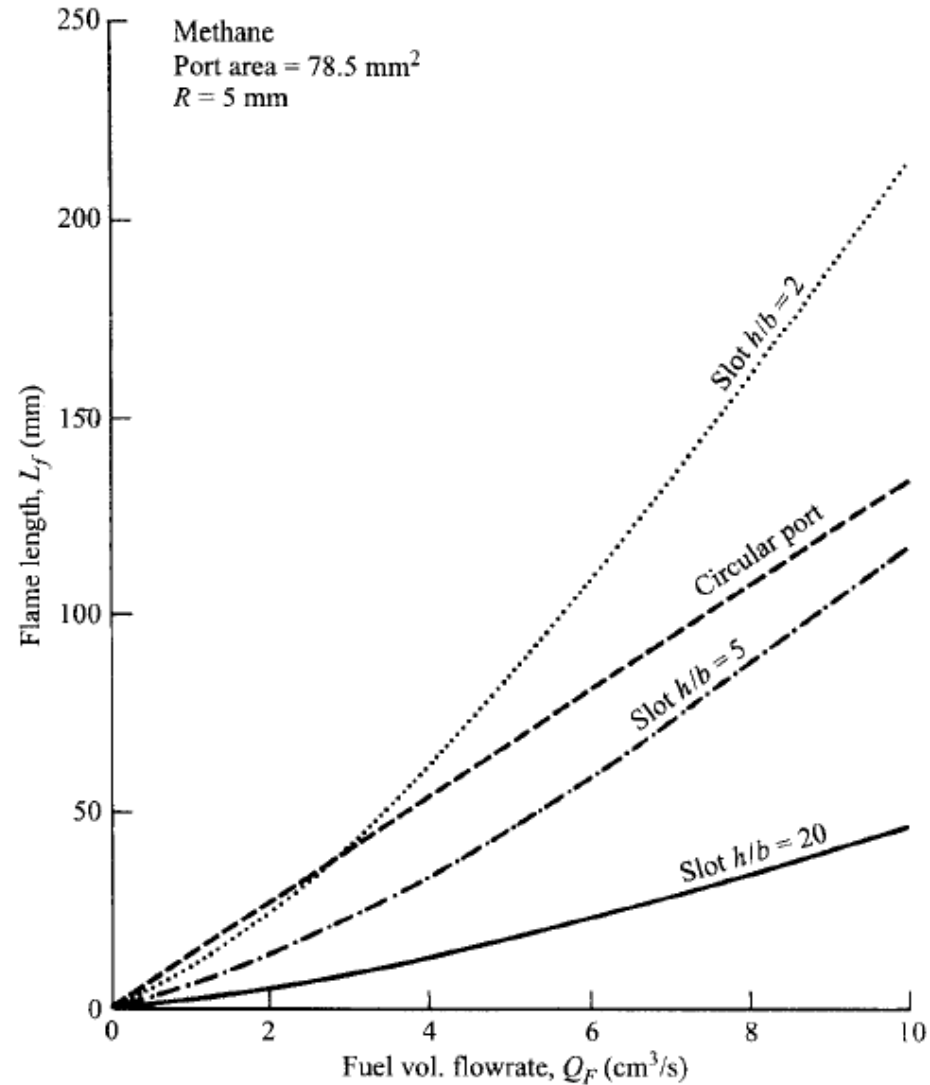
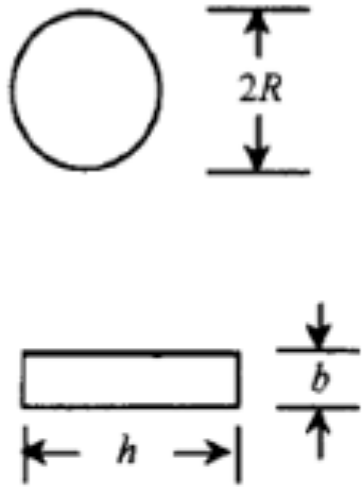
# Empirical Correlations by Roper

Port Geometry	Conditions
	<p>Circular</p> <p>Momentum- or buoyancy-controlled</p> $L_{f,thy} = \frac{\dot{Q}_{fuel}(T_{\infty}/T_F)}{4\pi D_{\infty} \ln(1 + 1/S)} \left(\frac{T_{\infty}}{T_P}\right)^{0.67}$ $L_{f,expt} = 1330 \frac{\dot{Q}_{fuel}(T_{\infty}/T_F)}{\ln(1 + 1/S)}$
	<p>Square</p> <p>Momentum- or buoyancy-controlled</p> $L_{f,thy} = \frac{\dot{Q}_{fuel}(T_{\infty}/T_F)}{16D_{\infty} [\text{inverf}((1 + S)^{-0.5})]^2} \left(\frac{T_{\infty}}{T_P}\right)^{0.67}$ $L_{f,expt} = 1045 \frac{\dot{Q}_{fuel}(T_{\infty}/T_F)}{[\text{inverf}((1 + S)^{-0.5})]^2}$
	<p>Slot</p> <p>Momentum-controlled</p> <p>Buoyancy-controlled</p> <p>Mixed momentum–buoyancy-controlled</p>

$S$  is the molar stoichiometric air-fuel ratio

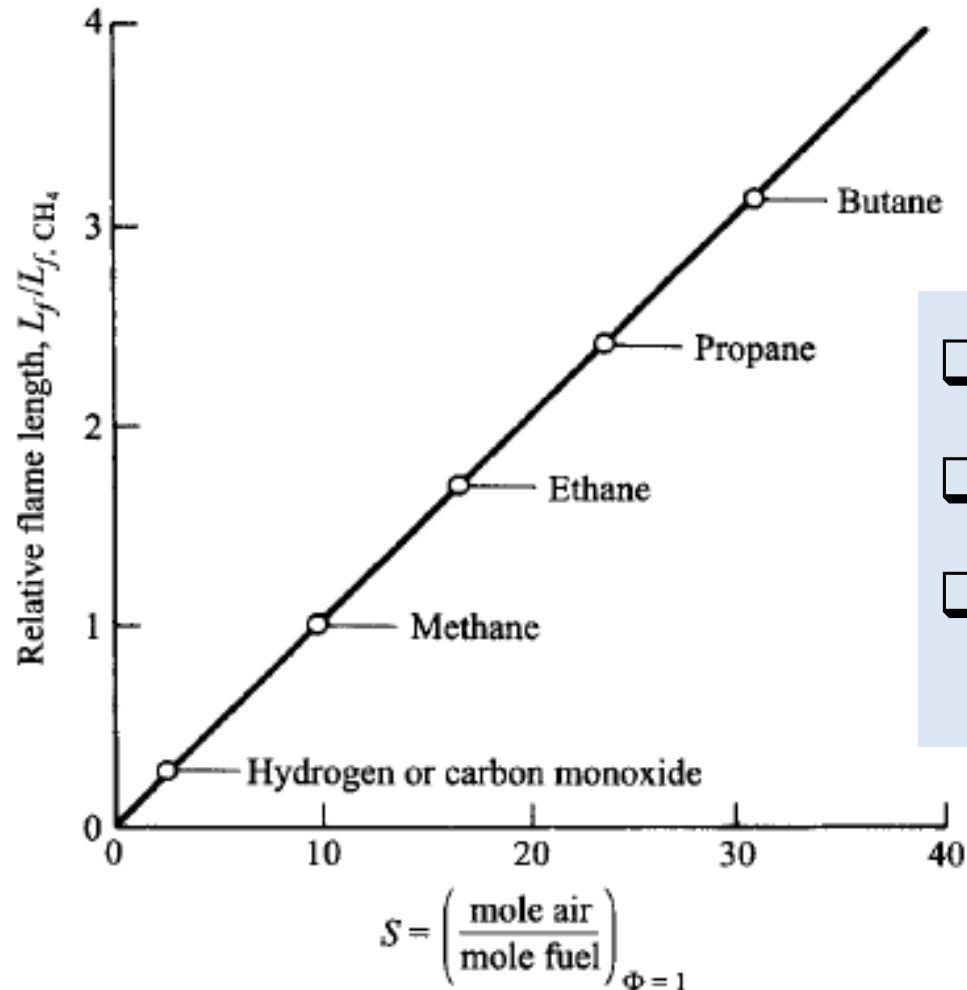
$\omega = \text{inverf}(\text{erf} \omega)$

# Flow rate and Geometry effects



# Factors affecting stoichiometry

## (1) Fuel type

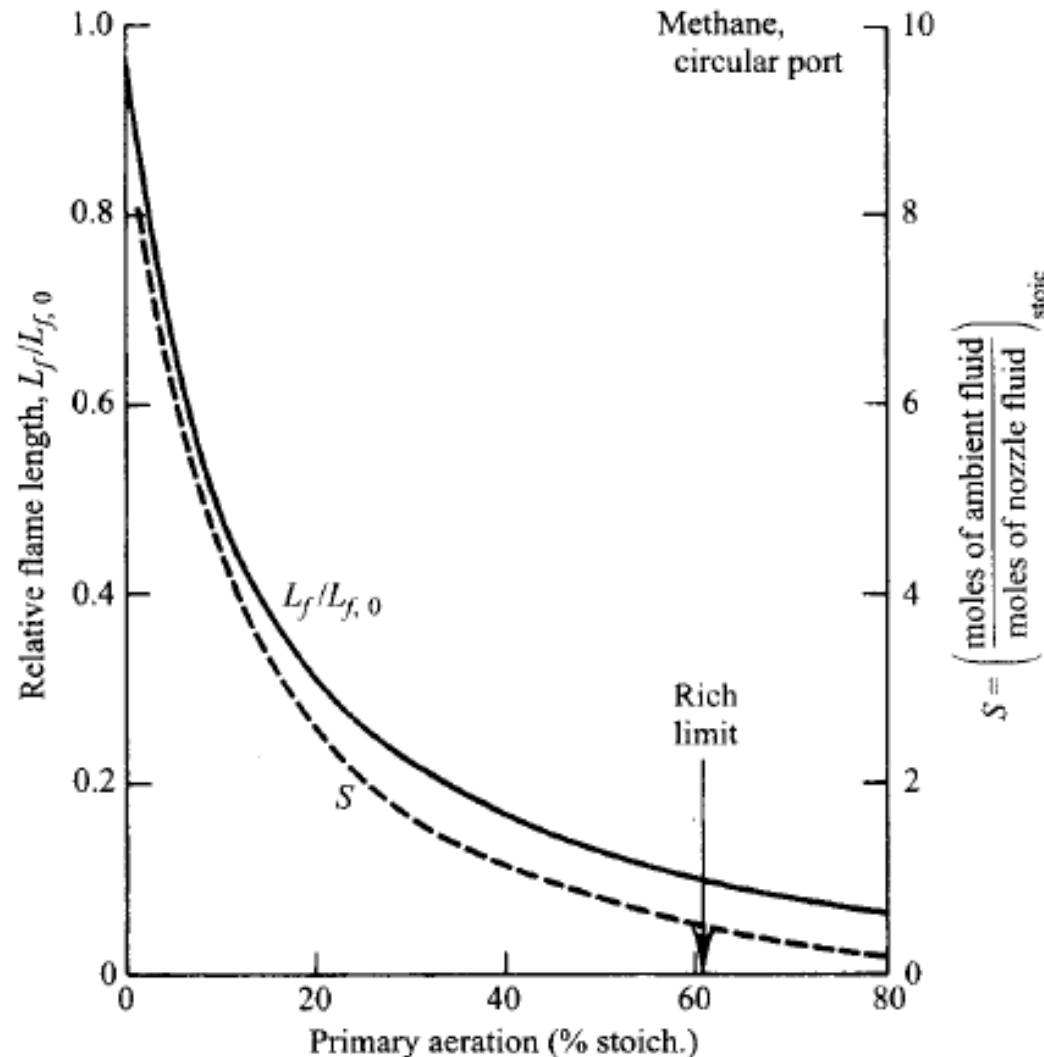


- ❑ Same circular port
- ❑ Equal flow rate
- ❑ Same mean diffusivity

*(this assumption is not good for hydrogen)*

# Factors affecting stoichiometry

## (2) Primary Aeration



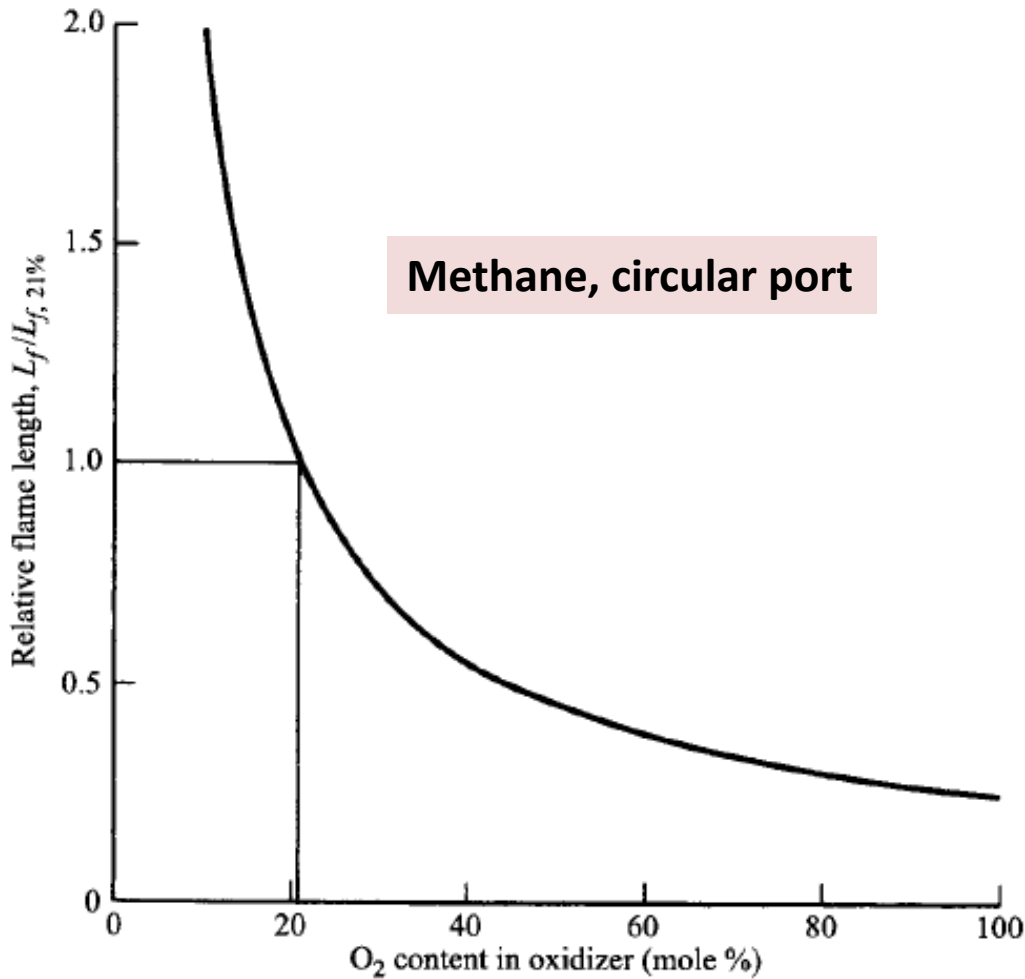
Gas-burning appliances premix some air with the fuel gas before it burns as a laminar jet diffusion flame, this is called **primary aeration**.

This primary aeration, a typically 40-60 percent of the stoichiometric air requirement, makes the flames short and prevent soot from forming, resulting in a blue flame.

The maximum amount of air that can be added is limited by safety consideration. If too much air is added, the rich flammability limit may be exceeded, which implies the mixture will support a premixed flame.

# Factors affecting stoichiometry

## (3) Oxygen content in oxidizer



Methane/air  
( $L_f=79$  mm)



Methane/50% O<sub>2</sub>  
( $L_f=25$  mm)

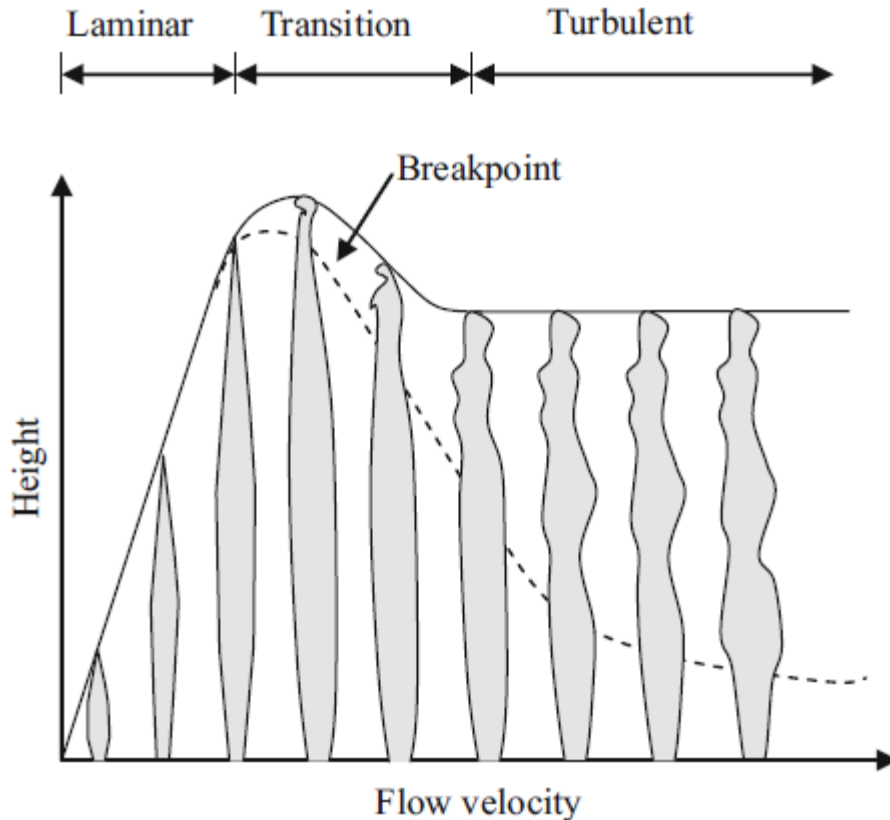


Methane/100% O<sub>2</sub>  
( $L_f=12$ mm)

## (4) Fuel dilution with inert gas

K.-O. Lee et al. Combustion & Flame, 121 (1-2), 323-333, 2000

# Turbulent Jet Flames



Height has a linear dependence when the jet velocity is below a certain value. The flame height becomes independent of jet velocity when the velocity is sufficiently high and reaches the fully turbulent regime

$$L_f \propto \frac{V_{jet} r_{jet}^2}{D_t} \propto \frac{V_{jet} r_{jet}^2}{V_{jet} r_{jet}} \propto r_{jet}$$

**Estimation of turbulent jet flames with hydrocarbon fuels burning with air**

$$\frac{L_f}{d_{jet}} = 6 \left( \frac{1}{(F/A)_{stoic}} + 1 \right) \sqrt{\frac{\rho_{fuel}}{\rho_{flame}}}$$

$(F/A)_{stoic}$  is the stoichiometric fuel-air mass ratio

# Lift-off Height and Blowout limit

Experimentally, it is observed that when the velocity of a jet increases to a point, the flame lifts off of the nozzle. Further increase in jet velocity leads to total flame blow out. This effect is related to the fact that when the jet velocity is increased, the lower portion of the flame that anchors the flame to the jet nozzle cannot propagate against the flow. Because there is a gap between the reaction and the nozzle tip, the fuel and air mix together and the flame in this area is similar to a premixed one. Thus it is expected that the conditions for lift off should be determined by the relative magnitude of the jet velocity and the premixed flame speed.

## Lift-off height proposed by Gautam

$$h = 50 \cdot v_{jet} \frac{V_{jet}}{S_{L,max}^2} \left( \frac{\rho_{jet}}{\rho_{\infty}} \right)^{1.5}$$

Blowout jet velocity: 
$$V_{jet,blowout} = S_{L,max} \left( \frac{\rho_{jet}}{\rho_{\infty}} \right)^{1.5} \cdot 0.17 Re_H (1 - 3.5 \cdot 10^{-6} Re_H)$$

$$Re_H = \frac{\rho_{jet} S_{L,max} H}{\mu_{jet}} \quad H = 4 d_{jet} \left[ \frac{y_{f,jet}}{y_{f,stoi}} \left( \frac{\rho_{jet}}{\rho_{\infty}} \right)^{0.5} \right] - 5.8$$

$y_{f,jet}$  is the mass fraction of fuel from the jet and  $y_{f,stoi}$  is the mass fraction of fuel in the stoichiometric mixture;  $v_{jet}$  is the kinematic viscosity of the jet fluid;  $\mu_{jet}$  is the dynamic viscosity of the jet fluid; and  $S_{L,max}$  is the maximum laminar flame speed.



# Nomenclature

$d_{jet}$	Burner diameter (m)
$D$	Mass diffusivity (m <sup>2</sup> /s)
$D_t$	Turbulent diffusivity
$F/A$	Fuel-air mass ratio
$g$	Gravitational acceleration (m/s <sup>2</sup> )
$L_f$	Flame length (m)
$MW$	Molecular weight (kg/kmol)
$\dot{Q}$	Volumetric flow rate (m <sup>3</sup> /s)
$\hat{Q}_c$	Heat of combustion (J/kmol)
$r$	Radial coordinate (m)
$\hat{r}$	Reaction rate (rate of production or destruction of a chemical species per unit volume) (kmol/m <sup>3</sup> -s)
$R$	Radius (m)
$r_{jet}$	Fuel jet radius (m)
$x$	Axial coordinate (m) or number of carbon atoms in fuel molecule
$S$	Molar stoichiometric air/fuel ratio
$S_{L,max}$	Maximum laminar flame speed (m/s)
$T$	Temperature (K)
$u$	Flame propagation speed into the unburned mixture (m/s)
$V_{jet}$	Fuel jet velocity (m/s)
$Y$	Mass fraction (kg/kg)
$y_{f,jet}$	Mass fraction of fuel from the jet
$y_{f,stoi}, y_{fs}$	Mass fraction of fuel in the stoichiometric mixture

## Greek Symbols

$\tau_{chem}$	Chemistry time (s)
$\tau_{conv}$	Convective time (s)
$\tau_{diff}$	Diffusive time (s)
$\nu$	Stoichiometric air–fuel ratio (kg /kg)
$\nu_{jet}$	Kinematic viscosity of the jet fluid (m <sup>2</sup> /s)
$\mu_{jet}$	Dynamic viscosity of the jet fluid (kg/m/s)
$\phi$	Equivalence ratio
$\rho$	Density (kg/m <sup>3</sup> )

# Nomenclature

## ***Subscripts***

$e$	Exit
$f$	Flame
$F$	Fuel
$i$	$i$ th species
$Ox$	Oxidizer
$Pr, P$	Products
$stoic$	Stoichiometric
$\infty$	Ambient

## ***Other Notation***

$[X]$	Molar concentration of X (kmol/m <sup>3</sup> )
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