S.1 Introduction to Laminar Non-premixed Flames

Laminar non-premixed flames are often also called as laminar diffusion flames.

- Laminar jet flames have been used to develop an understanding of how soot is formed in diffusion burning.
- A familiar example would be the Bunsen-burner Outer-cone Flame.
- In understanding laminar non-premixed flames, it is necessary to get an idea about what a Flame is.
- Many residential gas appliances (e.g. cooking ranges and ovens) employ laminar flames however that use fuel which is partially mixed with air which is essential to avoid soot.
- Understanding laminar flames is also necessary to study turbulent flames, since in both laminar and turbulent flows, the same physical processes apply while many turbulent flame theories are based on laminar flame structures.
- In the design of any system employing laminar jet flames, a primary concern is flame geometry, where often short flames are desired, while the effect of fuel type is also important.
Non premixed methane flame

Different flames of methane (source)
The picture depicts some different flames of the combustion of methane (CH₄), ranging from non-premixed (diffusion) flames to premixed flames
Bunsen-burner outer cone flame is one familiar example of laminar non-premixed (diffusion) flames

- It is to be noted that the inner cone is a premixed cone
- A schematic of a Bunsen burner along with the identification of the difference in the flame cones are shown in the diagram given
Bunsen-burner

Schematic of Bunsen-burner (source)
P1.1.1 Source

P1.1.2 Where am I?

Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Consideration of one dimensional flame propagation in a tube with cross section A

For a one dimensional flame propagating in a tube with a cross-section area of A, the terms Flame, Localized, Deflagration, and Detonation needs to be defined.

If the flame is stationary, the unburned mixture will propagate towards the flame with the velocity \( S_L = \text{Flame Speed} \)

P1.2.1 Source

Jeevan Jayasuriya, 2011.
“Combustion Theory Lecture 2: Thermal Chemistry”
Department of Energy Technology, Royal Institute of Technology, Sweden. Available at: https://bilda.kth.se/launchCourse.do?id=7452 [Accessed 05 January 2012]
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
P1.2.3 Flame

A flame is a self-sustaining propagation of a localized combustion zone at subsonic velocities (deflagration).

P1.2.4 Localized

The flame is said to be localized when the flame occupies only a small portion of the combustible mixture at any one time.

P1.2.5 Deflagration

Deflagration is a discrete combustion wave that travels subsonically (Speed = 40 – 200 cm/s).

P1.2.6 Detonation

Detonation is a discrete combustion wave that travels supersonically (Speed = 1-2 km/s).

P1.2.7 Flame Speed

The flame speed is defined as, the measured rate of expansion of the flame front in a combustion reaction.
Basic flame types can be identified according to the differences in the fuel and oxidizer mixing and according to the type of fluid motion.

- There are two basic flame types according to the differences in fuel/oxidizer mixing; **Premixed Flames** and **Non-premixed Flames**
- There are two basic flame types according to the type of fluid motion; **Laminar Flames** and **Turbulent Flames**
- The following figure gives some examples of these flame types

### According to Fuel/oxidizer mixing
- **Premixed**
  - 1. Flame???
  - 2. Bunsen flame (followed by a non-premixed candle for $\varphi>1$)
- **Non-premixed**
  - 1. Bunsen flame (followed by a non-premixed candle for $\varphi>1$)
  - 2. Low NOx stationary gas turbine

### According to Fluid Motion
- **Laminar**
  - 1. Wood fire
  - 2. Radiant burners for heating
  - 3. Candle flame
- **Turbulent**
  - 1. Pulverized coal combustion
  - 2. Aircraft turbine
  - 3. Diesel flame
  - $\text{H}_2/\text{O}_2$ rocket motor

**Basic Flame types and their examples** ([source](#))
P1.3.1 Source

Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
P1.3.3 Premixed Flames

Premixed flames are flames in which the oxidizer has been mixed with the fuel, prior to the reaching of flame front.

- Premixing of fuel and oxidizer creates a thin flame front, due to the readily availability of as all of the reactants
- Often a diffusion flame can be found farther downstream, if the mixture is rich

P1.3.4 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, however with some exceptions to the rule
In most combustion processes fuel and air are not initially mixed. This condition leads to a characteristic flame known as non-premixed or diffusion flame. Molecular diffusion - the rate of which is influenced by different factors such as rate of mixing and flow velocity – thus takes place at the air fuel interface. The region where the diffusion process occurs is also the region where the combustion exists and hence the extent of diffusion determines the region of the flame. One of the common and simple examples is that the air and fuel are injected in parallel into the combustion chamber. In such cases the thickness of the mixing layer increases as the flame progresses downstream and eventually becomes uniform. Thus a flame with uniform thickness is formed as it progresses.

In non-premixed flames it is entirely the rate of macular diffusion but not the chemical kinetics that sustains the combustion process. The pure fuel migrates towards the combustion zone as it is in the pre-mixed flames nevertheless due to the lack of oxygen the fuel is pyrolyzed and broken down into smaller molecules and radicals. This is also the cause of soot formation which gives the distinctive bright yellow color 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.
P1.3.6 Turbulent Flames

Perfect laminar flames do not exist in practice as they require either thermal diffusion (pre-mixed) or molecular diffusion (non-premixed) which involves certain degree of turbulence. Turbulence has a great influence over the mixing and thus the energy intensity of a combustion process. Turbulence is one of the three T’s of a good combustion process;

- Time
- Temperature
- Turbulence

At higher levels of combustion intensity turbulence acts negatively on the flame stability. In such cases recirculation is being used. Recirculation may be achieved by one or a combination of the following three methods.

Bluff body recirculation (video)
As could be seen in aero gas turbine reheat sections the bluff body produces a low pressure region behind it which draws gas into it in a recirculating flow pattern. Fuel is injected into this zone and continually re-ignited sustaining combustion.

Swirl
This is a very common recirculation method. When a swirler is placed on the air or fuel stream the resulting centrifugal force throws the flow outwards in a spiraling motion. Here also a low pressure region is created which draws back the flow stream to the center.
Sudden Expansion
This method relies on the sudden expansion of a confined jet into a stream flows in parallel. The co-flowing jet forces it to draw in products from downstream resulting in a donut shaped vortex around the base of the jet.

P1.3.6.1 Video

- Bluff body recirculation

Total time: 04:10
The size: 87.10 MB

P1.4 Video

- Non-premixed methane flame
Total time: 01:07
The size: 14.40 MB
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Important note:
This external site is recommended to learn more about the topic/phenomena under investigation.
By clicking on the continue button the user will be directed to an external website.
The CompEdu developers and platform are not responsible for the content of the external internet sites suggested. There is also no guarantee that the site is still valid.

P1.5 Different flames of methane

The picture depicts some different flames of the combustion of methane (CH4), ranging from non-premixed (diffusion) flames to premixed flames
Observe the color transition as the flame moves from diffusion state to pre-mixed state.

(Source 1)

P1.5.1 Source 1

Author: First name Last name, Year;
Title: ”???”
Publisher: Organization Name, ISSN, Date
Acknowledgements

Author: Saman Gunasekara, MSc, KTH, 2011
Author: Jeevan Jayasuriya, Affiliation, Year
Reviewer: First Name Last Name, Affiliation, Year
Reviewer: First Name Last Name, Affiliation, Year
Reviewer: First Name Last Name, Affiliation, Year

P1.6.1  First name Last name

Link to a third party website:
Site name: ???
Title of the article on the site: “Title”
Accessed: Date Month name, Year

(put an image of the person and hyperlink the image to the web address by right click on the snapshot)
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Please right click on the “Continue” button and select “Hyperlink...” and copy and paste the web address in the address part.

P1.7 Literature

Author: First name Last name, Year;
Title: "???"
Publisher: Organization Name, ISSN, Date

Jeevan Jayasuriya, 2011;
“Combustion Theory Lecture 2: Thermal Chemistry”
P1.8 Prerequisites

Basic knowledge about:

- Basic Thermodynamics
P1.9  LU and TU

Learning Units: 8
Teaching Units: 4

Explanation:

Learning Units (LU) correspond to estimated number of hours for self-learning of the chapter. Teaching Units (TU) correspond to estimated number of hours for a teacher to present the material in this chapter. Here, a unit, or lecture hour, corresponds to 45 clock minutes.

P1.10 Source

Author: First name Last name, Year;
Title: ”???”
Publisher: Organization Name, ISSN, Date
S.2 Educational objectives

At the end of this chapter, the student should be able to:

- Identify laminar diffusion flames from different flame types, by appearance, and discuss their differences.
- Describe and discuss the general characteristics of the velocity and nozzle-fluid concentration fields of laminar jets and describe the Reynolds number dependence of the spreading characteristics.
- Discuss and describe parameters controlling laminar diffusion flame lengths (flame size) and shape.
- Discuss and describe the phenomenon of soot formation and destruction from laminar jet flames.

S.3 Non-reacting Constant-Density Laminar Jet

To understand jet flames, considering a simple case of a non-reacting laminar jet of fluid (fuel) flowing into an infinite reservoir of quiescent fluid (oxidizer) is useful.
Essential features of the simple jet (source)

Based on such a jet, the following relationships can be derived

- For simplicity, the velocity profile is assumed to be uniform at the tube exit
- Jet momentum is conserved, while the jet velocity decreases
- The velocity field is similar to the fuel concentration field
- Hence,

\[ \text{Momentum flow of the jet at any } x, J = \text{Momentum flow issuing from the nozzle, } J_e \]
\[ Y_F(r, x) = \nu_x(r, x)/\nu_e \]

\[ 2\pi \int_0^\infty \rho(r, x)\nu_x^2(r, x)rdr = \rho_e \nu_e^2 \pi R^2 \]

\[ 2\pi \int_0^\infty \rho(r, x)\nu_x(r, x)Y_F(r, x)rdr = \rho_e \nu_e^2 \pi R^2 Y_{F,e} \]

Where,

- \( Y_F \) = Mass fraction of fuel
- \( r \) = Radial coordinate (m)
- \( R \) = Radius (m)
- \( x \) = Axial coordinate (m)
- \( \nu_x \) = Axial velocity component (m/s)
- \( \rho_e \) = Density of the fuel at the nozzle exit
- \( \nu_e \) = Velocity of the fuel at the nozzle exit

The assumptions used in this derivation are,

- Density \( \rho \) = constant everywhere, ideal gas
- Fick’s law for distribution
- Factor \( S_c \) (Schmidt number); \( S_c = \nu D = 1 \) (unity)
P3.1 Source


P3.2 Essential features of the simple jet

The figure illustrates a Nonreacting, laminar fuel jet issuing into an infinite reservoir of quiescent air, from a nozzle of radius $R$ into air
For simplicity, the velocity profile is assumed to be uniform at the tube exit.

- Close to the nozzle, a region called ‘potential core’ exists.
- In this region, the viscous shear and diffusion effects are not felt as yet, hence both the velocity and nozzle fluid mass fraction are uniform, and remain unchanged from their nozzle-exit values.

- In the region between potential core and ‘jet edge’, velocity and the fuel concentration (mass fraction) both decrease monotonically reaching a zero at the jet edge.

(Source)
Past the potential core (where \( x > x_c \)), viscous shear and mass diffusion effects are active, across the whole width of the jet.

The initial jet momentum is conserved throughout the entire flow field.

When the jet is being issued into the surrounding air, some of its momentum is transferred to the air, hence the velocity of the jet decreases while greater and greater quantities of air are entrained (dragged into) into the jet.

P3.2.1 Source

Edited by John J. Corrigan and John M. Morris

P3.3 Conservation Laws

Basic governing equations, -the boundary-layer equations- which express mass, momentum and species conversation can be obtained by simplifying the more general equations by the use of the assumptions stated before.

Hence, the constant density, viscosity and mass diffusivity assumptions yield the following equations on Mass Conservation, Axial Momentum Conservation, and Species Conservation.
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P3.3.2 Mass Conservation

The mass conservation equation is given by,

$$\frac{\partial v_x}{\partial x} + \frac{1}{r} \frac{\partial (v_r r)}{\partial r} = 0$$

Eqn. as

P3.3.3 Axial Momentum Conservation

The axial momentum conservation equation is given by,

$$v_x \frac{\partial v_x}{\partial x} + v_r \frac{\partial v_x}{\partial r} = v \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_x}{\partial r} \right)$$

Eqn. bs

P3.3.4 Species Conservation

The species conservation equation for the jet of fluid (i.e. the fuel) is given by,

$$v_x \frac{\partial Y_F}{\partial x} + v_r \frac{\partial Y_F}{\partial r} = \mathcal{D} \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial Y_F}{\partial r} \right)$$

Where $\mathcal{D} = \text{Diffusion Coefficient (m}^2/\text{s})$

Eqn. cs
Also, since only two species are there, (i.e., fuel and oxidizer), the mass fractions of the two must sum to unity, i.e.,

\[ Y_{Ox} = 1 - Y_F \]  

Eqn. ds

P3.4 Boundary Conditions

To solve the equations given in the previous section, for the unknown functions, \( v_x(r,x) \), \( v_r(r,x) \), and \( Y_F(r,x) \) requires several boundary conditions (three boundary conditions are required each for \( v_x \) and \( Y_F \), and one boundary condition for \( v_r \))

- Three boundary conditions for each for \( v_x \) and \( Y_F \) are such as, two as functions of \( x \) at specified \( r \), and one as a function of \( r \) at specified \( x \)
- One boundary condition for \( v_r \), as a function of \( x \) at specified \( r \)
P3.4.1 Where am I?

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Popup level 2 ...

Popup level 3 ...

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The velocity field can be obtained by assuming the profiles to be similar, where ‘similarity’ is in the sense, that the intrinsic shape of the velocity profiles is the same everywhere in the flow field.

- For the considered conditions, this implies that the radial distribution of $v_x(r,x)$ when normalized by the local centerline velocity $v_x(0,x)$ is a universal function that only depends on the similarity variable, $r/x$

- The solution for the axial and radial velocities is given by,

$$v_x = \frac{3}{8\pi} \frac{J_e}{\mu x} \left[ 1 + \frac{\xi^2}{4} \right]^{-2}$$

and,

$$v_r = \left( \frac{3J_e}{16\pi \rho_e} \right)^{1/2} \frac{1}{x} \frac{\xi - \frac{\xi^3}{4}}{\left( 1 + \frac{\xi^2}{4} \right)^2}$$

Where $J_e$ is the jet initial momentum flow,
\[ J_e = \rho_e v_e^2 \pi R^2 \]

Eqn. xz

And \( \xi \) contains the similarity variable, \( r/x \),

\[ \xi = \left( \frac{3\rho_e J_e}{16\pi} \right)^{1/2} \frac{1}{\mu} \frac{1}{x} \]

Eqn. yy

The axial velocity distribution in dimensionless form hence can be obtained by substituting Eqn. xz into Eqn. xx and rearranging,

\[ \frac{v_{x,0}}{v_e} = 0.375(\rho_e v_e R/\mu)\left(\frac{x}{R}\right)^{-1}\left[1 + \frac{\xi^2}{4}\right]^2 \]

Eqn. ya

The dimensionless centerline velocity decay is obtained by setting \( r = 0 \) (i.e., \( \xi = 0 \)),

\[ \frac{v_{x,0}}{v_e} = 0.375(\rho_e v_e R/\mu)\left(\frac{x}{R}\right)^{-1} \]

Eqn. yb

This can be used to predict Centerline Velocity Decay Pattern
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
The centerline velocity decay pattern for laminar jets can be predicted using the given equation (previous section), as in the following diagram:

Centerline velocity decay pattern for laminar jets (source)
The velocity decays inversely with axial distance, and is directly proportional to the jet Reynolds number, i.e.,

$$Re_j \equiv \frac{\rho_e v_e R}{\mu}$$

Looking at the equation for the boundary conditions (previous section), it is evident that the solution is not valid near the nozzle since $v_{x,0}/v_e$ should not exceed unity.

It can be seen that the decay is more rapid with the lower-$Re_j$ jets.

This is due to the fact that, when the Reynolds number is decreased, the relative importance of the initial jet momentum becomes smaller, compared to the viscous shearing action that slows the jet.

With higher $Re_j$, narrower jets; and with lower $Re_j$, wider jets can be observed.

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**P3.5.2.1 Source**

Edited by John J. Corrigan and John M. Morris

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**P3.6 Other Parameters**
Some other parameters that are often used to characterize jets are, *jet spreading rate* and *jet spreading angle* $\alpha$.

- To define these two parameters, ‘jet half-width’, $r_{1/2}$ needs to be introduced.
- Jet half-width $r_{1/2}$ is the radial location where the jet velocity has decayed to one-half of its centerline value, which is depicted in the figure given.
An expression for $r_{1/2}$ can be derived by setting $\nu_x/\nu_{x,0}$ (can be derived by dividing Eqn. ya and yb given previously) as to one half, and solving for $r (=r_{1/2})$

The ratio of the jet half-width to the axial distance $x$ is termed as the ‘jet spreading rate’

The jet spreading angle, $\alpha$ is the angle, whose tangent is the spreading rate

Therefore,

$$r_{1/2}/x = 2.97 \left( \frac{\mu}{\rho v_x R} \right) = 2.97 \text{Re}^{-1}$$

Eqn. vv

and,

$$\alpha \equiv \tan^{-1} \left( r_{1/2}/x \right)$$

Eqn. vx

From Eqn.s vv and vx, it is evident that high-$Re_j$ jets are narrow, while low-$Re_j$ jets are wide; which is also consistent with the Reynolds number dependence of the velocity decay, discussed before
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
S.4 Physical Description of a Jet Flame

A burning laminar fuel jet has much in common with an isothermal jet

Laminar Diffusion Flame Structure (source)
The figure depicts some essential features of jet flames

- As the fuel flows along the flames axis, it diffuses radially outward while the oxidizer (e.g. air) diffuses radially inwards.
- The flame surface is nominally defined to be existing where the fuel and oxidizer meet in stoichiometric proportions, that is,

Flame surface \( \equiv \) Locus of points where the equivalence ratio, \( \Phi \), equals unity
The flame length is given by,

\[ L_f \approx \frac{3}{8\pi} \cdot \frac{Q_F}{\mathcal{D} \cdot Y_{f,\text{stoich}}} \]

P4.1 Source

Edited by John J. Corrigan and John M. Morris

P4.2 Laminar Diffusion Flame Structure

When studying the laminar flame structure, essential features of the jet flames can be depicted as following

Flame length, \( L_f \) is determined by the axial location where;

\[ \Phi (r=0, x=L_f) = 1 \]  

As the fuel flows along the flame axis, it diffuses radially outward, while the oxidizer diffuses radially inwards

Flame surface is defined to exist where, fuel and oxidizer meet in stoichiometric proportions
Flame surface ≡ Locus of points where; equivalence ratio equals unity (Φ = 1)

- Buoyancy forces are neglected in vertical case; where these forces narrow the flame (ρ decreases)

(Source 1)
If buoyancy forces are included in the horizontal case, then the flame length is given by

\[ Y_F = \frac{3}{8\pi} \frac{Q_F}{\mathcal{D}_{Y_{F,stoic}}} \left[ 1 + \frac{\xi^2}{4} \right]^2 \]

If \( Y_F = Y_{F,stoich} \) and \( r = 0 \),

(Source 2)
\[ Q_F = v_e \cdot \pi R^2 \]

Where \( Q_F \) is the volumetric flow at outlet of nozzle) m\(^3\)/s

---

P4.2.1 Source 1

Redrawn using Stephen R, Turns, 2006;
Edited by John J. Corrigan and John M. Morris

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P4.2.2 Source 2

Redrawn using Stephen R, Turns, 2006;
Edited by John J. Corrigan and John M. Morris

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P4.3 Soot Formation and Destruction Zones in Laminar Jet Flames

For hydrocarbon flames, often soot is present, which is also the reason behind the typical orange or yellow appearance.
Not all the soot that is produced maybe oxidized when transferred through the high-temperature oxidizing regions, depending on the fuel type and flame residence time. Due to such a case, appearance of soot ‘wings’ is possible, with the soot breaking through the flame. The soot that breaks through is referred to as ‘smoke’ in general.
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S.5 Definition of Mixture Fraction

Mixture fraction denoted by $f$ is defined as the ratio of mass of material having its origin in the fuel stream, to the mass of mixture.

That is;

$$f = \frac{\text{Mass of material having its origin in the fuel stream}}{\text{Mass of mixture}}$$

Eqn. uu

Where, it is considered as having, one single inlet stream of pure fuel, one single inlet stream of pure oxidizer, and one single product.

- In the fuel stream, $f = 1$
- In the oxidizer stream, $f = 0$

P5.1 Three Species System

For a three species system, mixture fraction can be determined as following:

- For a three species system,
1 kg fuel + \( v \) kg oxidizer \( \rightarrow \) \((v + 1)\) kg products

\[
\Rightarrow f = Y_F + \left( \frac{1}{v+1} \right) Y_{Pr}
\]

\[
f_{stoic} = \frac{1}{v+1} \quad \text{because} \quad Y_F = 0 \quad \text{and} \quad Y_{Pr} = 1
\]
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
To solve jet flame problems, it is required that the density $\rho^*$ to be related to the mixture fraction $f$

$$f = f_{stoic} \quad (Y_{Pr})$$

$$f_{stoic} < f \leq 1 \quad (Y_F, Y_{Pr})$$

$$0 \leq f < f_{stoic} \quad (Y_{Ox}, Y_{Pr})$$

Simplified State Relationships

Simplified Model Jet Diffusion Flame (source)
employing the flame sheet approximation

- In order to do this, the **Simplified State Relationships** need to be obtained
- The **Ideal Gas Equation of State** needs to be employed, to obtain the required relationship \( p = p(t) \)

### P6.1 Source

Redrawn using Stephen R, Turns, 2006;
Edited by John J. Corrigan and John M. Morris

### P6.2 Simplified Model Jet Diffusion Flame

Simplified model of jet diffusion flame employing the flame sheet approximation is used to solve jet flame problems.

- In the simplified model, inside the flame sheet only fuel and product exist
- In addition, in such a consideration, outside flame sheet only oxidizer and product exist
- The dimensionless density \( \rho^* \) can be expressed as,
\[ \rho^* = \frac{\rho}{\rho_e} \]

\[ f = f_{stoic} \quad (Y_{Pr}) \]

**Simplified Model Jet Diffusion Flame** employing the flame sheet approximation *(Source)*
P6.3 Simplified State Relationships

To solve jet flame problems, it is required that the density $\rho^*$ to be related to the mixture fraction $f$, simplified state relationships are employed.

- Relationships between species mass fraction ($Y_F$, $Y_{Ox}$, and $Y_{Pr}$) and the mixture fraction, $f$;

  $$
  Y_F = Y_F(f) \\
  Y_{Ox} = Y_{Ox}(f) \\
  Y_{Pr} = Y_{Pr}(f)
  $$

  \textbf{Eqn. 6.3.1}

- The relationship between mixture temperature and the mixture fraction, $f$;

  $$
  T = T(f)
  $$

  \textbf{Eqn. 6.3.2}

- \textbf{Ideal Gas Equation of State};
Flame Sheet Approximation: where fuel and oxidizer are reacting in stoichiometric proportions at the flame.

Simplified state relationships for species mass fractions $Y_F(f), Y_{Ox}(f)$, and $Y_{Pr}(f)$ (Source 1)
Simplified state relationships for mixture temperature $T(f)$

(Source 2)

P6.3.1 Source 1

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Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
P6.3.4  Ideal Gas Equation of State

Ideal gas equation of state is given by the following equation,

\[ P = \frac{PMW_{mix}}{R_U T} \]  

Eqn. 6.3.3.1

In this, the mixture molecular weight is determined from the species mass fractions;

\[ MW_{mix} = \left( \sum \frac{y_i}{MW_i} \right)^{-1} \]  

Eqn. 6.3.3.2

P6.3.5  Flame Sheet Approximation

In the flame sheet approximation, fuel and oxidizer react in stoichiometric proportions at the flame.

Chemical kinetics are assumed to be infinitely fast, resulting in the flame being represented as an infinitesimally thin sheet.

P6.3.6  Simplified State relationships Summary

The simplified state relationships can be summarized as below.
| Inside the flame  
(f_{stoic} < f \leq 1) | At the flame  
(f = f_{stoic}) | Outside the flame  
(0 \leq f < f_{stoic}) |
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>$Y_F = \frac{f - f_{stoic}}{1 - f_{stoic}}$</td>
<td>$Y_F = 0$</td>
<td>$Y_F = 0$</td>
</tr>
<tr>
<td>$Y_{ox} = 0$</td>
<td>$Y_{ox} = 0$</td>
<td>$Y_{ox} = 1 - \frac{f}{f_{stoic}}$</td>
</tr>
<tr>
<td>$Y_{Pr} = \frac{1 - f}{1 - f_{stoic}}$</td>
<td>$Y_{Pr} = 1$</td>
<td>$Y_{Pr} = \frac{f}{f_{stoic}}$</td>
</tr>
</tbody>
</table>

**Simplified state relationships for species mass fractions** $Y_F(f)$, $Y_{ox}(f)$, and $Y_{Pr}(f)$ (Source 1)

**Simplified Model Jet Diffusion Flame employing the flame sheet approximation** (Source 2)
P6.3.7 Equations on Temperature Variations

With the use of simplified state relationships, several equations can be derived based on temperature variations within and outside the flame.

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

\[
T = T(f) = f \left[ (T_{F,e} - T_{Ox,\infty}) - \frac{f_{stoic}}{1 - f_{stoic}} \frac{\Delta h_c}{c_p} \right] + T_{Ox,\infty} + \frac{f_{stoic}}{1 - f_{stoic}} c_p \Delta h_c
\]

Eqn. 6.3.7.1

- At the flame ($f = f_{stoic}$)
\[ T \equiv T(f) = f_{stoic} \left[ \frac{\Delta h_c}{c_p} + T_{F,e} - T_{Ox,\infty} \right] + T_{Ox,\infty} \]

Eqn. 6.3.7.2

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

\[ T = T(f) = f \left[ \frac{\Delta h_c}{c_p} + T_{F,e} - T_{Ox,\infty} \right] + T_{Ox,\infty} \]

Eqn. 6.3.7.2

Where,

\[ T_{Ox,\infty} = \text{Temperature of oxidant} \]
\[ T_{F,e} = \text{temperature of entering fuel} \]
\[ \Delta h_c = \text{Heat of combustion} \]

S.7 Various Jet Flame Length Solutions

Jet flame length (equations) can be solved for different density conditions
Momentum integral estimates for variable-density laminar jet flames

<table>
<thead>
<tr>
<th>$P_\infty/P_f$</th>
<th>$P_\infty/P_{\text{ref}}$</th>
<th>$I(P_\infty/P_f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>3.7</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>5.2</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Constant-density flame length solution is given by,

$$L_f \approx \frac{3}{8\pi} \frac{1}{D} \frac{Q_F}{Y_{F,\text{stoic}}}$$

(Eqn. 7.1)

Variable-density flame length solution (which is better) is given by,

$$L_f \approx \frac{3}{8\pi} \frac{1}{Y_{F,\text{stoic}}} \frac{\dot{m}_F}{\mu_{\text{ref}}} \frac{\rho_\infty}{\rho_{\text{ref}}} \frac{1}{I(P_\infty/P_f)}$$

Where, $P_f$ is the estimated flame density, while the Schmidt and Lewis numbers are assumed to be unity, and the absolute viscosity $\mu$ is assumed to be directly proportional to temperature, that is,

$$\mu = \mu_{\text{ref}} \frac{T}{T_{\text{ref}}}$$

(Eqn. 7.2)

The table gives momentum integral estimates for variable density laminar jet flames.
Variable density flames are 2.4 times longer than the constant density flames for hydrocarbon fuels, because of the buoyancy forces.

P7.1 Source

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S.8 Roper’s Correlation for the Laminar Jet Flame Length

Roper’s correlation is a continuation of Burke-Schumann Approach, however with the allowance for the characteristic velocity to vary with axial distance as modified by buoyancy and in accordance with continuity.
In 1977 Roper published a new theory describing the laminar jet diffusion flame, which retained the essential simplicity of the Burke-Schumann analysis, but relaxed the requirement of a single constant velocity (Detailed theory can be found in “Roper, F.G., Combustion and flames, 29 (1977)”).

Roper’s approach provided reasonable estimates of flame lengths for both circular and noncircular nozzles.

For the circular port (with the dimensions shown), the flame length is given by,

$$ L_{f,th y} = \frac{Q_F \left( \frac{T_\infty}{T_F} \right)}{4 \pi D \ln \left( 1 + 1/S \right)} \left( \frac{T_\infty}{T_F} \right)^{0.67} $$

Eqn. 8.1

For the square port (with the dimensions shown), the flame length is given by,
\[ L_{f,thy} = \frac{Q_F \left( \frac{T_\infty}{T_F} \right)}{16D_\infty \left[ inverf \left( 1 + S \right) \right]^{0.5}} \left( \frac{T_\infty}{T_f} \right)^{0.67} \]  

Eqn. 8.2

---

**P8.1 Source**

Redrawn using Stephen R, Turns, 2006;  
Edited by John J. Corrigan and John M. Morris  

---

**P8.2 Burke-Schumann Approach**


- Their theory predicted flame lengths reasonably well for axisymmetric (circular-point) flames, although many simplifying assumptions were employed, for example, the velocity field was everywhere constant and parallel to the flame axis

- In 1977 Roper published a new theory describing the laminar jet diffusion flame. The new theory retained the essential simplicity of the Burke-Schumann analysis, but
relaxed the requirement of a single constant velocity. Detailed theory can be found in “Roper, F.G., Combustion and flames, 29 (1977)”. 
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Roper’s Correlation; which was developed, and experimentally verified, can be employed to determine laminar jet flame lengths for various burner geometries, and flow regimes, as following.

- The various burner geometries are such as, Circular port, Square port, and Slot burner.
- The various flow regimes considered are, Momentum controlled, Buoyancy controlled, and Transition region, which will be discussed for the case of slot burner.
P8.3.1 Where am I?

Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
P8.3.2  Circular Port

Roper’s correlation for laminar jet flame length, for a circular port can be expressed as,

\[ L_{f,thy} = \frac{Q_F (T_\infty / T_F)}{4\pi D_\infty \ln(1 + 1/S)} \left( \frac{T_\infty}{T_f} \right)^{0.67} \]  

\[ L_{f,exp} = 1330 \frac{Q_F (T_\infty / T_F)}{\ln(1 + 1/S)} \]  

Where,

- \( L_{thy} \) – theoretical length
- \( L_{exp} \) – L experimental length
- \( S \) – molar stoichiometric oxidizer-fuel ratio
- \( D_\infty \) - a mean diffusion coefficient evaluated for the oxidizer at the oxidizer stream temperature
- \( T_\infty \) and \( T_F \), and \( T_f \) - the fuel stream and mean flame temperature respectively
Circular port (source)

- In the equation, all quantities are evaluated in SI units (m, m\(^3\)/s, etc.)
- Note: the burner diameter does not explicitly appear in either of these expressions
- \( S \) is estimated from:
  - For pure-fuel stream and for \( C_xH_y \) (stoichiometric air-fuel ratio):
    \[
    S = \frac{x + y/4}{x_{O_2}}
    \]
    \text{Eqn. 8.5}
    Where, \( x_{O_2} \) = mole fraction of \( O_2 \) in air
  - With primary aeration in fuel stream;
    \[
    S = \frac{1 - \psi_{pri}}{\psi_{pri} + 1/S_{pure}}
    \]
    \text{Eqn. 8.6}
Where,

- $S_{\text{pure}}$ – from the equation for pure fuel stream above,
- $\Psi_{pri}$ – primary aeration (0.4-0.6 is common)

Fuel distribution with inert gas reduces the flame length;

\[
S = \frac{x + y/4}{\left(\frac{1}{1 - x_{dil}}\right)x_{O_2}}
\]

Where, $x_{dil}$ is the diluent mole fraction in fuel stream (e.g. N$_2$)

Eqn. 8.7

P8.3.2.1 Source

Redrawn using Stephen R, Turns, 2006;
Edited by John J. Corrigan and John M. Morris

P8.3.3 Square Port

Roper’s correlation for laminar jet flame length, for a square port can be expressed as,
Square port \textbf{(source)}

\[
L_{f,thy} = \frac{Q_F \left( \frac{T_\infty}{T_F} \right)}{16D_\infty \left[ \text{inverf} \left( \left(1 + S \right)^{-0.5} \right) \right]^2} \left( \frac{T_\infty}{T_F} \right)^{0.67}
\]

\[
L_{f,expf} = 1045 \left[ \text{inverf} \left( \left(1 + S \right)^{-0.5} \right) \right]^2 Q_F \left( \frac{T_\infty}{T_F} \right)
\]

Where, \textit{inverf} is the inverse error function. (Values of the error function \textit{erf} can be found in table 9.4 in the course book \cite{Turns2006}.)
P8.3.4 Slot Burner

In determining Roper’s correlation for laminar jet flame length, for a slot burner, the dimensions of the burner are taken as, \( h \) (slot length), and \( b \) (slot width) as shown in the diagram as well.

![Diagram of slot burner dimensions]

Slot burner dimensions (Source)

To determine whether a flame is momentum- or buoyancy-controlled, the flame Froude number, \( Fr_f \) must be evaluated.
By definition, the Froude’s number is given by

\[ Fr_f \equiv \left( \frac{v_e I Y_{F,stoic}}{aL_f} \right)^2 \]  

\[ \text{Eqn. 8.10} \]

where,

- \( v_e \) – exit velocity
- \( I \) – Momentum flow ratio or momentum integral
- \( Y_{F,stoic} \) – stoichiometric mass fraction of fuel (kg/kg)
- \( a \) – Buoyant acceleration (m/s\(^2\))
- \( L_f \) – Flame length (m)

If,

- \( Fr_f >> 1 \): Momentum controlled
- \( Fr_f \approx 1 \): Mixed (Transition)
- \( Fr_f << 1 \): Buoyancy controlled

The Froude’s number physically represents the ratio of the initial jet momentum flow to the buoyant force experienced by the flame

P8.3.4.1 Source

Redrawn using Stephen R, Turns, 2006;
P8.3.5  Momentum controlled - Slot burner

Roper’s correlation for a slot burner in a momentum controlled flow regime can be expressed as,

\[ L_{f,\text{thy}} = \frac{b \beta^2 Q_F}{h \Omega \infty Y_{F,\text{stoic}}} \left( \frac{T_{\infty}}{T_F} \right)^2 \left( \frac{T_f}{T_{\infty}} \right)^{0.33} \]

Eqn. 8.11

And,

\[ L_{f,\text{expt}} = 8.6 \times 10^4 \frac{b \beta^2 Q_F}{h \Omega Y_{F,\text{stoic}}} \left( \frac{T_{\infty}}{T_F} \right)^2 \]

Eqn. 8.12

Where,  
\( b \) - the slot width  
\( h \) - the slot length

and, the function \( \beta \) is given by,

\[ \beta = \frac{1}{4 \text{inverf}\left[1/(1+S)\right]} \]

Eqn. 8.13

\( I \) - the ratio of the actual initial momentum flow from the slot to that of uniform flow,
\[ I = \frac{J_{e,\text{act}}}{(\dot{m}_F v_e)} \]

(inverf = inverse error function, erf = error function)

If the flow is uniform, \( I = 1 \), and for a fully developed, parabolic exit velocity profile (assuming \( h >> b \)), \( I = 1.5 \)

Equations 8.11 and 8.12 apply only for the case of stagnant oxidizer

---

**P8.3.6  Buoyancy controlled - Slot burner**

Roper's correlation for a slot burner in a buoyancy controlled flow regime can be expressed as,

\[ L_{f,\text{thy}} = \left[ \frac{9 \beta^4 Q_f^4 T_\infty^4}{8 \mathcal{D}_\infty^2 a h^4 T_F^4} \right]^{1/3} \left[ \frac{T_f}{T_\infty} \right]^{2/9} \]  

Eqn. 8.14

And,

\[ L_{f,\text{expt}} = 2 \cdot 10^3 \left[ \frac{\beta^4 Q_f^4 T_\infty^4}{a h^4 T_F^4} \right]^{1/3} \]  

Eqn. 8.15

Where, \( a \) - the mean buoyant acceleration; evaluated from,

\[ a \approx 0.6 g \left( \frac{T_f}{T_\infty} - 1 \right) \]  

Eqn. 8.16

\( g \) - the gravitational acceleration
P8.3.7 Transition region - Slot burner

For the transitional region where both jet momentum and buoyancy are important, Roper’s correlation can be expressed as,

\[
L_{f,T} = \frac{4}{9} L_{f,M} \left( \frac{L_{f,B}}{L_{f,M}} \right)^3 \left[ 1 + 3.38 \left( \frac{L_{f,M}}{L_{f,B}} \right)^3 \right]^{-2/3} - 1
\]

Eqn. 8.17

Where, the subscriptions \( M \), \( B \) and \( T \) refer to momentum-controlled, buoyancy-controlled, and transition (mixed) respectively.

S.9 Flow Rate and Geometry Effects

A comparison of flame lengths for a circular-port and a slot-burner, having various exit aspect ratios, \( hi/b \), and the same port area, is given in the figure below.
Methane
Port Area = 78.5 mm$^2$
$R = 5$ mm

Predicted flame lengths for circular and slot burners having equal port areas (source)
From the figure, some observations can be obtained as below.

- A linear dependence of flame length on flow rate for the circular port, and the somewhat greater-than-linear dependence for the slot burners.
- As the slot burner ports become more narrow, (h/b increasing), the flames become significantly shorter for the same flow rate.
- It is noteworthy to mention also that, when having equal port areas, same mean exit velocities exist.

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**P9.1 Source**

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Edited by John J. Corrigan and John M. Morris

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**S.10 Factors Affecting Stoichiometry**

Several factors that affect the stoichiometry are discussed in this section, as the following.
Flame length increases when H/C decreases

Dependence of flame length on fuel stoichiometry (source)
In the figure, Flame lengths for various fuels are shown relative to methane.

- The Molar stoichiometric ratio, \( S \)

- In addition, some other parameters which affect \( S \) are discussed, such as Fuel type, Primary aeration, Oxygen content of oxidizer, and the Fuel dilution with inert gas.

---

**P10.1 Source**


---

**P10.2 Molar stoichiometric ratio \( S \)**

The molar stoichiometric ratio \( S \), is defined in terms of the nozzle fluid and the surrounding reservoir fluid, that is,

\[
S = \left( \frac{\text{moles, ambient fluid}}{\text{moles, nozzle fluid}} \right)_{\text{stoic}}
\]

Eqn. 10.1
Therefore, $S$ depends on the chemical compositions of both the nozzle-fluid stream and the surrounding fluid.

E.g.: the values of $S$ would be different for a pure fuel burning in air, and in a nitrogen-diluted fuel burning in air.

Also, the mole fraction of oxygen in the ambient air also affects $S$. 
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Fuel type affects molar stoichiometric ratio $S$, which can be shown as following.

- For pure fuel stream and for $C_xH_y$ (Stoichiometric air-fuel ratio),

$$S = \frac{x + y/4}{\chi_{O_2}}$$

Eqn. 10.2

Where, $\chi_{O_2} = \text{mole fraction of O}_2\text{ in air}$
P10.1.1 Where am I?

Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
P10.1 Primary aeration

The effects of primary aeration on $S$ can be explained as following.

- Premix of air in the fuel flow prevents soot formation and makes the flames shorter (Blue flame)
- In the range of 40-60% primary aeration, flame lengths are reduced approximately 85-90% from their original no-air-added lengths
- Too much air $\rightarrow$ preferred flame $\rightarrow$ flashback

$$S = \frac{1 - \psi_{pri}}{\psi_{pri} + \frac{1}{S_{pure}}}$$

Eqn 10.3

Where $S_{pure}$ from equation for pure fuel streams, with,

$$S = \frac{x + y/4}{\chi_{O_2}}$$

Eqn 10.4

And, $\psi_{pri} =$ primary aeration (0.4 -0.6 is common)
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Oxygen content of oxidizer affects the flame length.

- A pure $O_2$–oxidizer makes a flame length of about $\frac{1}{4}$ the value in air for CH$_4$- combustion
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
Fuel dilution with inert gas reduces flame length:

\[ S = \frac{x + \frac{y}{4}}{\frac{1}{1 - \chi_{\text{dil}}} \chi_{\text{O}_2}} \]

Where \( \chi_{\text{dil}} \) is the diluent mole fraction in fuel stream (e.g. \( \text{N}_2 \))

**Eqn. 10.5**
Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
The formation and destruction of soot is an important feature of non-premixed hydrocarbon-air flames.

- The incandescent soot within the flame is the primary source of the diffusion flame’s luminosity.
- Soot also contributes to radiant heat losses from flames with peak emission at wavelengths in the infrared region of the spectrum.
- Soot formation in diffusion flames generally agreed to occur within a limited range of temperature; $1300 \, \text{K} < T < 1600 \, \text{K}$. 

S.11 Soot Formation and Destruction
In relation to the figure,

- Soot breakthrough = smoke
- Soot is formed on the fuel side of the flame zone
- Soot is oxidized when it flows through an oxidizing zone
- Soot ‘wings’ are soot that is not-oxidized

(a) & (b): soot formation and destruction zones in laminar non-premixed jet flames (Source 2)
In relation to the figure,

- Soot is contained in the region where the scattered light intensity is high

Important considerations are,

- Is it not possible to produce a stable sooting laminar flame with methane?
- CO does not produce soot at all!! Why?

Radial profiles of temperature and scattered light for a laminar ethylene jet diffusion flame (Source 1)
**P11.2 Four steps of soot formation**

Soot formation can mainly be generalized into four steps.

1. Formation of soot precursor species (PAH) via acetylene
2. Particle inception, formation of small particles (molecules → particles)
3. Surface growth and particle agglomeration
4. Particle oxidation at flame tip

P11.2.1 Where am I?
P11.3 Smoke point

Smoke point can be determined experimentally by increasing the fuel flowrate until smoke is observed at the flame tip.

- The greater the fuel flowrate → the lower the sooting propensity of the fuel
- The amount of soot formed in a diffusion flame is strongly dependent on the fuel type

In relation to the figure,

- There is no soot observed from the methane flame, while it is observed from ethane and propane flames.
- In addition, propane has higher sooting propensity than ethane.

Different diffusion flames from different fuels, methane, ethane and propane
(Source)
P11.3.1 Source

Note: this drawing is prepared by Microsoft Visio. The sample file can be downloaded from CompEdu website. Please copy/paste the graph as an image by using Edit > Paste Special > Picture (Enhanced Metafile)
S.12 Summary

In this section, the following aspects of the laminar diffusion flame are highlighted.

- Introduction of general characteristics of the velocity and nozzle-fluid concentration fields of laminar jets and spreading characteristics
- Description of general characteristics of the temperature, fuel, and oxidizer mass fractions, and velocity field of laminar jet flames
- Introduction to flame length correlations for circular, square, and slot-port burners
- Description of an essential characteristics of diffusion flames – soot formation

Self Assessments

P12.1 This you must know

These are multiple choice questions covering fundamental concepts and the student MUST be able to answer all of them to pass the self-assessment.
As the questions are very basic, it’s possible that similar or even identical questions appear in the "This you must know" sections in several chapters.

The questions can be such that one or several answers are correct. The number of correct answers should be given in the corresponding question.

(The goal is to have at least 10 "This you must know" per chapter)

**Vibration is defined as...** (1 answer is correct)
- An exponential growth of response with time.
- The static displacement of a system to a constant load. **Correct answer**
- A response of a system that oscillates about some mean position.
- The study of the motion of system without respect for forces causing or induced by the motion.

**Define Creep (1 answer is correct)**
- Slow flow of metal under high temperature or great pressure environments **Correct answer**
- Destruction of a material due to a chemical or electrochemical reaction with its environment
- Building up of contamination on the blade surface
- Material loss due to friction
Define Corrosion (2 answers are correct)

- Slow flow of metal under high temperature or great pressure environments
- Destruction of a material due to a chemical or electrochemical reaction with its environment
- Building up of contamination on the blade surface
- Oxidation of a material

Correct answer

P12.2 Quiz

These are multiple choice questions of a general character. The percentage of correct answers to these questions indicates the level the student would have achieved on an exam with these questions.

The questions can be such that one or several answers are correct. The number of correct answers should be given in the corresponding question.

(The goal is to have at least 10 "Quizzes" per chapter)

When considering a simplified analysis on non-reacting constant-density laminar jet, several assumptions are employed. In the following, these assumptions are given. However, not all can be the correct assumptions. Choose all the correct answers containing the appropriate assumptions: (4 answers are correct)
The following figure shows the centerline velocity decay for laminar jets. The factor $Re_j$ is such that, $Re_j = \frac{\rho e v_e R}{\mu}$. Choose the correct statements about $Re_j$ from the given answers. (4 answers are correct)
More rapid decay occurs with higher $Re_j$
More rapid decay occurs with lower $Re_j$
Low $Re_j$ gives narrow jets
High $Re_j$ gives wide jets
- High $Re_j$ gives narrow jets
- Low $Re_j$ gives wide jets
- ‘Re’ is the external radius
- ‘Re’ is the Reynolds number

The following diagram describes the laminar diffusion frame structure. Select the answer containing correct terms to replace the boxes L, M and N (red fonts) in the correct order; from the given alternatives below. (1 answer is correct)
\[ T_f, v_x, T_{\infty} \]

- \( \Phi = 1, \Phi < 1 \) and \( \Phi > 1 \)
- \( \Phi < 1, \Phi > 1 \) and \( \Phi = 1 \)
- \( \Phi = 0, \Phi < 0 \) and \( \Phi > 0 \)
- \( \Phi < 1, \Phi = 1 \) and \( \Phi > 1 \)

Correct answer
The following figure and statements are related to the physical description of a jet flame (laminar diffusion flame structure). In the statements, \( \Phi \) is the equivalence ratio. However, not all the alternatives are correct. Select all the correct statements from these. (5 answers are correct)
The following statements are based on mixture fraction $f$, where by definition it is the ratio between ‘mass of material having its origin in the fuel stream’ and ‘mass of mixture’. However, this definition is valid under certain constraints. The following contains these constraints, but possibly not all might be correct. Choose all the correct constraints. (3 answers are correct)
- This is valid only up to a three species systems

- There should be only one single product

- There should be only up to maximum three inlet streams of fuel

- There should be only one single inlet stream of pure oxidizer

- $f = 0$ in the fuel stream, and $f = 1$ in the oxidizer stream

- There should be only one single inlet stream of pure fuel

When considering the simplified jet flame model employing the flame-sheet approximation, there are two main constraints to be taken into account, which are (select the correct answers from the given) (2 answers are correct)

- Inside the flame sheet only fuel and product exist

- Inside the flame sheet only oxidizer and product exist

- Outside the flame sheet only fuel and product exist

- Outside the flame sheet only oxidizer and product exist

- None of the given statements are not the correct constraints
By definition, ‘flame-sheet approximation’ is; (1 answer is correct)

- Fuel and oxidizer react in different proportions at the flame; while the chemical kinetics are assumed to be fast, resulting in the flame being represented as a thin sheet
- Fuel and oxidizer react in smaller-than-stoichiometric proportions at the flame; while the chemical kinetics are assumed to be infinitely slow, resulting in the flame being represented as a significantly large sheet
- Fuel and oxidizer react in larger-than-stoichiometric proportions at the flame; while the chemical kinetics are assumed to be fast, resulting in the flame being represented a thin sheet
- Fuel and oxidizer react in stoichiometric proportions at the flame; while the chemical kinetics are assumed to be infinitely slow, resulting in the flame being represented as a thin sheet
- Fuel and oxidizer react in stoichiometric proportions at the flame; while the chemical kinetics are assumed to be infinitely fast, resulting in the flame being represented as an infinitesimally thin sheet

The following two figures depict; (a) simplified state relationships for species mass fractions for $Y_F(f)$, $Y_{Ox}(f)$, and $Y_{Pr}(f)$, and (b) Simplified state relationships for mixture
temperature $T(f)$. Select the correct terms, in correct order, to replace the letters in the boxes, J, K, L, M and N. (1 answer is correct)

- $Y_{Ox}$, $Y_F$, $Y_{Pr}$, $T_f$ and $T_{Ox,∞}$
- $Y_F$, $Y_{Ox}$, $Y_{Pr}$, $T_{Ox,∞}$ and $T_f$
- $Y_{Pr}$, $Y_{Ox}$, $Y_F$, $T_f$ and $T_{Ox,∞}$
- $Y_{Pr}$, $Y_{Ox}$, $Y_F$, $T_{Ox,∞}$ and $T_f$
- $Y_{Ox}$, $Y_F$, $Y_{Pr}$, $T_{Ox,∞}$ and $T_f$
- $Y_F$, $Y_{Ox}$, $Y_{Pr}$, $T_f$ and $T_{Ox,∞}$

Correct answer
The physical representation of the Froude’s’ number is; (1 answer is correct)

- The ratio of the initial jet momentum flow to the buoyant force experienced by the flame
- The ratio of the initial jet flame length to the buoyant force experienced by the flame
- The ratio of the buoyant forces experienced by the flame to the initial jet momentum flow
- The ratio of the buoyant forces experienced by the flame to the initial jet flame length
- None of the given statements give the correct ratio

The following statements are based on the following figure; ‘predicted flame lengths for circular and slot burners’ (on flow rate and geometry effects). However, it might be that not all the statements are true. Choose all the correct statements from the given. (here, $h/b$ is the exit aspect ratio) (4 answers are correct)
It shows linear dependence of flame length on flow rate for the circular port and the somewhat greater-than-linear dependence for the slot burners.

As the slot burner ports become more narrow, \((h/b\) increasing), the flames become significantly shorter for the same flow rate.
The following statements are based on the figure below on the dependence of flame length on fuel stoichiometry; and factors affecting stoichiometry. However, not all the statements are correct. Choose all the correct statements. (6 answers are correct)

<table>
<thead>
<tr>
<th>Statement</th>
<th>Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>It shows non-linear dependence of flame length on flow rate for the circular port and the somewhat greater-than-linear dependence for the slot burners</td>
<td>Check</td>
</tr>
<tr>
<td>As the slot burner ports become more narrow, ((h/b)) decreasing, the flames become significantly larger for the same flow rate</td>
<td>Check</td>
</tr>
<tr>
<td>The figure is for circular and slot burners of different sizes of port area</td>
<td>Check</td>
</tr>
<tr>
<td>The figure is for circular and slot burners having equal port areas</td>
<td>Correct answer</td>
</tr>
<tr>
<td>Both these burners have same mean exit velocities</td>
<td>Correct answer</td>
</tr>
<tr>
<td>These different types of burners have different mean exit velocities</td>
<td>Check</td>
</tr>
</tbody>
</table>

The following statements are based on the figure below on the dependence of flame length on fuel stoichiometry; and factors affecting stoichiometry. However, not all the statements are correct. Choose all the correct statements. (6 answers are correct)
- Flame length increases when the ratio of Hydrogen to Carbon decreases
- Flame length decreases when the ratio of Hydrogen to Carbon decreases
<table>
<thead>
<tr>
<th>Statement</th>
<th>Correct Answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>The molar stoichiometric ratio $S$ is by definition equal to the stoichiometric amount of moles of nozzle fluid, to the stoichiometric amount of moles of ambient fluid</td>
<td></td>
</tr>
<tr>
<td>The flame lengths of different types of fuels are shown relative to that of ethane</td>
<td>Correct answer</td>
</tr>
<tr>
<td>The flame lengths of different types of fuels are shown relative to that of methane</td>
<td>Correct answer</td>
</tr>
<tr>
<td>Premix of air in the fuel flow prevents soot formation and makes the flames shorter (Blue flame)</td>
<td>Correct answer</td>
</tr>
<tr>
<td>Premix of air in the fuel flow enhances soot formation and makes the flames longer (Blue flame)</td>
<td>Correct answer</td>
</tr>
<tr>
<td>In the range of 40-60% primary aeration, flame lengths are reduced approximately 85-90% from their original no-air-added lengths</td>
<td>Correct answer</td>
</tr>
<tr>
<td>Regarding the oxygen content of oxidizer affecting the flame length, a pure $O_2$–oxidizer makes a flame length of about $\frac{1}{4}$ the value in air for $CH_4$- combustion</td>
<td>Correct answer</td>
</tr>
<tr>
<td>In the range of 40-60% primary aeration, flame lengths are increased approximately 85-90% from their original no-air-added lengths</td>
<td>Correct answer</td>
</tr>
<tr>
<td>Regarding the oxygen content of oxidizer affecting the flame length, an $O_2$–oxidizer makes a flame length of about the same value in air for $CH_4$- combustion</td>
<td>Correct answer</td>
</tr>
</tbody>
</table>
Formation & destruction of soot is an important feature of non-premixed hydrocarbon/air flames. The following figures depict the soot formation and destruction zones in laminar non-premixed jet flames. Identify the correct terms to replace the boxes P, Q, R, S and T, from the given alternative answers, in the correct order. (1 answer is correct)

- Soot oxidation zone
- Soot particle growth zone
- Soot particle inception zone
- Soot breakthrough
- Soot wings

Correct answer
The following statements are based on soot formation and destruction, in laminar flames diffusion. Select all the correct statements from the given. (5 answers are correct)

<table>
<thead>
<tr>
<th>Statement</th>
<th>Correct answer</th>
</tr>
</thead>
<tbody>
<tr>
<td>The incandescent soot within the flame is the primary source of the diffusion flame’s luminosity</td>
<td>Check</td>
</tr>
<tr>
<td>The incandescent soot within the flame does not have significant impact on the diffusion flame’s luminosity</td>
<td>Check</td>
</tr>
<tr>
<td>Soot also contributes to convection heat losses from flames, with peak emission at wavelengths in the visible light region of the spectrum</td>
<td>Check</td>
</tr>
<tr>
<td>Statement</td>
<td>Check</td>
</tr>
<tr>
<td>---------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>The four main steps of soot formation are (in the correct order of occurrence), particle inception (formation of small particles), surface growth and particle agglomeration, formation of soot precursor species (PAH) via acetylene, and particle oxidation at flame tip</td>
<td>✔</td>
</tr>
<tr>
<td>The lower the fuel flowrate is, the greater is the sooting propensity of the fuel</td>
<td>✔</td>
</tr>
<tr>
<td>Soot – also contributes to radiant heat losses from flames, with peak emission at wavelengths in the infrared (IR) region of the spectrum</td>
<td>✔</td>
</tr>
<tr>
<td>The four main steps of soot formation are (in the correct order of occurrence), formation of soot precursor species (PAH) via acetylene, particle inception (formation of small particles), surface growth and particle agglomeration, and particle oxidation at flame tip</td>
<td>✔</td>
</tr>
<tr>
<td>The greater the fuel flowrate is, the lower is the sooting propensity of the fuel</td>
<td>✔</td>
</tr>
<tr>
<td>The amount of soot formed in a diffusion flame is strongly dependent on the fuel type</td>
<td>✔</td>
</tr>
<tr>
<td>The amount of soot formed in a diffusion flame is independent on the fuel type</td>
<td>✔</td>
</tr>
</tbody>
</table>

Corresponding level achieved on an exam:
P12.3 Open-ended questions

These are questions where the students should write an answer or describe something. Sometimes the answer is given as a "popup" to the question, but for most questions there are no answers given. The students need then to find the answers themselves.

However, it is of course always highly appreciated if the teacher can also give some "Hints" to the solution. These could be in the direction of:

Hint 1: Perhaps you may want to consider xxxx?
Hint 2: Perhaps the definition of xxx might be useful to consider?
Hint 3: The xxx might perhaps be influenced by, among many other aspects, yyyyyy?
Hint 4: xxx
Hint 5: xx
Etc

Presently these hints will just serve as a help to the students, but the intention is that in a later update of CompEdu these hints will “cost points”, at the same time as the students will “gain points” when they answer well on any of the self-assessment questions.

Of course, it is not expected that these “open-ended questions” will be automatically corrected by the computer. They will instead, if the author agrees, be sent to a teacher who will manually correct them. However, in the self-assessment phase the hints will still be very useful to a student who has “got stuck”.
(The goal is to have at least 10 "Open-ended questions" per chapter)

What is Preventive Maintenance?

What is Predictive Maintenance?

How is it possible to determine the time between inspections of a gas turbine?

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**P12.4 Exercise**

For these exercises, the student has to perform “hand calculations” or use a calculation/computer program to determine the result of the assignment. These calculation exercises might also have been given on a specific page of the chapter. The calculation exercises are, inasmuch as is feasible, built up interactively so that students will have the opportunity to receive direct and immediate feedback. This feedback may simply be the correct answer but may also include possible hints for arriving at the solution.

Different options exist. The easiest is to give the solution as a pdf-file. Another option is to program the exercise such that it gives the students individual input data, and also includes “hints” the student can “buy” if they would be interested. More sophisticated options is presently also considered for development. Of course, any developer is very welcome to come with new ideas on this topic.

(The long-term goal is to have at least 10 "Calculation exercises" per chapter)

**Solution**
P12.4.1 Solution