Flame Stretch

1 Idealized Premixed Flame

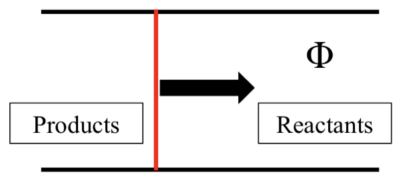

Figure 1: Idealized Premixed Flame

The assumptions of idealized premixed flame include:

1. One dimensional
2. Planar
3. Adiabatic, $T_b^0 = T_{ad}$
4. Mass flux conservation: $\rho_u u_u = \rho_b u_b = \rho_u S_L^0$

2 Non-Ideal Premixed Flames

Assumptions include:

1. Non-adiabatic
2. 3-Dimensional
3. Non-uniform and/or unsteady flow
4. $S_u \neq S_L^0$
5. Mass burning flux nor equal to $\rho_u S_L^0$

3 Stretched Flames

3.1 Overview

Flames subject to aerodynamic non-uniformity and/or unsteady effects are called **stretched flames**. Normally the stretch effects include:

1. **Hydrodynamic Stretch Effects:** net displacement or distortion of the flame surface due to tangential and normal components of the flow.

2. **Flame Stretch Effects:** modification of the temperature and/or species profiles in the transport zone resulting in changes in the flame propagation rate.

Stretched flames can cause the following change:

1. Misalignment between convective and diffusive fluxes near the flame

2. Flames will not be infinitely thin

3. Change in flame speed, flame shape and flame stability

3.2 Stretch Rate

In math, we define the stretch rate K (with the unit as 1/s) as the normalized differential change in flame surface area as a function of time:

$$K = \frac{1}{A}\frac{dA}{dt} \tag{1}$$

The stretch rate can be expressed in another way:

$$K = \underbrace{\nabla_t \cdot u_t}_{K_a} + \underbrace{(\underline{\boldsymbol{v_F}} \cdot \underline{\boldsymbol{n}})(\nabla \cdot \underline{\boldsymbol{n}})}_{K_b} \tag{2}$$

Where:

1. K_a : stretch due to tangential velocity gradients at the flame surface

2. K_b : stretch due to unsteady flame curvature

Two different types of stretch:

1. Positive stretch: flame in tension

2. Negative stretch: flame in compression

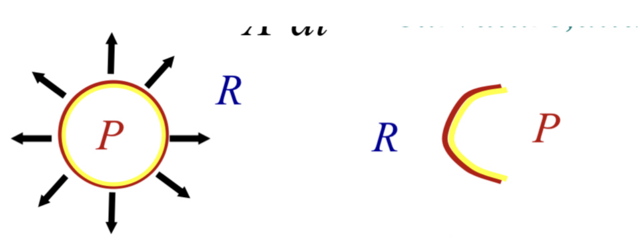

Figure 2: Positive Stretch Rate

Figure 3: Negative Stretch Rate

3.3 Lewis Number

Three main factors to affect the stretch:

1. **Thermal Diffusion:** focuses into reactants, enhances S_L
2. **Mass Diffusion:** of reactants away from centerline, can reduce reactants, reaction rate and thus S_L
3. **Differential Diffusion:** can lead to not stochiometric mixture. If greater diffusional loss of deficient reactant, will reduce S_L

Now we analyze this problem in a detailed way. We define the **most deficient** reactant as the reactant with the largest gradient, which is generally the controlling parameter.

Three main diffusivities:

1. Thermal diffusivity: α
2. Deficient reactant diffusivity: D_i
3. Abundant reactant diffusivity: D_j

Now we define:

1. **Non-unity Lewis number:** imbalance between thermal and mass diffusivity.

$$Le_{non-unity} = \frac{\alpha}{D_i} \tag{3}$$

2. **Differential Diffusion:** imbalance between deficient and abundant species diffusivities.

$$Le_{\text{differential}} = \frac{D_i}{D_j} \tag{4}$$

If $Le = 1$, then opposing effects tend to cancel.

4 Bunsen Flames

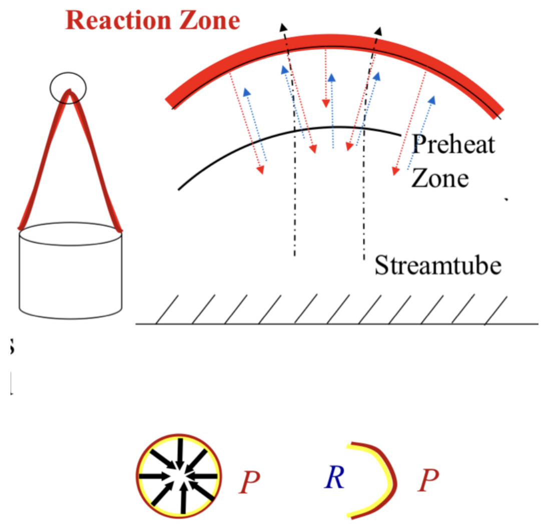

Figure 4: Bunsen Flames

A Bunsen burner is a common piece of laboratory equipment that produces a single open gas flame, which is used for heating, sterilization, and combustion. The flame is a stationary, axisymmetric flame. In this flame, the heat fluxes are **entering** the streamtube, so we define the stretch as **negative stretch**.

In **negative stretch** case, because heat fluxes are into the streamtube, they will bring the energy into the preheat zone, enhance the flame speed. On the other side, mass diffusion fluxes bring the reactant out of the preheat zone, so they will reduce the flame speed. Recall the definition of Lewis number:

$$Le = \frac{\alpha}{D} \tag{5}$$

Therefore, when $Le > 1$, thermal conduction outweighs mass diffusion so flame speed enhanced, S_L increase. When $Le < 1$, mass diffusion outweighs thermal conduction, so flame speed decreases, S_L drops.

We also need to consider the differential diffusion. We take Methane (CH4) - Air combustion as an example:

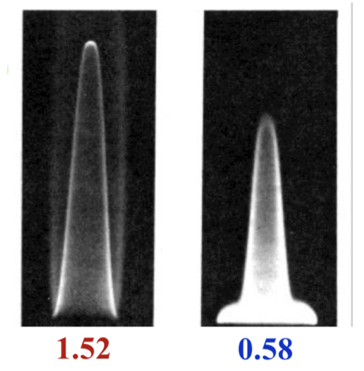

Figure 5: Methane Bunsen Flame Tip

Analysis process (lean mixture, light fuel, negative stretch):

1. Fuel lighter than air, $MW_{fuel} < MW_{mix}$
2. If the mixture is lean, then the deficient reactant is fuel. Then:

$$Le_{deficient} = \frac{\alpha_{mix}}{D_{fuel}} \tag{6}$$

   This Lewis number is tending to be smaller than 1 (D_{fuel} is larger than D_{mix})

3. Notice that Bunsen flame is negative stretch, when $Le < 1$, mass diffusion outweighs thermal conduction, so flame speed decreases.
4. So the tip flame will be slower, tip **weak (open)**.

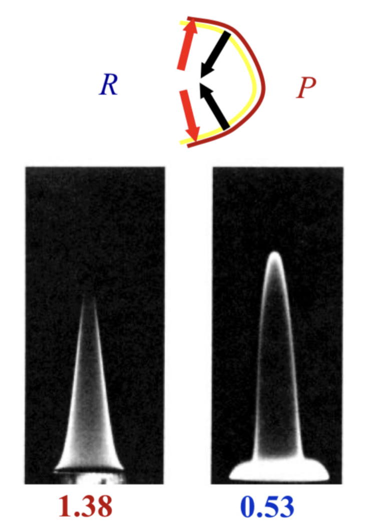

Figure 6: Propane Bunsen Flame Tip

Analysis process (rich mixture, heavy fuel, negative stretch):

1. Fuel heavier than air, $MW_{fuel} > MW_{mix}$
2. If the mixture is rich, then the deficient reactant is air. Then:

$$Le_{deficient} = \frac{\alpha_{mix}}{D_{air}} \tag{7}$$

   This Lewis number is tending to be smaller than 1 (D_{air} is larger than D_{mix})

3. Notice that Bunsen flame is negative stretch, when $Le < 1$, mass diffusion outweighs thermal conduction, so flame speed decreases.
4. So the tip flame will be slower, tip **weak (open)**.

5 Other Types of Flames

5.1 Stagnation Flame

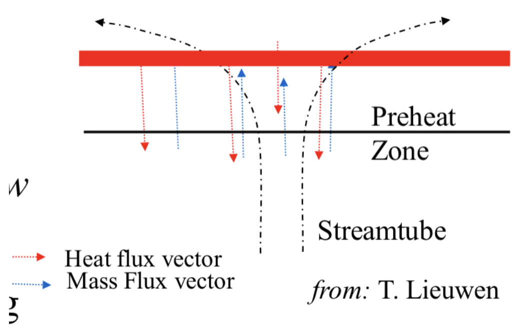

Figure 7: Stagnation Flame

In this flame, the heat fluxes are tending to exit the preheat zone, so the thermal diffusion here will reduce the flame speed. This is a positively stretched flame.

5.2 Spherical Flame

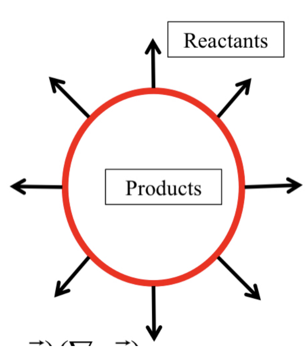

Figure 8: Spherical Flame

Remarks:

1. Stretch rate changes as a function of radius
2. Curvature is present but flow velocities align with flame surface normal
3. Stationary spherical flame would be stretchless

6 Flame Speed Corrections

For stretched flames, we need to modify 1D flame speed to account for curvature, flow divergence. For small perturbations, we use asymptotic analysis (Markstein) for expression:

$$S_L = S_L^0 - lK = S_L^0 = Ma\delta_f K \tag{8}$$

Here, l is the **Markstein Length**, K is the stretch rate, Ma is the Markstein number:

$$Ma = \frac{l}{\delta_f} \tag{9}$$

We could also use **Karlovitz number** to express the flame speed:

$$Ka = \frac{\text{Residence time for crossing unstretched flame}}{\text{Characteristic time for flame stretching}} = \frac{\delta_f/S_L}{1/K} = \frac{\delta_f K}{S_L} \tag{10}$$

$$S_L = S_L^0 - MaKaS_L \tag{11}$$

$$\frac{S_L^0}{S_L} = 1 + MaKa \tag{12}$$