Propagation Limit and Stability

1 Overview

With the knowledge from previous chapters, we still have some questions to answer:

1. **When can we get a flame to propagate in a stabel manner:** flammability limits, flashback and blowoff
2. **How can we make sure a flame can not propagate:** flame quenching
3. **What does it take to initiate a flame:** ignition

2 Quench

Quenching refers to the process where the flame is extinguished, typically due to rapid cooling or dilution by a non-reactive gas.For given passage (like cylindrical tube), if we make diameter less than some critical value, a flame will not propagate through the tube, **even though the velocity of the gas in the tube is below the adiabatic flame speed.** This could prevent flame propagating back into feed system.

We define this critical value as the quenching distance d_q. Then the flame is quenched for $d < d_q$. Assume quenching limit caused by balance between chemical energy release and energy loss.

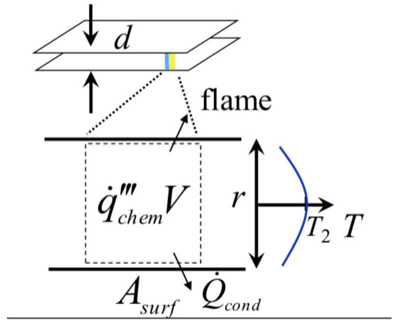

Figure 1: Quench Model

From the conservation equation:

$$\dot{Q}_{cond} = \dot{Q}_{chem} \tag{1}$$

$$\dot{Q}_{chem} = \dot{q}'''_{chem}V = \dot{m}'''_f[-\Delta h_R]V = -\dot{m}'''_f \Delta h_R A_{surf} d_q \tag{2}$$

Recall the flame speed model:

$$S_L \approx \sqrt{\frac{\bar{k}}{\rho_1 \bar{c}_p} \frac{2\Delta h_{R,T_{ref}}}{\rho_1 \bar{c}_p (T_2 - T_1)} \frac{\int_{T_1}^{T_2} RRdT}{(T_2 - T_1)}} \tag{3}$$

$$S_L = \sqrt{\alpha \frac{2\Delta h_{R,T_{ref}}}{\rho_1 \bar{c}_p (T_2 - T_1)} RR} \tag{4}$$

Notice that in this reaction (mentioned here):

$$[RR] = \frac{density}{s} = [\dot{m}'''_f] \tag{5}$$

Therefore:

$$\dot{m}'''_f \Delta h_R = \frac{S_L^2}{2\alpha}(T_2 - T_1)\rho_1 c_p \tag{6}$$

For the conduction:

$$\dot{Q}_{cond} = \dot{q}''_{cond}A = -k2A_{surf}\frac{dT}{dx}|_{wall} \approx -k2A_{surf}\frac{T_2 - T_1}{d_q/2} \tag{7}$$

Here, the first "2" means there are two walls, one at the top and one at the bottom. The second "/2" means the heat is conducted from both sides, so only need to pass half distance.

Combine both sides:

$$d_q^2 = \frac{k}{\rho_1 c_p}\frac{8\alpha}{S_L^2} = \frac{8\alpha^2}{S_L^2} \tag{8}$$

$$d_q \approx 2\sqrt{2}\delta_f \tag{9}$$

So the quenching distance is on the order (larger) of the flame thickness. Also notice that quenching is due to the head loss at the wall, so:

$$d_{q,cylin} > d_{q,plates} \tag{10}$$

3 Flammability

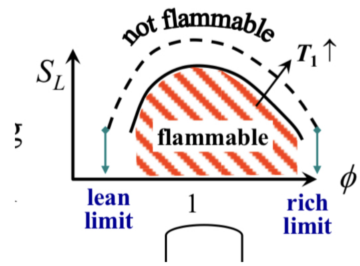

Figure 2: Flammability

Only within a range of ϕ can get a flame to be self-propagating. Outside this range, there is not enough heat release. The lean and rich limits (ϕ_{lean}, ϕ_{rich}) depend on fuel/ox/diluents, T_1, p and configuration. Take Methane-Air combustion as an example:

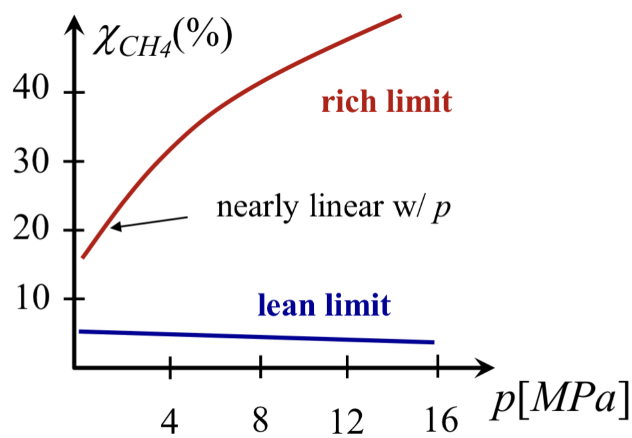

Figure 3: Pressure Dependence

Remarks:

1. **Rich limit has a strong relation with pressure:** This is due to the way combustion chemistry works. For combustion to occur, the fuel molecules must collide with oxygen molecules with enough energy to react and produce heat. When the mixture is rich, there are more fuel molecules relative to the number of oxygen molecules, meaning there's a greater chance that a fuel molecule will collide with an oxygen molecule.In high-pressure conditions, the collision rate increases due to the increased number of molecules present in a given volume, and this tends to widen the flammability range. However, this has a more significant effect on the rich limit because there are more fuel molecules available to collide with the increased number of oxygen molecules, hence enhancing the probability of combustion. In contrast, the lean limit is less sensitive to pressure changes because there are fewer fuel molecules to start with. Increasing the pressure (and

therefore the collision rate) doesn't help as much if there's simply not enough fuel present to sustain a combustion reaction.

2. Surface/geometry issues more important at low pressures

Buoyancy can also affect the flame in small tubes:

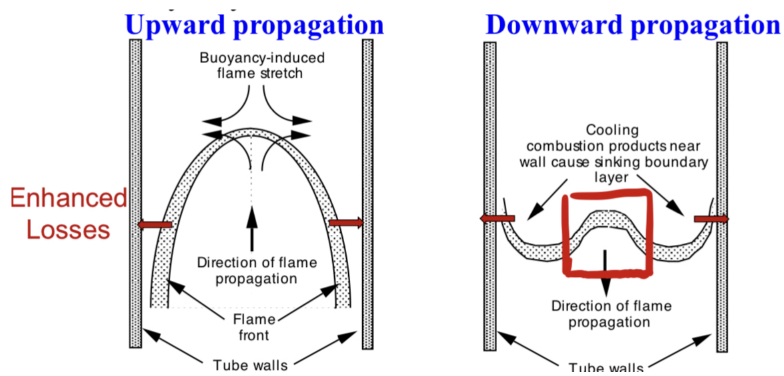

Figure 4: Buoyancy Effect

In the downward propagation case, buoyancy causes the decrease of the flame speed at the middle region.

4 Stability

Flame stability refers to the ability of a flame to maintain consistent combustion under given conditions. In more technical terms, it's the ability of a flame to resist extinction or blow-off under changes in the conditions of the flow field, such as the velocity, temperature, and fuel-air mixture.

4.1 Thermal Conduction

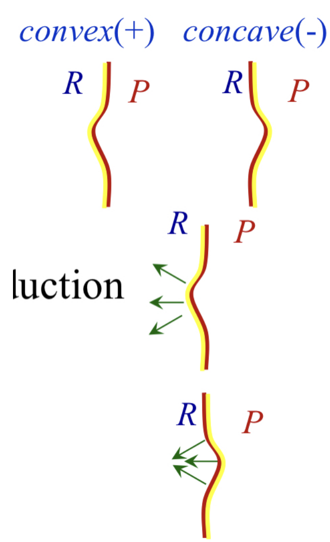

Figure 5: Thermal Conduction Effect

Now we consider only thermal conduction. For the convex bump, the thermal conduction causes the heat loss at the bump, which will decrease S_L and flatten the flame. For the concave bump, the thermal conduction causes the heat focusing at the bump, whihc will increase S_L and flatten the flame. Therefore, **thermal conduction always flattens flame, perturbations decay.**

4.2 Mass Diffusion

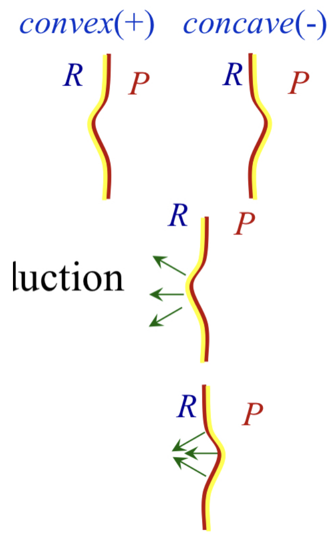

Figure 6: Thermal Conduction Effect

Now we consider only reactant diffusion. For the convex case, the reactant will diffuse to convex bulge, increase the flame speed at the middle region, which will grow the perturbation. For the concave case, the reactant diffuses away from the bulge, decrease the flame speed at the middle region, which will grow the perturbation. Therefore, **mass diffusion always grows perturbations.**

4.3 Lewis Number

In summary, perturbations will grow if reactant diffusion outweighs thermal diffusion, which means $Le < 1$. Also, flames are unstable to perturbation for **light fuels, leaner mixtures**, because fuel is diffusing faster, which will make the flame out of flammability range. Similarly, flames are unstable for **heavy fuels, richer mixtures**.

4.4 Flame Stretch

The stability can also be expressed by Markstein number. From the graph, $Ma > 0$ means stable, same as $Le > 1$. $Ma < 0$ means unstable, same as $Le < 1$.

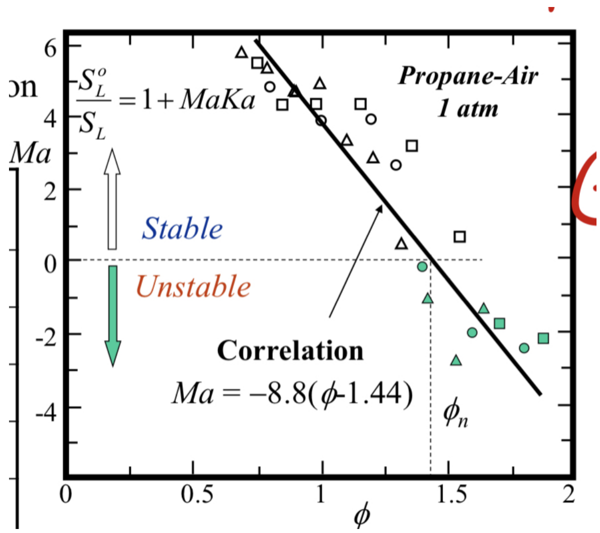

Figure 7: Markstein Number

Recall the expression of Karlovitz number:

$$\frac{S_L^0}{S_L} = 1 + MaKa \tag{11}$$

Notice that $Ka > 0$ for positive stretch and $Ka < 0$ for negative stretch. Therefore, the unstable cases include:

1. $S_L < S_L^0$ for negative stretch (because $Ma < 0$)
2. $S_L > S_L^0$ for positive stretch

If the stretch rate is too large, flame temperature and S_L drops, eventually leads to extinction at K_{ext}, which is called **extinction strain rate**. This usually occurs at $Ka \approx 1$. Also, higher S_L leads to higher K_ext.

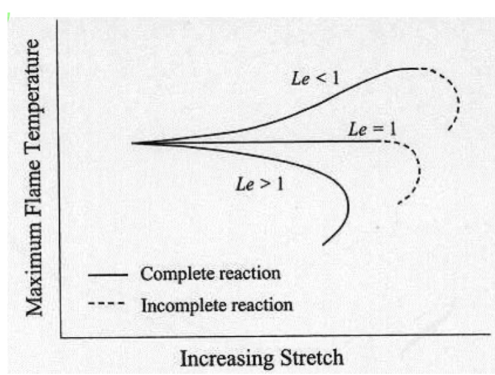

Figure 8: Extinction Stretch

5 Flame Stabilization

5.1 Overview

The requirement for flame to remain spatially stable is the normal component of local approach velocity must equal local flame speed. This is also called **anchor**.

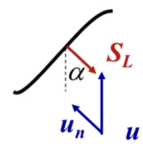

Figure 9: Anchor

The non-stationary behavior leads to either:

1. **Flashback:** $u_e < S_L$, flame moves upstream
2. **Blowoff:** $u_e > S_L$, flame exits combustor or extinguishes

5.2 Bunsen Burner

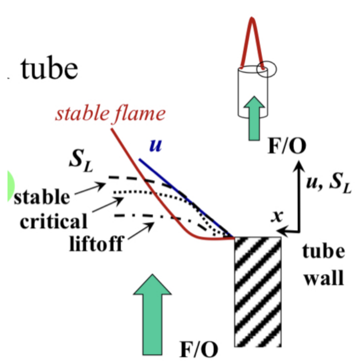

Figure 10: Bunsen Burner

Take Bunsen burner as an example. Some remarks:

1. S_L will tend to decrease near wall due to the heat loss
2. u will tend to decrease near wall due to boundary layer effect
3. Assume linear u profile near tube
4. Stabilization depends on S_L vs u variation

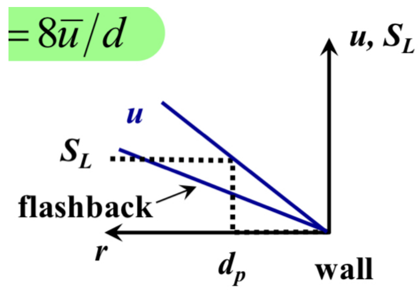

Figure 11: Flashback

Flashback occurs for $u < S_L$ anywhere at exit.

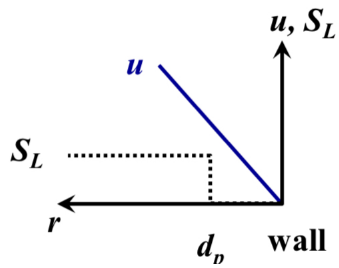

Figure 12: Blowoff

If $u > S_L$ everywhere, flame ca not exist at exit of tube, the flame will first **liftoff**. During the liftoff process, lifted flame can see lower local u (because of jet expansion), and flame moves far away from wall so the heat loss decreases, which will increase the flame speed S_L. This time, stability may be achieved above burner. If stable configuration could not reach, we call it **blowoff**.