7. Turbulent Premixed Flames

- **Background:**
  - Structure of turbulent premixed flames;

![Diagram of turbulent premixed flames](image_url)
- Instantaneous flame fronts (left) and turbulent flame brush envelope (right).
• Definitions:
  - Laminar flame thickness:
    \[ \delta_L \sim \frac{\alpha}{S_L} = \frac{D}{S_L} = \frac{\nu}{S_L} \] (1)
  - Above equality implies that we assumed,
    Schmidt Number: \( Sc = \frac{\nu}{D} = 1 \)
    Lewis Number: \( Le = \frac{\alpha}{D} = 1 \)
    Prandtl Number: \( Pr = \frac{\nu}{\alpha} = 1 \)
- Turbulent Reynolds number

\[ \text{Re}_\Lambda = \frac{u' \Lambda}{\nu} \]  

(2)

where \( \Lambda \) is the integral length scale of turbulence.

- Turbulent Damköhler number: ratio of characteristic flow time, \( \tau_{flow} \), to the characteristic chemical time, \( \tau_c \).

\[ \text{Da} = \frac{\tau_{flow}}{\tau_c} \]  

(3)
- Characteristic flow time: $\tau_{flow} = \Lambda / u'$
- Characteristic chemical time: $\tau_c = \delta_L / S_L$
- Then Damköhler number is:

$$Da = \frac{S_L \Lambda}{u' \delta_L}$$  \hspace{1cm} (3a)

- Turbulence length scales:
  $\lambda$: Taylor microscale
  $\eta$: Kolmogorov length scale
- Karlovitz number:

\[ Ka = \left( \frac{\Lambda}{\eta} \right)^2 = \frac{\delta_L u'}{S_L \lambda} \]  \hspace{1cm} (4)

- Turbulent Reynolds number based on \( \lambda \):

\[ Re_\lambda = \frac{u' \lambda}{\nu} \]  \hspace{1cm} (5)

- Turbulent Reynolds number based on \( \eta \):

\[ Re_\eta = \frac{u' \eta}{\nu} \]  \hspace{1cm} (6)

\[ Re_\Lambda \approx Re_\lambda^2 \approx Re_\eta^4 \]  \hspace{1cm} (7)
● **Turbulent Burning Velocity:**

- One of the most important unresolved problems in premixed turbulent combustion is the determination of the turbulent burning velocity.

- Above statement assumes that turbulent burning velocity is a well-defined quantity that only depends on local mean properties.

- However, there is no consensus in literature whether the turbulent burning velocity is a characteristic quantity that can be defined unambiguously for different geometries.
7. Turbulent Premixed Flames

- Weak Turbulence
- SI Engine regime
- Distributed reactions
- Reaction sheets

\[ \frac{u'}{S_L} = 1 \]
\[ \frac{\eta}{\delta_L} = 1 \]
\[ \frac{\Lambda}{\delta_L} = 1 \]

Dampkohler Number, \( Da \)

Turbulent Reynolds Number, \( Re_{\Lambda} \)
- Turbulent premixed flame propagation was first investigated by Damköhler (1940).

- He identified two limiting cases based on the magnitude of the scale of turbulence as compared to the thickness of the laminar premixed flame.

- For large scale turbulence, Damköhler assumed that the interaction between a turbulent premixed flame (wrinkled flame) front and the turbulent flame front is purely kinematic.
Laminar flame structure.

\[ u = \bar{u} + u' \]
- Damköhler equated the mass flux $\dot{m}$ through the instantaneous turbulent flame surface area $A_T$ with the mass flux through the cross-sectional area $A_o$. He used $S_L$ for mass flux through $A_T$, and $S_T$ for mass flux through $A$.

$$\dot{m} = \rho_u S_L A_T = \rho_u S_T A_o \quad (8)$$

$$\frac{S_T}{S_L} = \frac{A_T}{A_o} \quad (9)$$
- Using geometric approximations, Damköhler proposed that (for large-scale, small-intensity turbulence),

\[
\frac{A_T}{A_o} = 1 + \frac{u'}{S_L}
\]  \hspace{1cm} (10)

In view of Eq.2,

\[
\frac{S_T}{S_L} = 1 + \frac{u'}{S_L}
\]  \hspace{1cm} (11)

- \(u'\), turbulent fluctuating velocity in the unburned gas.
- Using similar geometric arguments, Schelkin showed that:

\[
\frac{S_T}{S_L} = \left[ 1 + \left( \frac{2u'}{S_L} \right)^2 \right]^{1/2}
\] (12)

- Relationship proposed by Klimov:

\[
\frac{S_T}{S_L} = 3.5 \left( \frac{u'}{S_L} \right)^{0.7}
\] (13)
- Clavin & Williams:

\[
\frac{S_T}{S_L} = \left\{ 0.5 \left[ 1 + \left( 1 + 8 \frac{u'^2}{S_L^2} \right)^{1/2} \right] \right\}^{1/2}
\]  

(14)

- Gülder:

\[
\frac{S_T}{S_L} = 1 + 0.62 \left( \frac{u'}{S_L} \right)^{1/2} \text{Re}_{\Lambda}^{1/4}
\]  

(15)
- For small-scale and high-intensity turbulence, Damköhler argued that turbulence only modifies the transport between the reaction zone and the unburned gas.

\[ \frac{S_T}{S_L} \sim \left( \frac{D_T}{D} \right)^{1/2} \]  

(16)

Since \( D_T \propto u'\Lambda \) and \( D \propto S_L\delta_L \)

- Then we have,

\[ \frac{S_T}{S_L} \sim \left( \frac{u'\Lambda}{S_L\delta_L} \right)^{1/2} \]  

(17)
- For small-scale high-intensity turbulence conditions (usually called as distributed reaction regime), there are not many formulations available. In this regime, turbulent mixing is rapid as compared to the chemistry.

- For the distributed reaction regime the following semi-empirical model has been proposed, Gülder (1990):

\[
\frac{S_T}{S_L} = 6.4 \left( \frac{S_L}{u'} \right)^{3/4}
\]  

(18)
State-of-the-art:

- Definition of turbulent burning velocity is not uniform/universal.
- Experimental data scatter is significant between different experimental rigs.
- Numerical simulation:
  - Flamelet model/assumption
  - Turbulent burning closure
  - Direct numerical simulation
Experimental Measurement Methods:

- Conical stationary flames on cylindrical nozzles.
- Swirling flames.
- Constant volume vessels.
- Stagnation point flames.
  - Laser-based diagnostics to study flame structure.
  - Statistical approaches to estimate the flame front surface area.