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AN INITIAL STEP IN THE EXPERIMENTAL CHARACTERIZATION OF ULTRA-LEAN HYDROGEN/AIR TURBULENT SPHERICAL FLAMES FOR INTERNAL COMBUSTION ENGINE APPLICATIONS



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Introduction

- Reducing NO_x emissions from hydrogen spark ignition engines (H₂SIEs) can be achieved through ultra-lean operation ($\phi < 0.6$), maintaining low flame temperatures and high thermal efficiency.
- In H₂SIEs, turbulent burning velocity (S_T) is influenced by thermochemical state and turbulence-flame interactions.
- Accurate determination of S_T is crucial for simulations and retrofitting, especially under high pressure where small changes in ϕ affect combustion regimes and flame morphologies.
- This study measured S_T for ultra-lean premixed turbulent outwardly propagating flames (PTOPF) under various conditions: $0.2 < \phi < 0.6$, $0.1 \text{ MPa} < p_u < 0.4 \text{ MPa}$, and $u' = 0.49 - 2.45 \text{ m/s}$.

Experimental setup

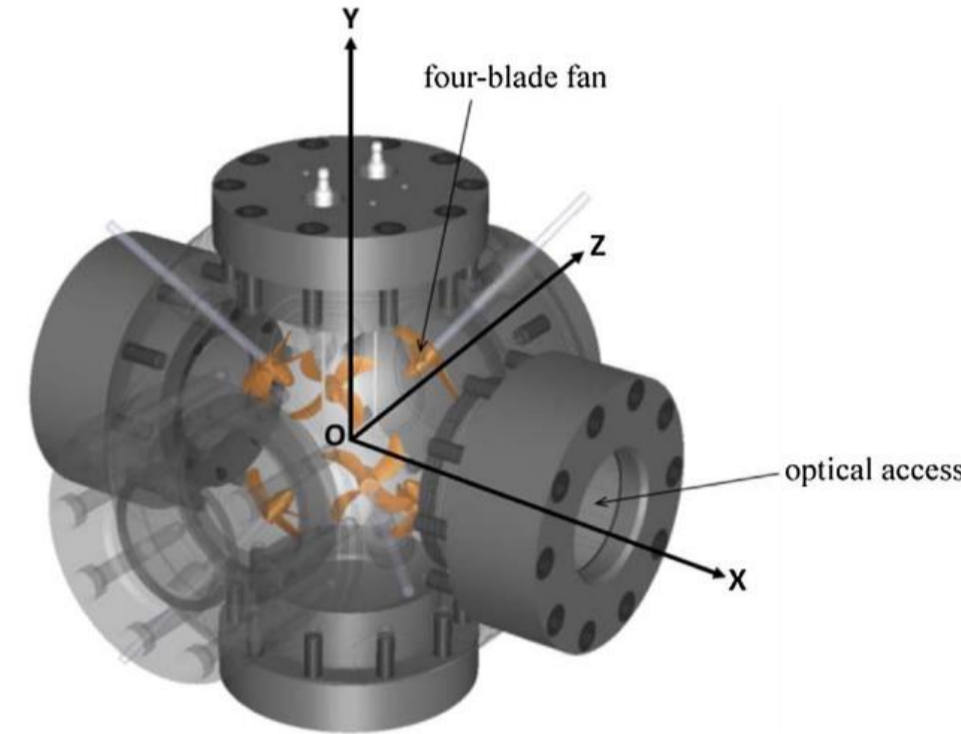
- Spherical stainless steel combustion chamber: $V = 4.2 \text{ L}$, $R = 10 \text{ cm}$, $L_T = 2.34 \text{ mm}$ [1].
- Six four-blade fans: Homogeneous and isotropic turbulence (up to 20 mm) [1].

Table 1. Turbulent intensity evolution with rotation fans speed, determined through LDV, LR-PIV and HR-PIV [1].

Fans rotation speed, [rpm]	3000	6000	9000	12000	15000
R.M.S. Turbulent fluctuation velocity u' [m/s]	0.49	0.98	1.47	1.97	2.45

- Two orthogonal pairs of quartz windows.
- Capacitive discharge system: Two tungsten electrodes ($E_{\min} = 5 \text{ mJ}$).

Figure 1. Experimental apparatus: Spherical combustion vessel.



Methodology

- Schlieren imaging processing \rightarrow edge-detection MATLAB code.

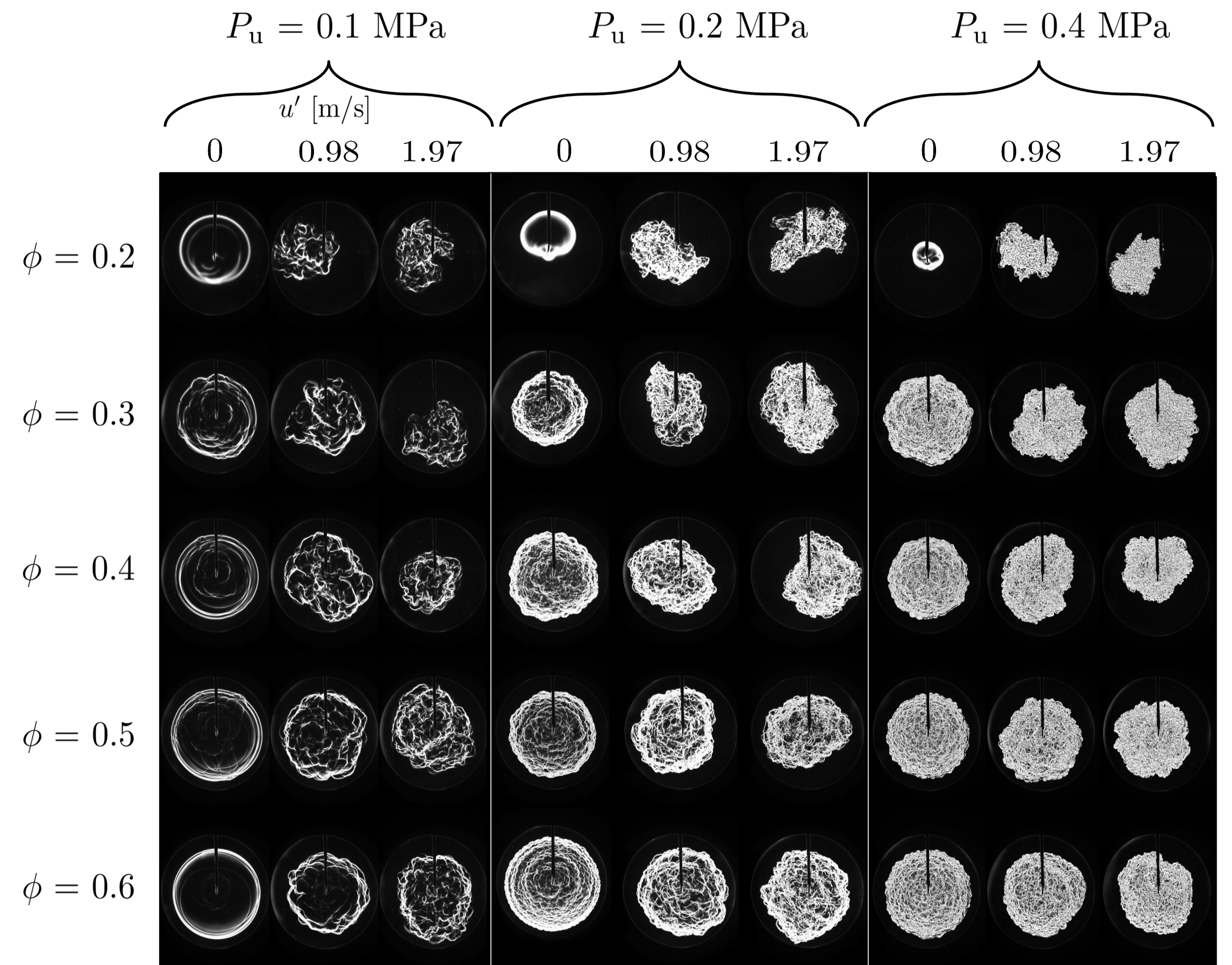


Figure 2. Schlieren images of ultra-lean H₂/air flames. $R_A = 15 - 18 \text{ cm}$.

- The **equivalent flame propagation speed** (V_T) = slope of dR_A/dt where R_A is the **area-based equivalent flame radius**.
- The **turbulent burning velocity**: $S_T = \sigma V_T$
- For comparison with different experiments: $S_{T,c=0.1} = (1.44)^2 S_T$ [2]
- Laminar flame properties \Rightarrow 1D freely propagating flame from Cantera.
 - Detailed H₂/air kinetic mechanism Villenave et al. [3]

Results: Equivalent propagation speed

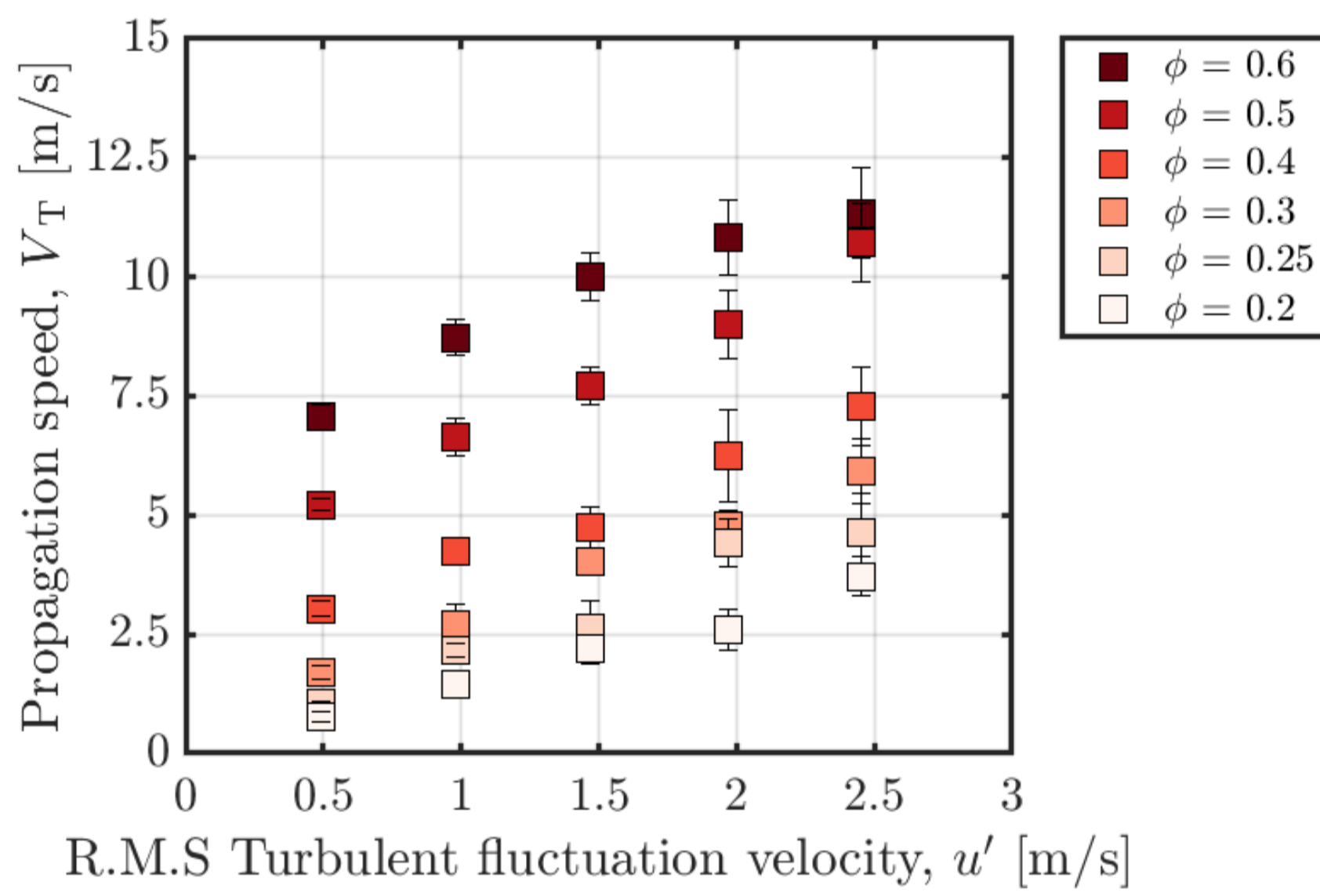


Figure 3. Variations of V_T with u' for $p_u = 0.2 \text{ MPa}$ and ϕ at $T_u = 373 \text{ K}$

- V_T increases with...

$\rightarrow \phi$ due to H₂ % vol. increases.

$\rightarrow u'$ due to a **positive** flame-turbulence interaction.

\rightarrow Leanest PTOPF ignited with E_{\min} do not suffer from total extinction.

Results: S_T-correlation validation

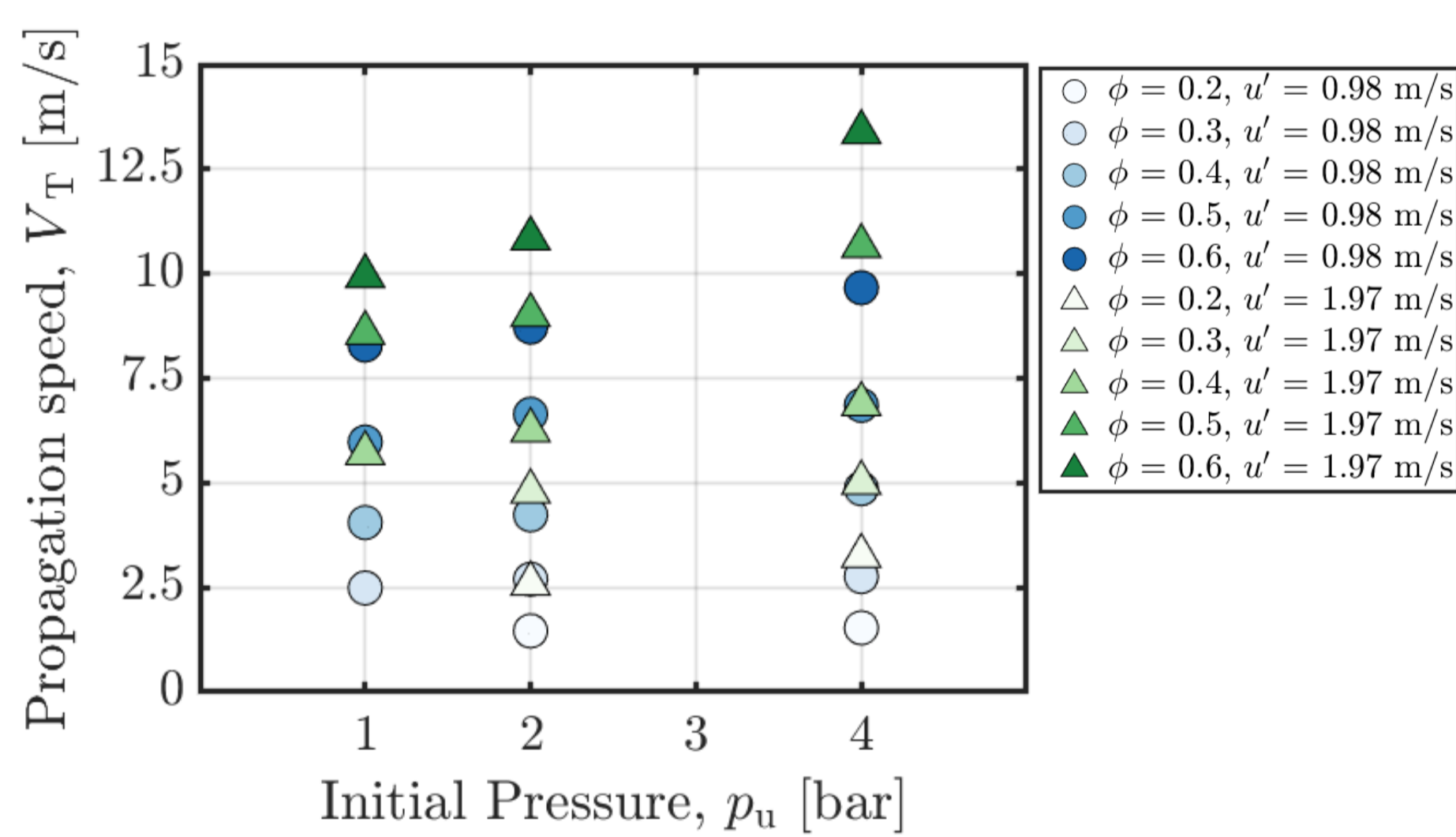


Figure 4. Variations of V_T with p_u for different u' and ϕ at $T_u = 373 \text{ K}$

- V_T increases with...

$\rightarrow p_u$ due to the combination of two phenomena.

\rightarrow **Preferential diffusion** ($Le < 1$): wrinkle the flame with the formation of small-scale cellular structures = **Local acceleration** flame front.

\rightarrow **Thinning** of the flame front with p_u increases.

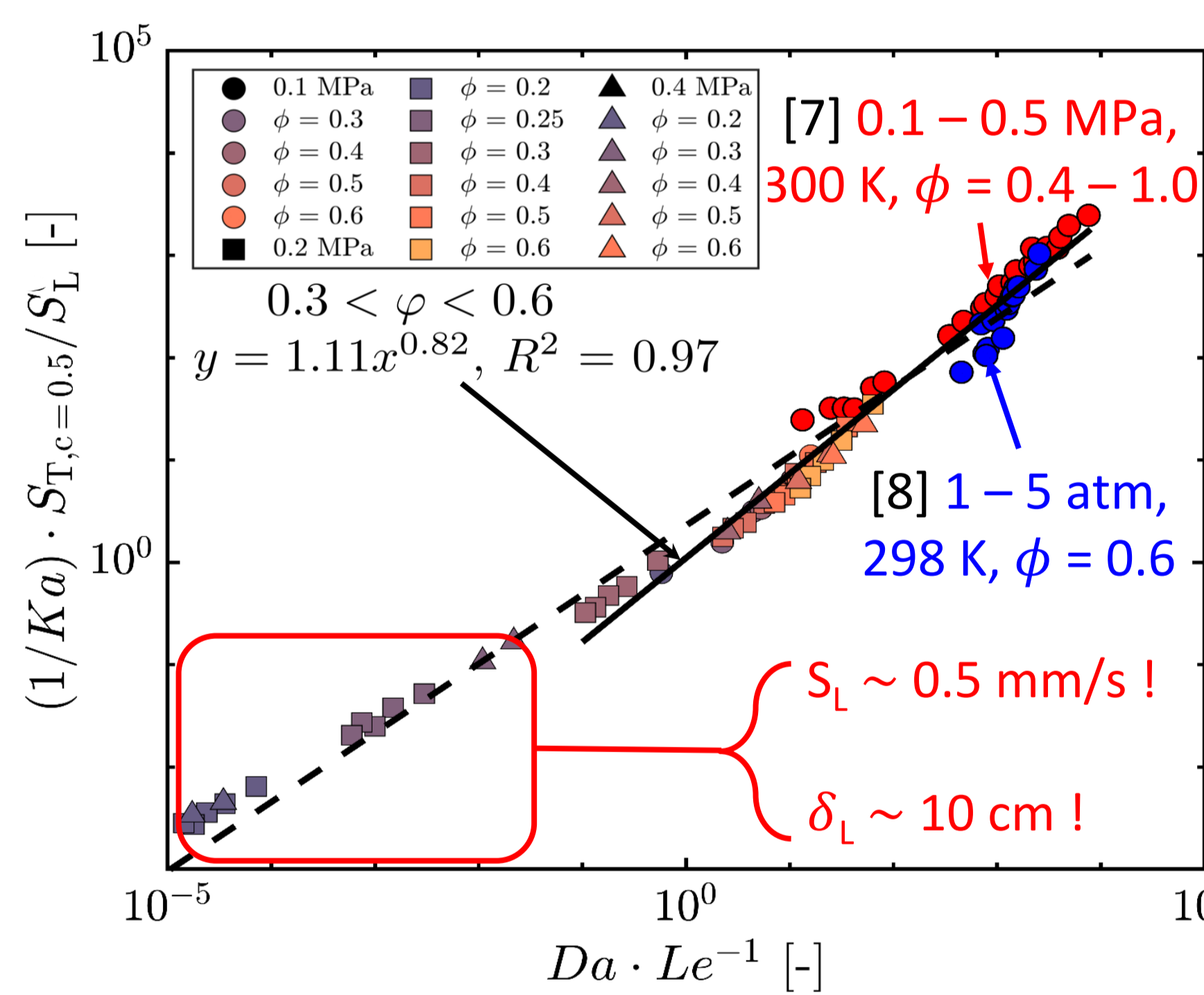


Figure 5. General turbulent flames correlation.

- Correlation S_T/S_L is **sensitive** to u'/S_L , δ_L/L_T and $Le \rightarrow$ interaction of **multi-scale** turbulent eddies with the flame front.
- PRISME [4] **correlation** for TRFE in the form: $S_T/S_L \sim (Da \cdot Ka)$ Validated on Gasoline fuel [4] and NH₃ [5].
- Re-scaled** with Le^{-1} to take into TD.
- Fitting displays **very good agreement** with an exponent within the range proposed by Wang et al. [6].

Results: Impact of thermo-diffusive response

- Linear stability analysis** by Matalon et al. [9] provides the dispersion relation in the following form:

$$\tilde{\omega} = \omega_{DL} \tilde{k} - \underbrace{(B_1 + Ze(Le_{eff} - 1)B_2 + PrB_3)}_{\omega_2} \tilde{k}^2$$

Ze : Zel'dovich number
 Le_{eff} : Lewis number
 Pr : Prandtl number

2D [10]

$$\frac{S_M}{S_L} = \begin{cases} \exp(0.057\omega_2) & \text{if } \Pi < \Pi_C \\ 1 + 0.22\omega_2 & \text{if } \Pi > \Pi_C \end{cases}$$

$$\frac{\delta_M}{\delta_L} = \begin{cases} \exp(-0.045\omega_2) & \text{if } \Pi < \Pi_C \\ (1 + 0.13)^{-1}\omega_2 & \text{if } \Pi > \Pi_C \end{cases}$$

3D [11]

$$\frac{S_F}{S_L} = \begin{cases} \exp(0.08\omega_2) & \text{if } \Pi < \Pi_C \\ 1 + 0.47\omega_2 & \text{if } \Pi > \Pi_C \end{cases}$$

$$\frac{\delta_F}{\delta_L} = \begin{cases} \exp(-0.06\omega_2) & \text{if } \Pi < \Pi_C \\ (1 + 0.26)^{-1}\omega_2 & \text{if } \Pi > \Pi_C \end{cases}$$

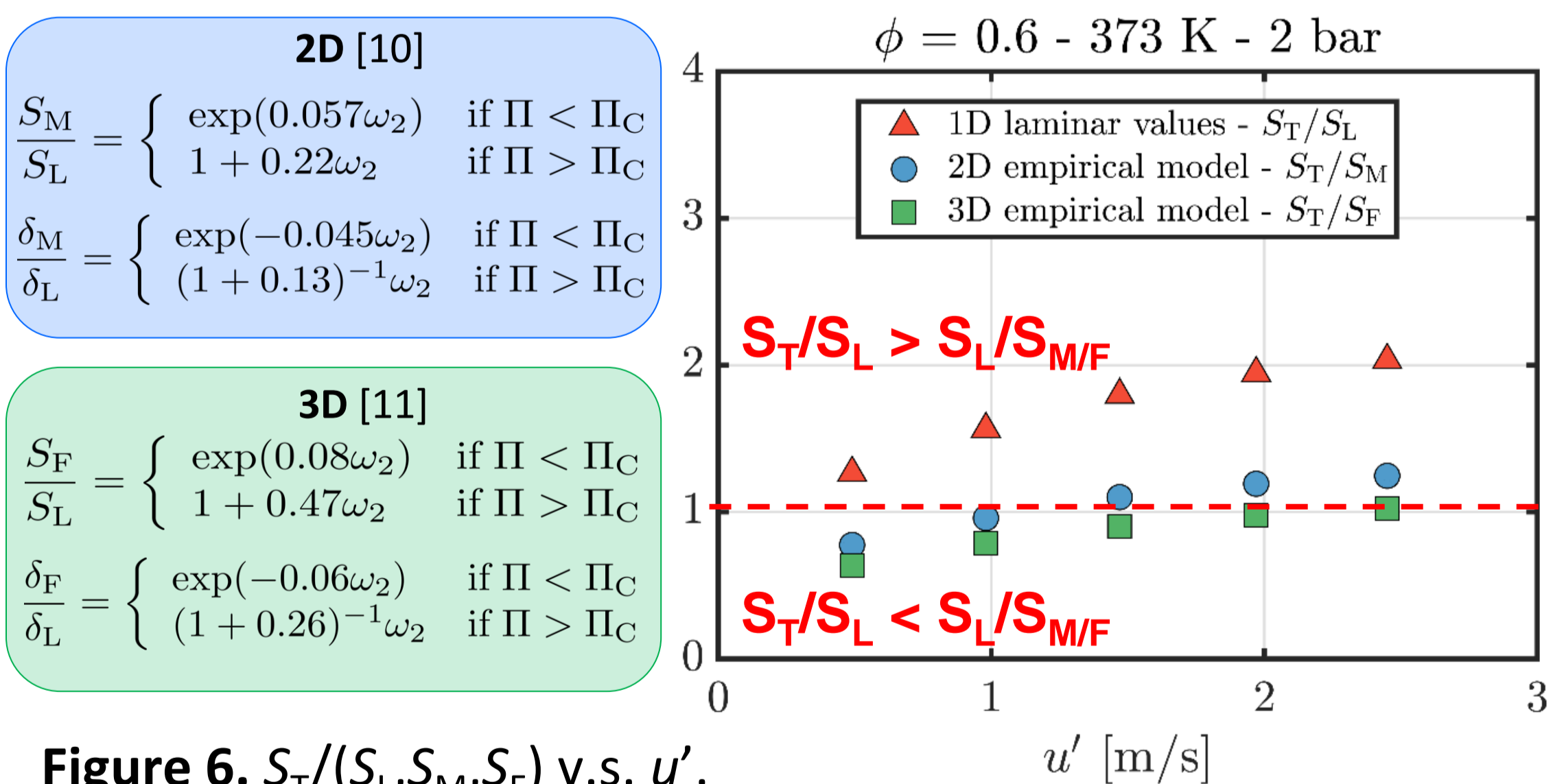


Figure 6. $S_T/(S_L S_M S_F)$ v.s. u' .

- For example with 3D:
 - $\phi = 0.6$: PTOPF are **wrinkled**.
 - $\phi = 0.4$: PTOPF are **corrugated**.
 - $\phi = 0.2$: "lower" Ka values.
 - Uncertainty KM.

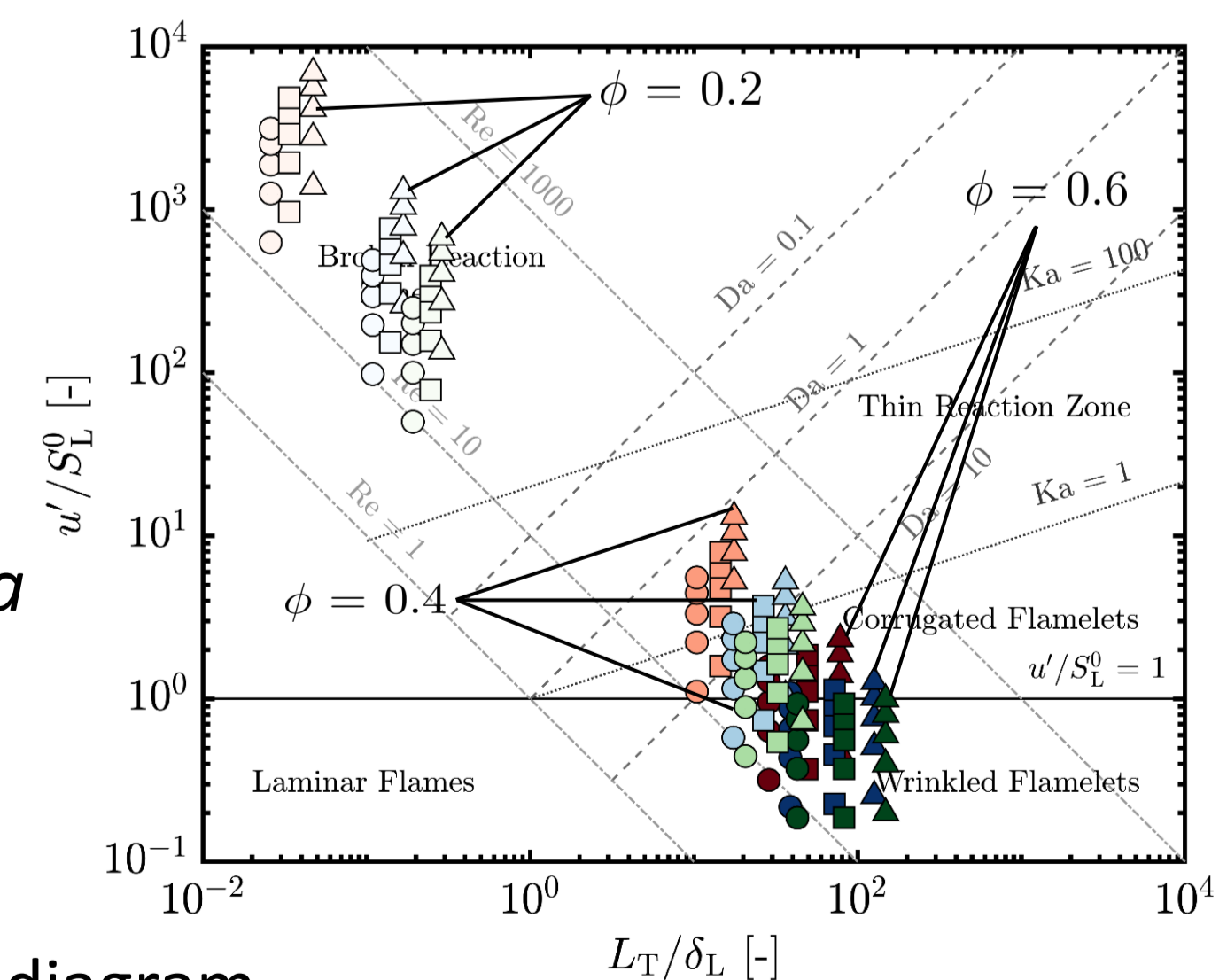


Figure 7. Peters-Borghi diagram.

Conclusion and Perspectives

- New PTOPF experiments to measure S_T for ultra-lean H₂/air mixtures at $\phi = 0.2 - 0.6$, $p_u = 0.1 \text{ MPa} - 0.4 \text{ MPa}$, $u' = 0.49 - 2.45 \text{ m/s}$ and $T_u = 373 \text{ K}$.
- V_T increases with rising u' , ϕ and p_u .
- Significant sources of uncertainty in characterizing PTOPF due to lack of experimental data and definitions for ultra-lean H₂/air laminar flame parameters.
- PRISME correlation, which considers Le , Ka , and Da , in very good agreement with both literature and current datasets.
- Finally, correction accounting for the thermo-diffusive response for lean premixed H₂/air flame (ω_2) provide promising insights to revisit currently used definitions.
- Perspectives: PIV-tomography, Water addition (Thesis available at PRISME).