5th Meeting of the Spanish Section of the Institute of Combustion

BURNING VELOCITY OF CONCAVE (NEGATIVELY STRETCHED) FLAME TIPS: EXPERIMENTS AND MODELING

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CONTENT

- Introduction and Motivation.
- Numerical techniques
- Experimental facility
- .Gas velocity field.
- Flame tomography and mean curvature
- Flame speed and stretch
- Conclusions.

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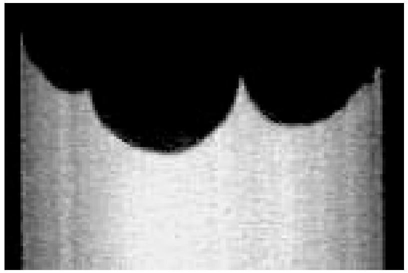
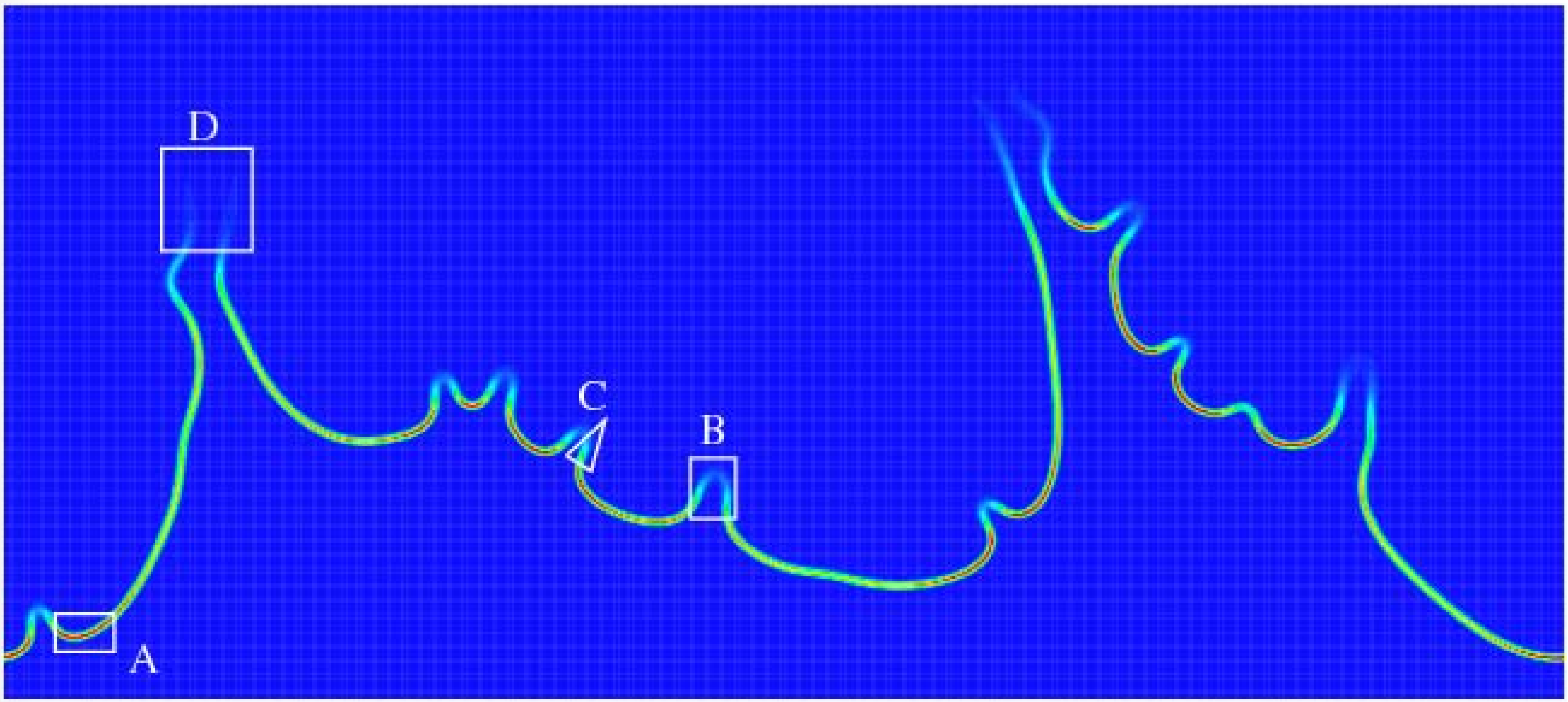
FLAME DYNAMICS



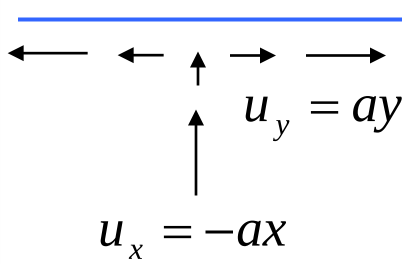
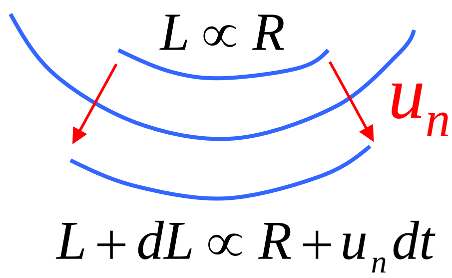
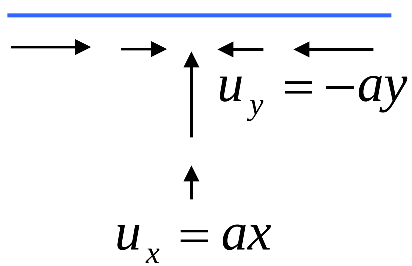
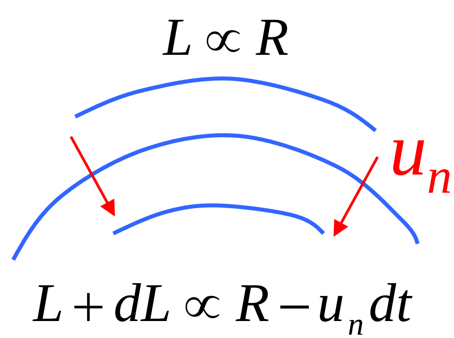
Cellular flame

(IRPHE, Marseille)

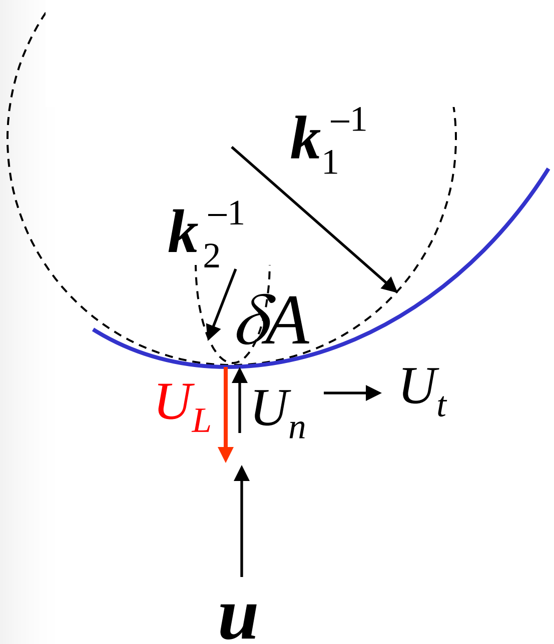


(CCSE – Berkeley)

FLAME DYNAMICS

Strained flame	Curved flame	
$\frac{1}{L}\frac{dL}{dt}=\frac{\partial u_s}{\partial s}$	$\frac{1}{L}\frac{dL}{dt}=\pm\frac{u_n}{R}$	
		Positive stretch (Front extension)
		Negative stretch (Front compression)

LINEAR FLAME DYNAMICS



$\mathscr{L}$ = Markstein length

$$\frac{U_n}{U_L} - 1 = -\frac{\mathscr{L}}{U_L}\frac{\delta\dot{A}}{\delta A}$$

$$\frac{1}{\delta A}\left(\delta\dot{A}\right) = \underbrace{-U_L \nabla\cdot\boldsymbol{n} - \boldsymbol{n}\cdot\nabla\boldsymbol{u}\cdot\boldsymbol{n}}_{S\,=\,\text{Total stretch}}$$

(Clavin & Joulin, 1983)

Front curvature
$\nabla\cdot\boldsymbol{n} = k_1 + k_2$

Flow straining

LINEAR FLAME DYNAMICS

$$Ma \equiv \mathscr{L} / \delta$$

$$\textbf{Markstein number} \equiv \frac{\textbf{Markstein length}}{\textbf{flame thermal thickness}\ (\lambda / \rho c_p U_L)}$$

Activation Energy Asymptotic Methods: $Ma = \frac{1}{\gamma} J + \beta (Le - 1) \frac{1-\gamma}{2\gamma} D$

(Clavin & G-Y, 1983)

$$J = \frac{\gamma}{1-\gamma} \int_0^1 h(\theta) \frac{1}{1+\theta\gamma/(1-\gamma)} \mathrm{d}\theta$$

$$D = -\frac{\gamma}{1-\gamma} \int_0^1 h(\theta) \frac{\ln\theta}{1+\theta\gamma/(1-\gamma)} \mathrm{d}\theta$$

$$\theta \equiv (T - T_u)/(T_b - T_u)$$

$$\beta \equiv E_a / RT_u$$

$$\gamma \equiv (T_b - T_u)/T_b$$

$$h(\theta) \equiv \frac{\lambda / c_p}{(\lambda / c_p)_u}$$

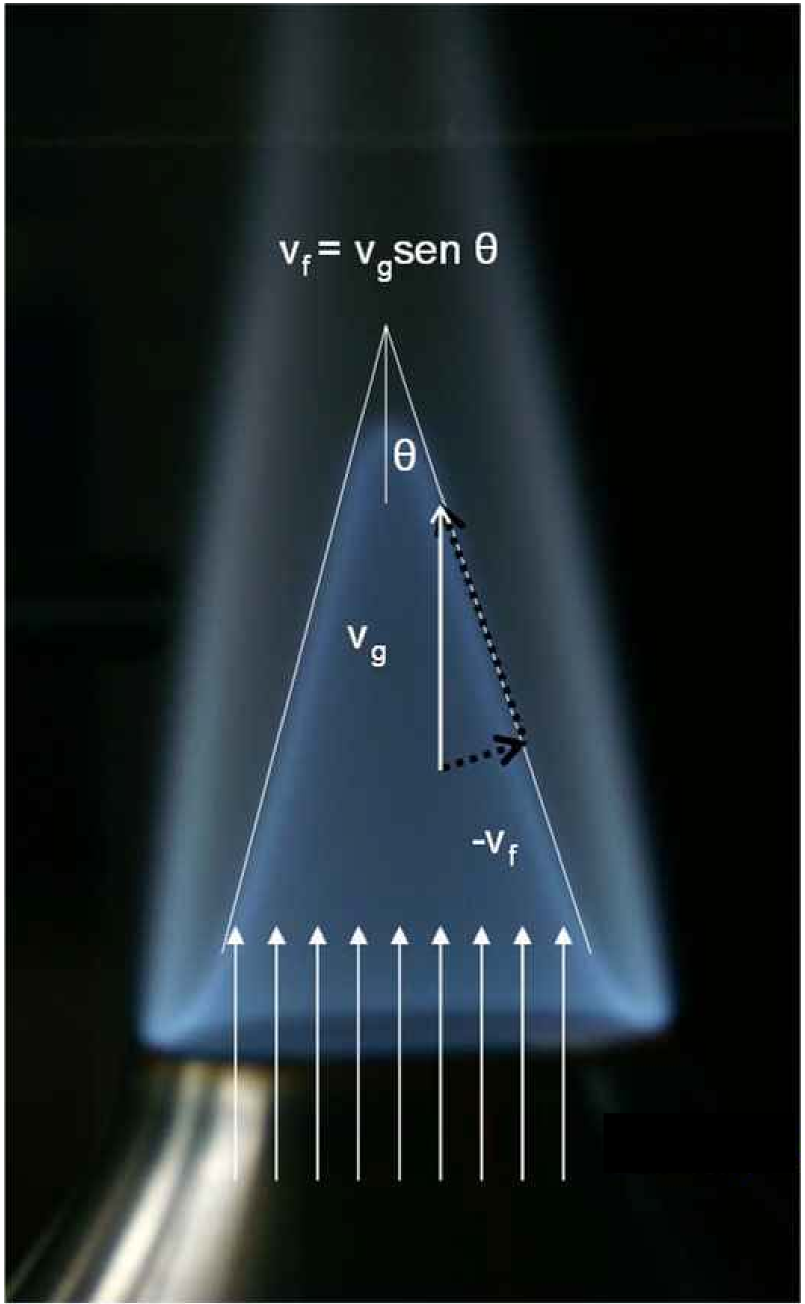
GENERALIZED RELATION
(Clavin & Joulin, 1988)

Different effects have different Markstein lengths

$$\frac{U_n}{U_L} - 1 = \mathscr{L}_c \nabla \cdot \boldsymbol{n} + \mathscr{L}_s \frac{1}{U_L} \boldsymbol{n} \cdot \nabla \boldsymbol{u} \cdot \boldsymbol{n}$$

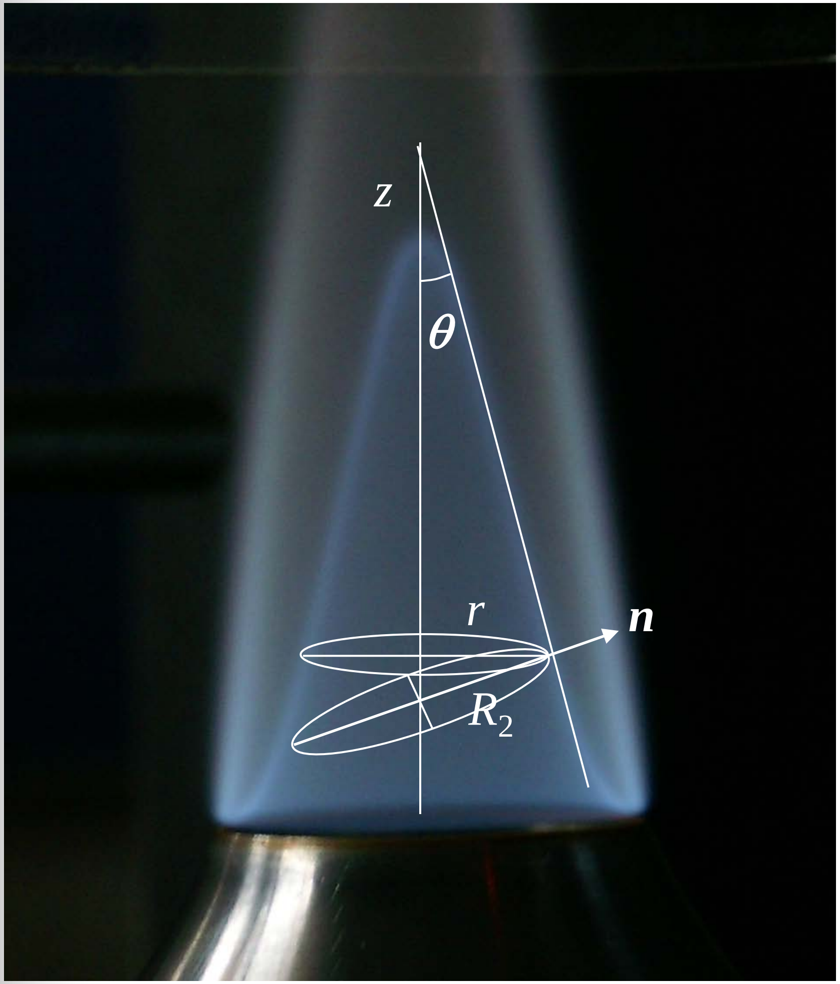
Linear theory leads to: $\mathscr{L} = \mathscr{L}_c = \mathscr{L}_s$

LAMINAR JET BURNER (BUNSEN) FLAME



R. W. Bunsen (1811-99)

PRINCIPAL CURVATURES OF A JET FLAME



1. Curvature of the 2-D section:

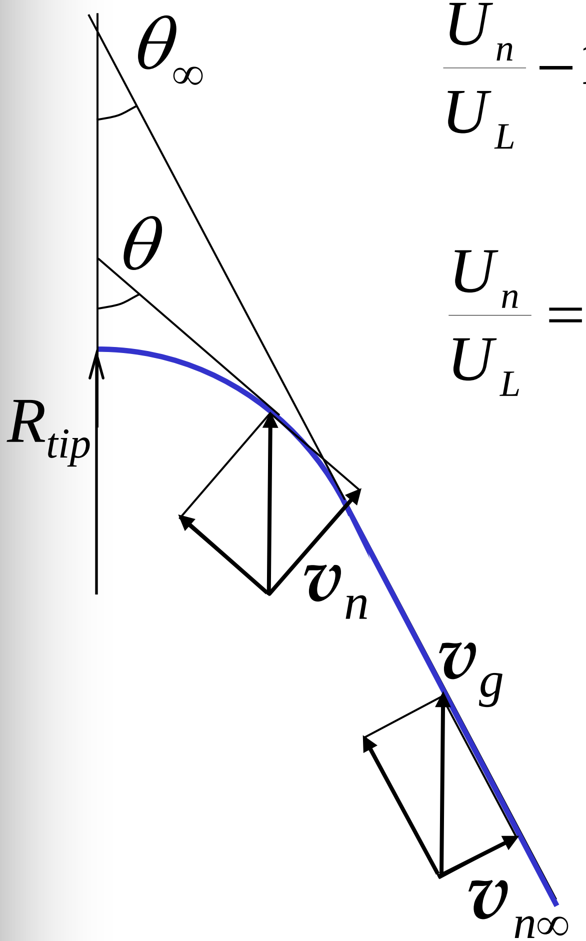
$$z_f = z(r)\,, \qquad R_1 = -\frac{\left(1+z'^2\right)^{3/2}}{z''}$$

$$\sin\theta = \frac{1}{\sqrt{1+z'^2}}\,, \quad \cos\theta = -\frac{z'}{\sqrt{1+z'^2}}$$

2. Curvature due to axial symmetry:

Moivre's formula: $R_2 = \dfrac{r}{\cos\theta}$

CURVED (NON STRAINED) JET FLAME

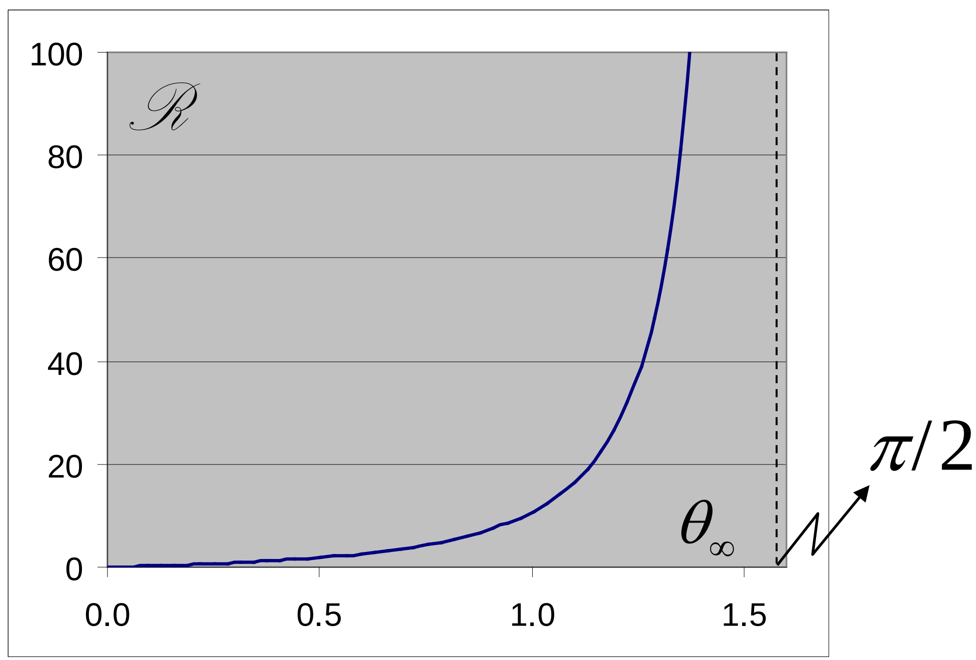


$$\left.\begin{aligned} \frac{U_n}{U_L} - 1 &= \mathscr{L}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) \\ \frac{U_n}{U_L} &= \frac{v_g \sin\theta}{U_L} = \frac{\sin\theta}{\sin\theta_\infty} \end{aligned}\right\}$$

$$\frac{1}{\sin\theta_\infty} - 1 = \mathscr{L}\frac{2}{R_{tip}}$$

$$\mathscr{R} \equiv R_{tip}/\mathscr{L} = \frac{2\sin\theta_\infty}{1-\sin\theta_\infty}$$

$$\boxed{v_{n\infty} \cong U_L \;\Rightarrow\; \frac{v_g}{U_L} = \frac{1}{\sin\theta_\infty}}$$



SHAPE OF A CURVED JET FLAME

$$\frac{U_n}{U_L} - 1 = \mathscr{L}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$z' \equiv \frac{dz}{dr} \equiv \frac{d(z/\mathscr{L})}{d(r/\mathscr{L})} \equiv \frac{d\zeta}{d\rho} \equiv \dot{\zeta}$$

$$R_1/\mathscr{L} = -\frac{\left(1+\dot{\zeta}^2\right)^{3/2}}{\ddot{\zeta}}$$

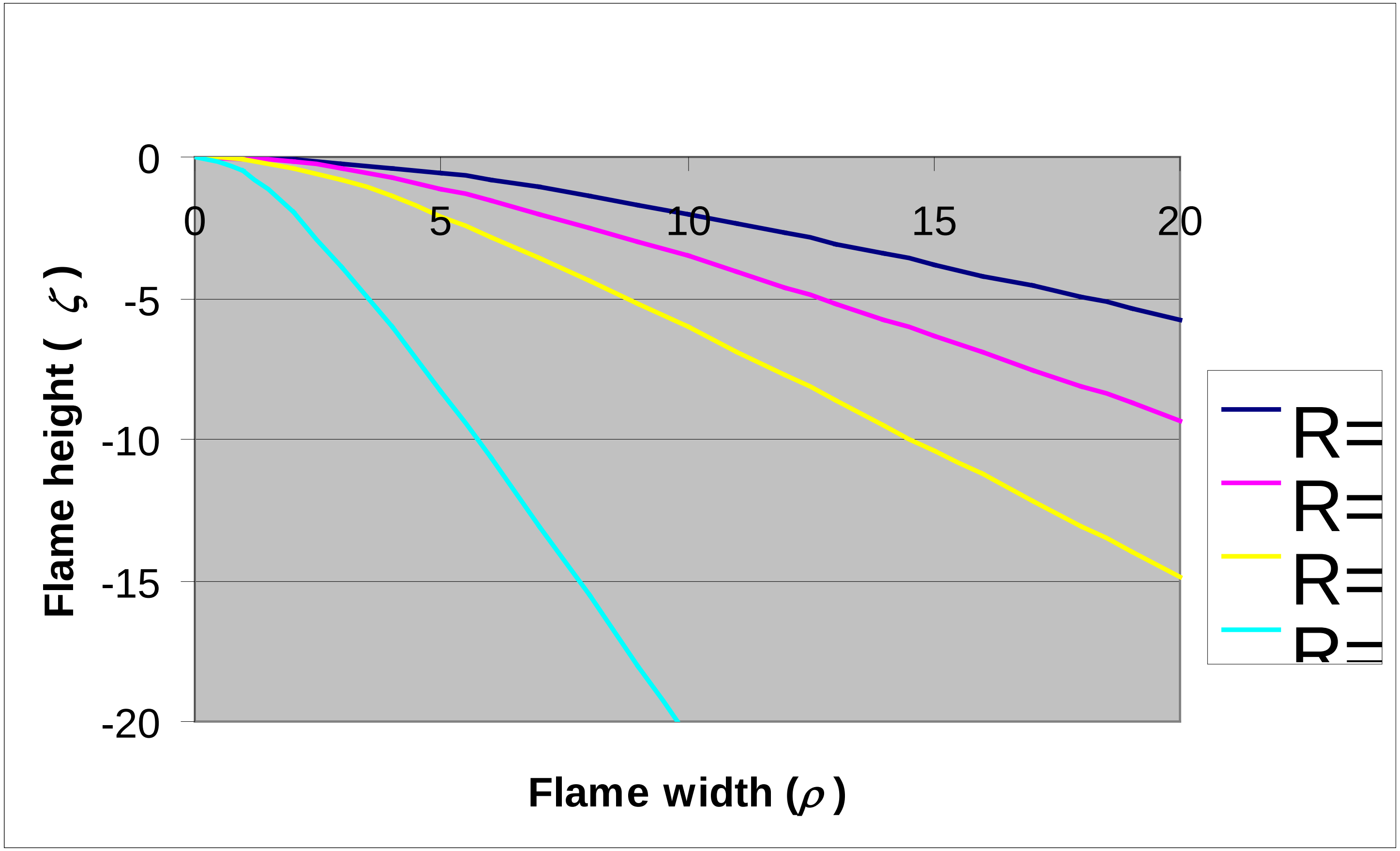
$$R_2/\mathscr{L} = -\frac{r\sqrt{1+\dot{\zeta}^2}}{\dot{\zeta}}$$

$$\ddot{\zeta} = \left(\sqrt{1+\dot{\zeta}^2} - \frac{1}{\sin\theta_\infty} - \frac{\dot{\zeta}}{\rho}\right)\left(1+\dot{\zeta}^2\right)$$

$$\zeta(0) = 0$$

$$\dot{\zeta}(0) = 0$$

SHAPE OF A CURVED JET FLAME



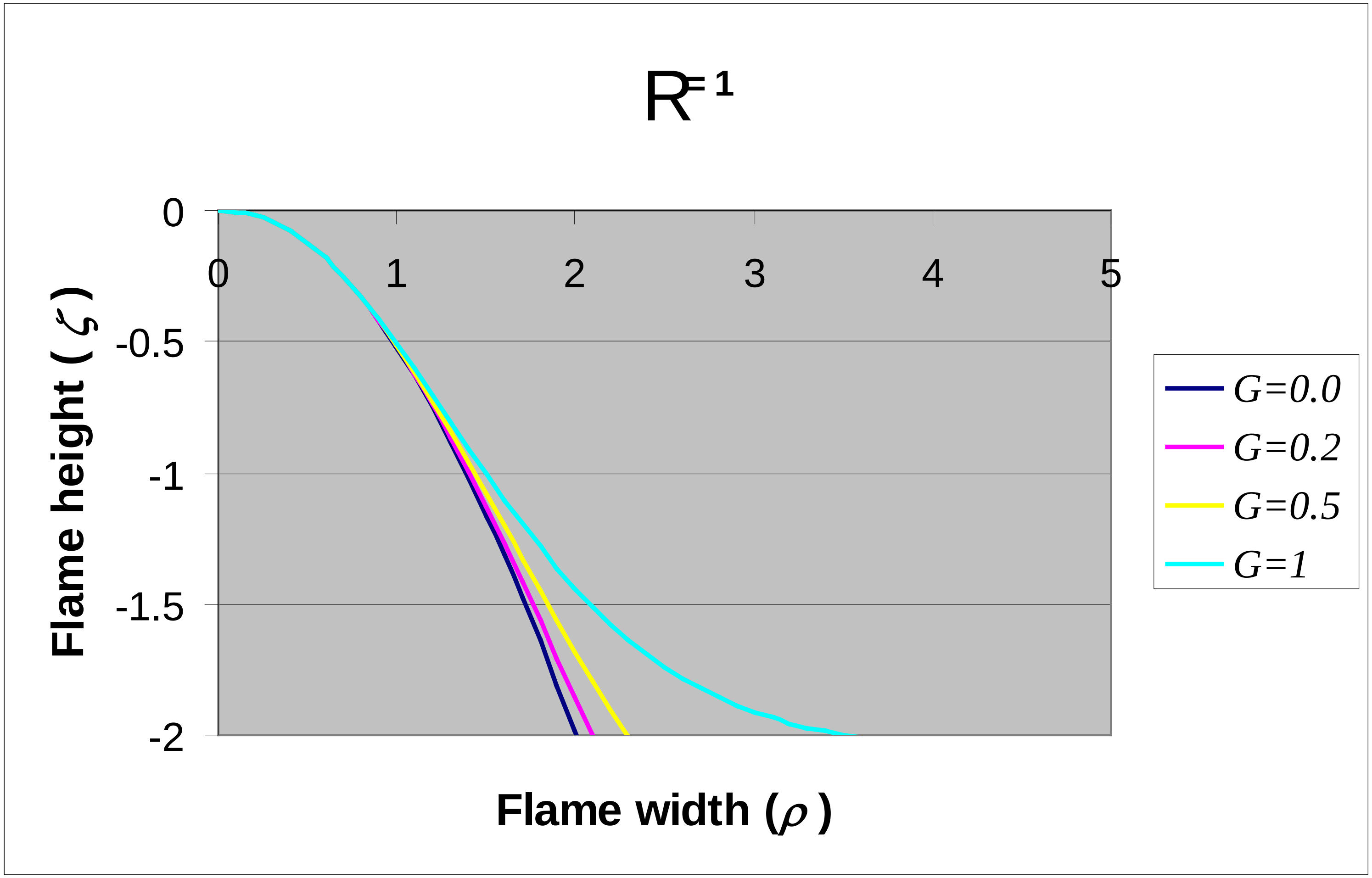
CURVED AND STRAINED JET FLAME

$$\frac{\boldsymbol{v}_g}{U_L} = \left(-\frac{G}{2}\rho,\ 0,\ \frac{v_{tip}}{U_L} + G\zeta \right) \Rightarrow \quad \boldsymbol{n}\cdot\left(\nabla \boldsymbol{v}_g\right)\cdot \boldsymbol{n} = G\,\frac{1-\dot{\zeta}^2/2}{1+\dot{\zeta}^2}$$

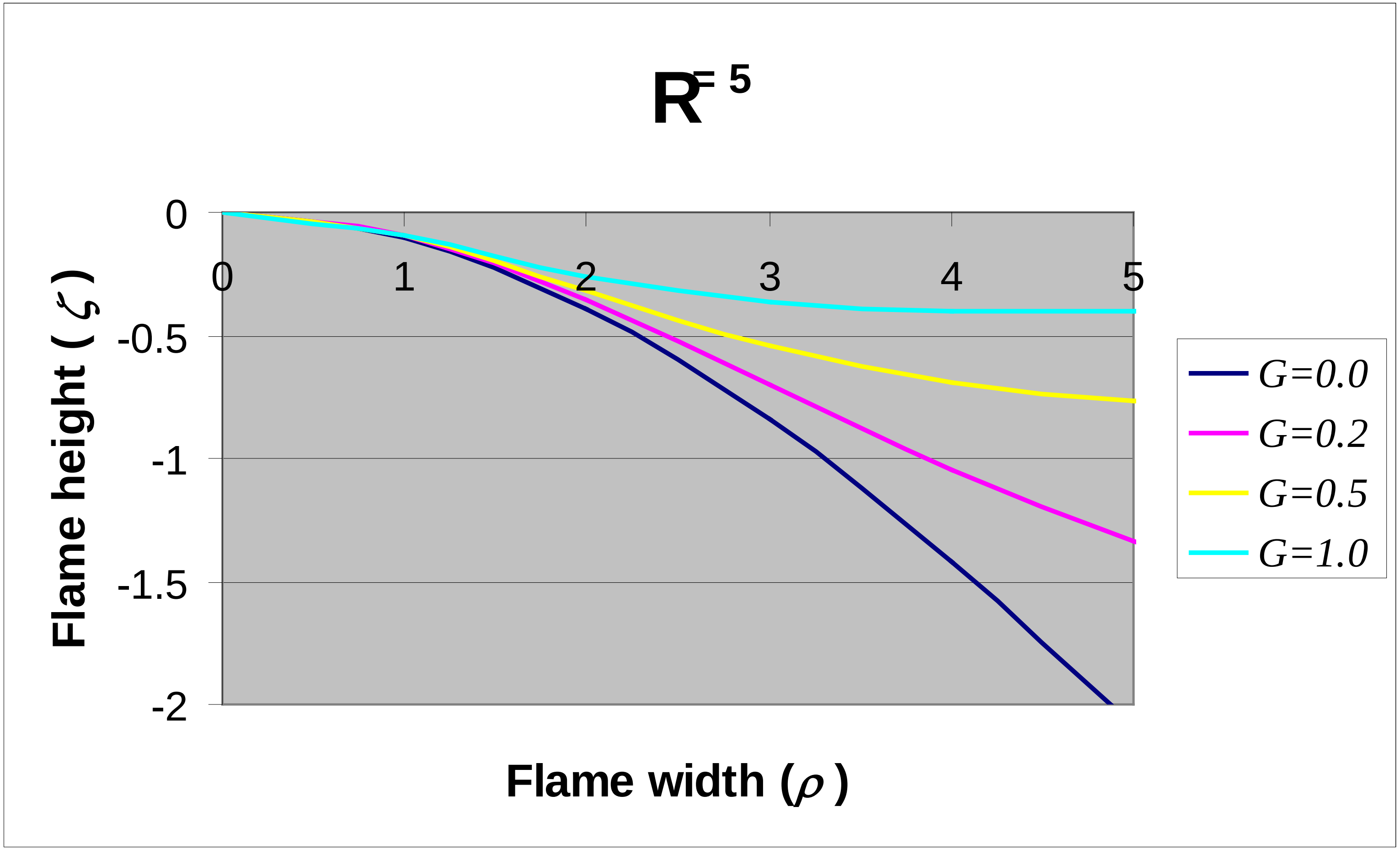
$$\frac{U_n}{U_L} = -\left(\frac{\boldsymbol{v}_g}{U_L}\cdot \boldsymbol{n} \right) = \frac{G\left(\zeta + \rho\dot{\zeta}/2\right) + v_{tip}/U_L}{\sqrt{1+\dot{\zeta}^2}}$$

$$\begin{cases} \ddot{\zeta} = \left[\sqrt{1+\dot{\zeta}^2} - \dfrac{1}{\sin\theta_\infty} - \dfrac{\dot{\zeta}}{\rho} + G\left(\dfrac{1-\dot{\zeta}^2/2}{\sqrt{1+\dot{\zeta}^2}} - \dfrac{\rho\dot{\zeta}}{2} - \zeta - 1 \right) \right]\left(1+\dot{\zeta}^2\right) \\ \zeta(0) = 0 \\ \dot{\zeta}(0) = 0 \end{cases}$$

SHAPES OF A CURVED AND STRAINED JET FLAME



SHAPES OF A CURVED AND STRAINED JET FLAME



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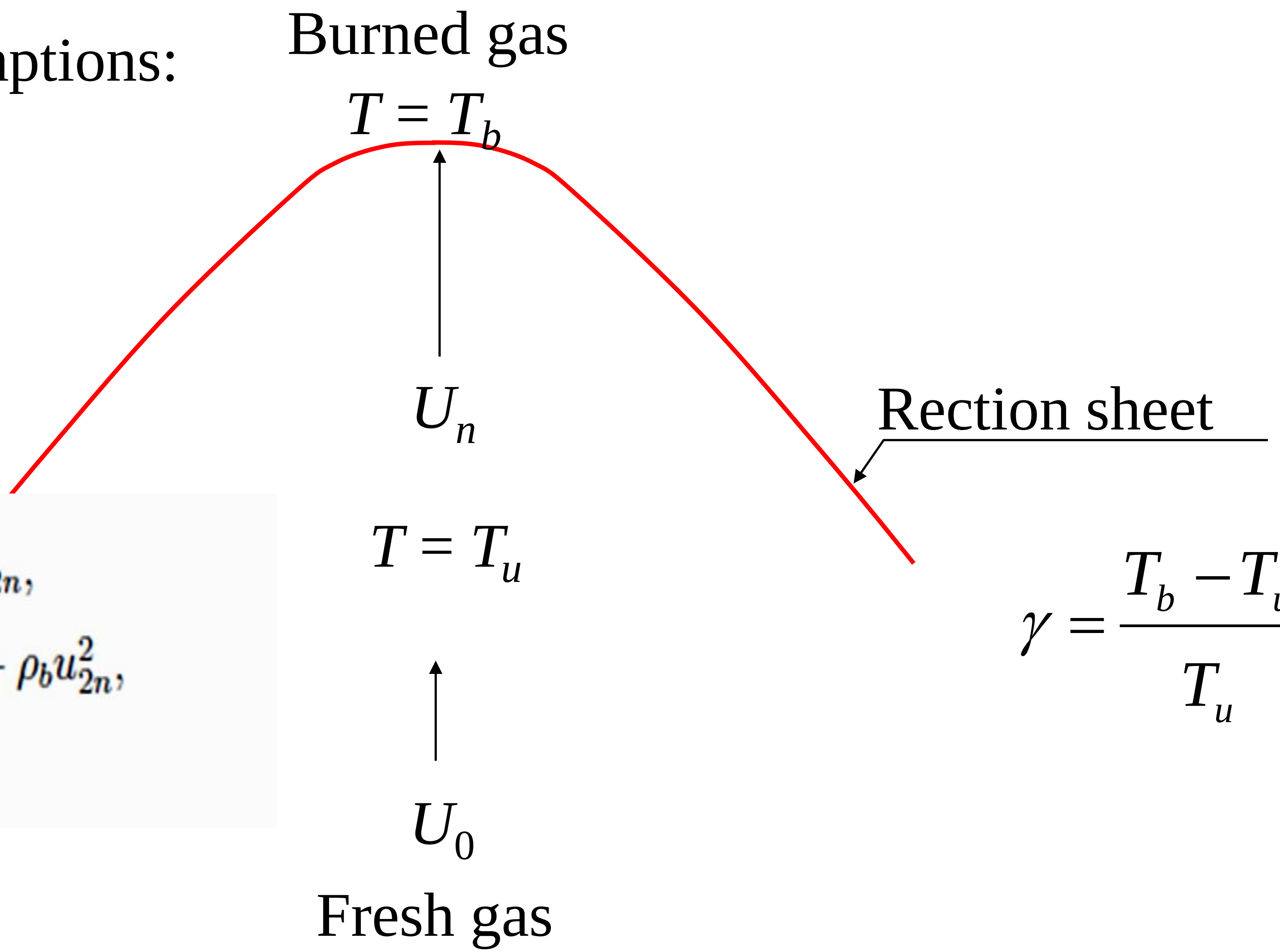
Numerical thechniques

- Assumptions:
  - Ideal inviscid gas
  - Axisymmetric
  - Irreversible Arrhenius reaction
  - High activation energy
  - l_e=O(1) => reaction region non affected by curvature
  - Quasi-isobaric low Mach number approximation
  - No gravity

reaction layer :
infinitely thin free
boundary

AEA JUMPS LOCATE THE REACTIVE FRONT

• Asumptions:



$$\rho_u u_{1n} = \rho_b u_{2n},$$

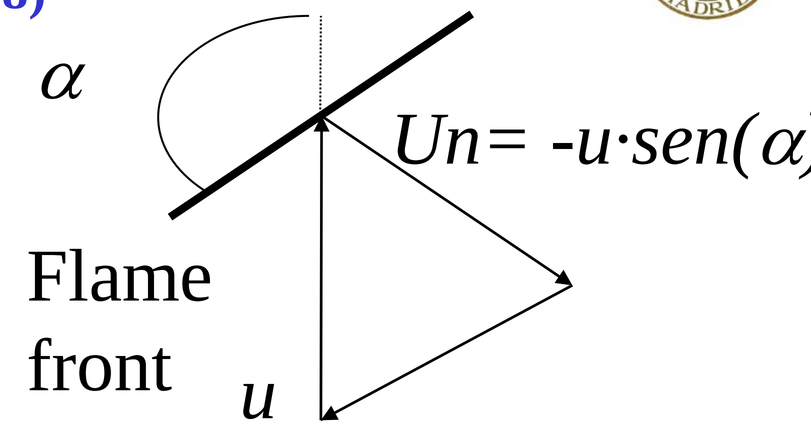
$$p_1 + \rho_u u_{1n}^2 = p_2 + \rho_b u_{2n}^2,$$

$$u_{1t} = u_{2t},$$

$$\gamma = \frac{T_b - T_u}{T_u}$$

GENERALIZED RELATION
(Clavin & Joulin, 1988)

$$\frac{U_n}{U_L}-1$$



$$\frac{U_n}{U_L}-1=\mathcal{L}_K\left(\nabla\cdot\boldsymbol{n}\right)+\mathcal{L}_G\left(\frac{1}{U}\boldsymbol{n}\cdot\nabla\boldsymbol{u}\cdot\boldsymbol{n}\right)$$

$$\left(\nabla\cdot\boldsymbol{n}\right)+ \qquad \left(\frac{1}{U_L}\boldsymbol{n}\cdot\nabla\quad\boldsymbol{n}\right)$$

u

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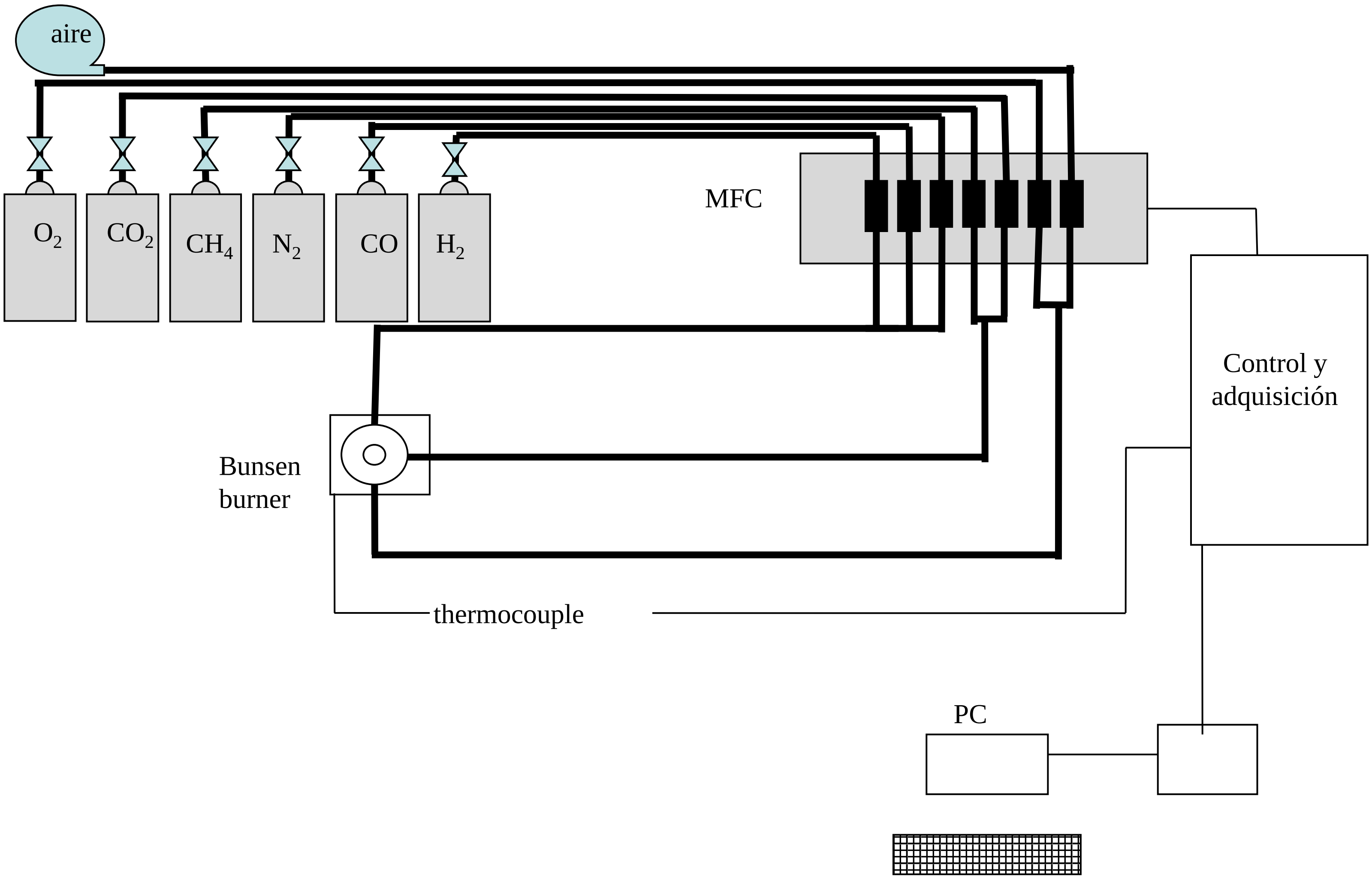
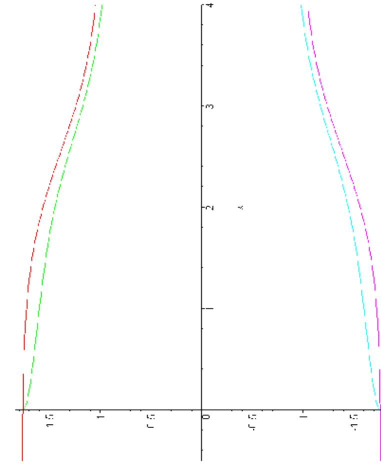
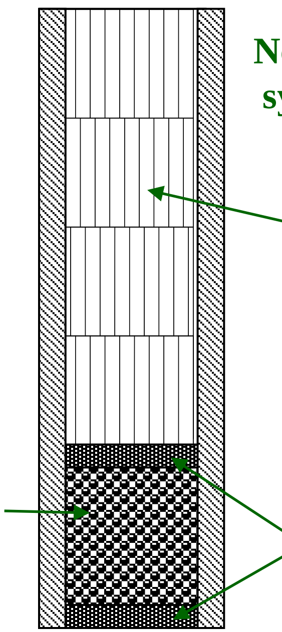
Experimental facility



LAMINAR JET BURNER



Nozzle inner profile



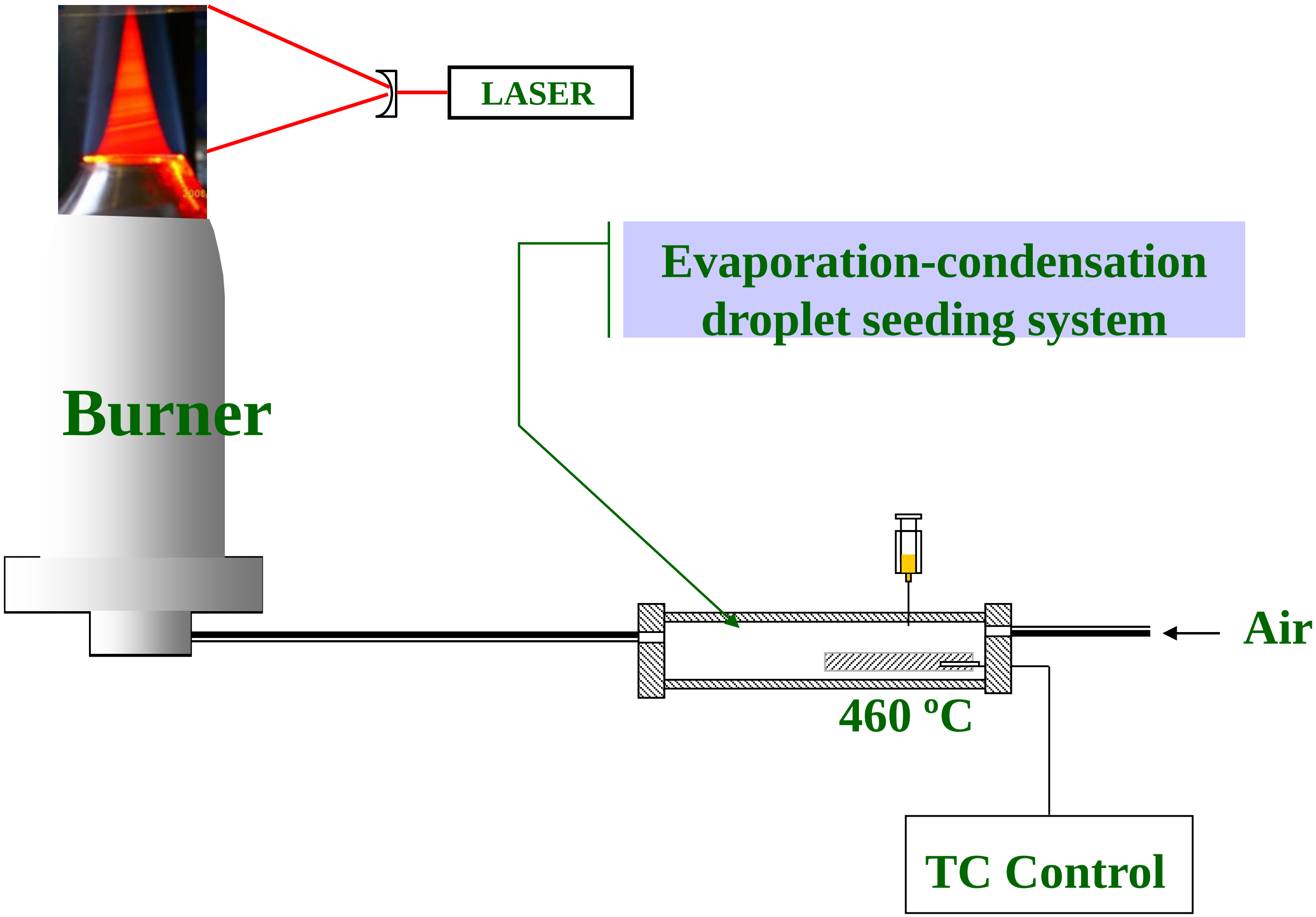
Nozzle-plenum system

Al honeycomb

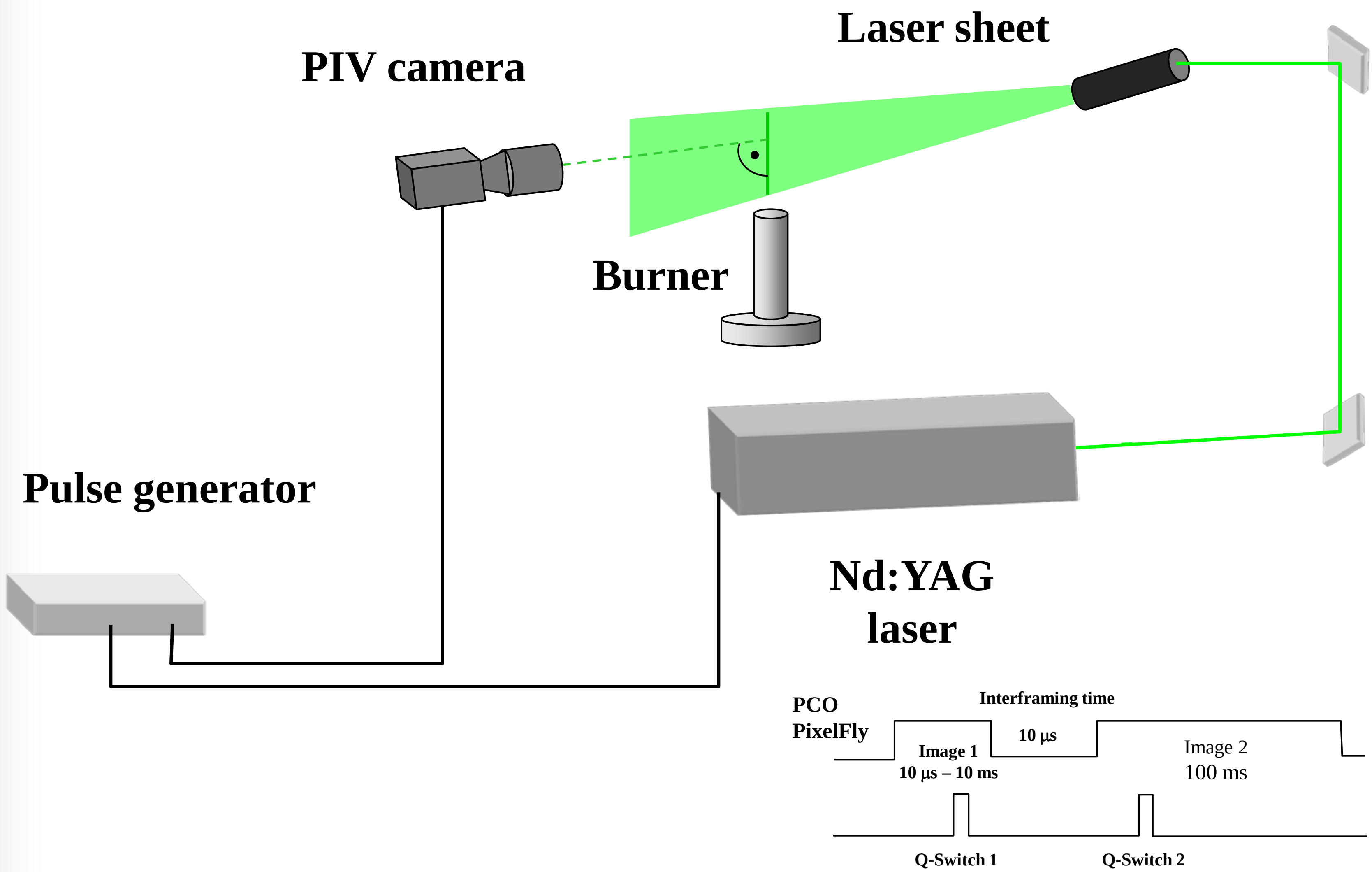
Al balls (4 mm)

Synterized Cu porous plates

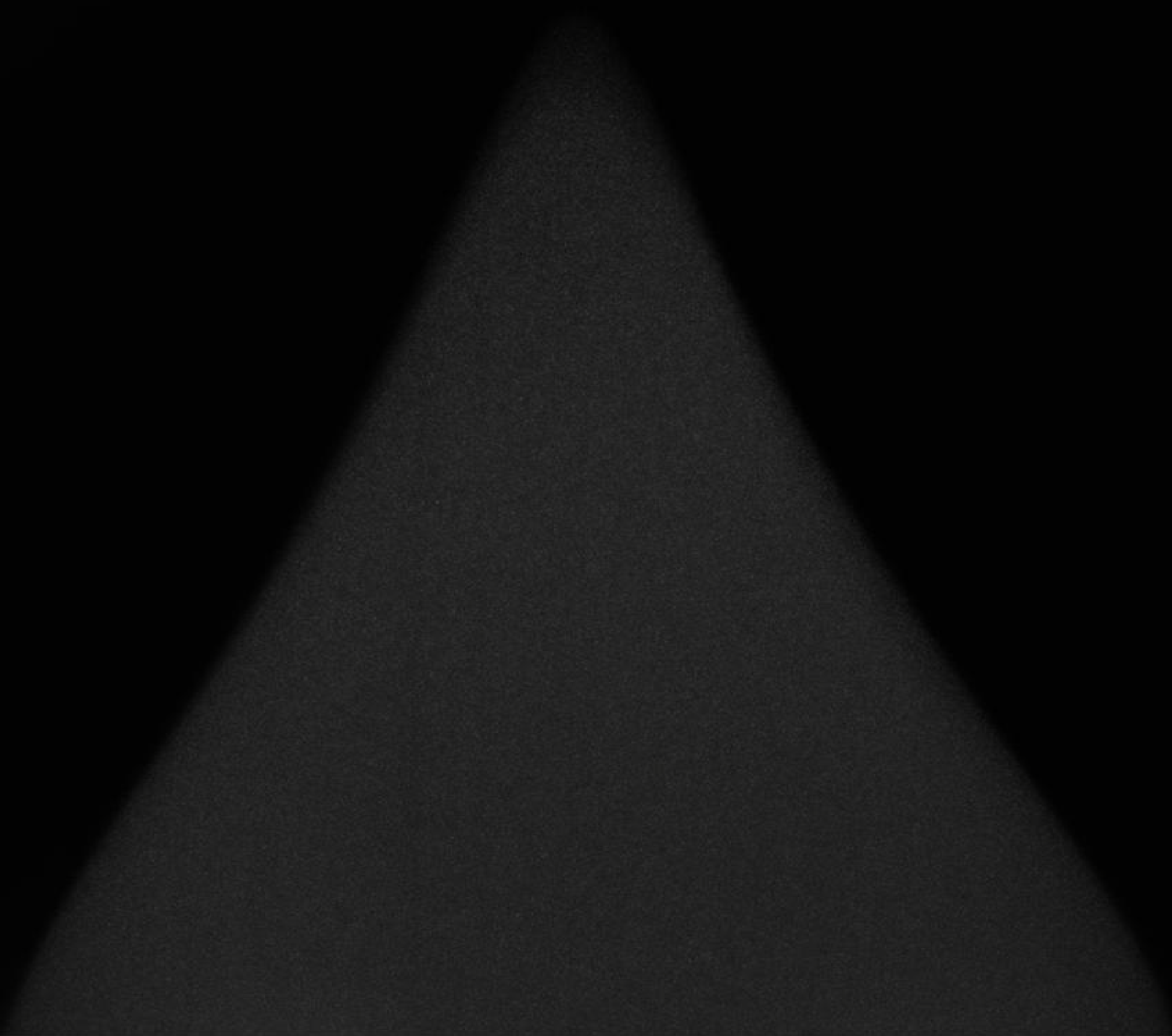
OIL DROPLET VISUALIZATION



PIV DIAGNOSTICS SYSTEM



PARTICLES



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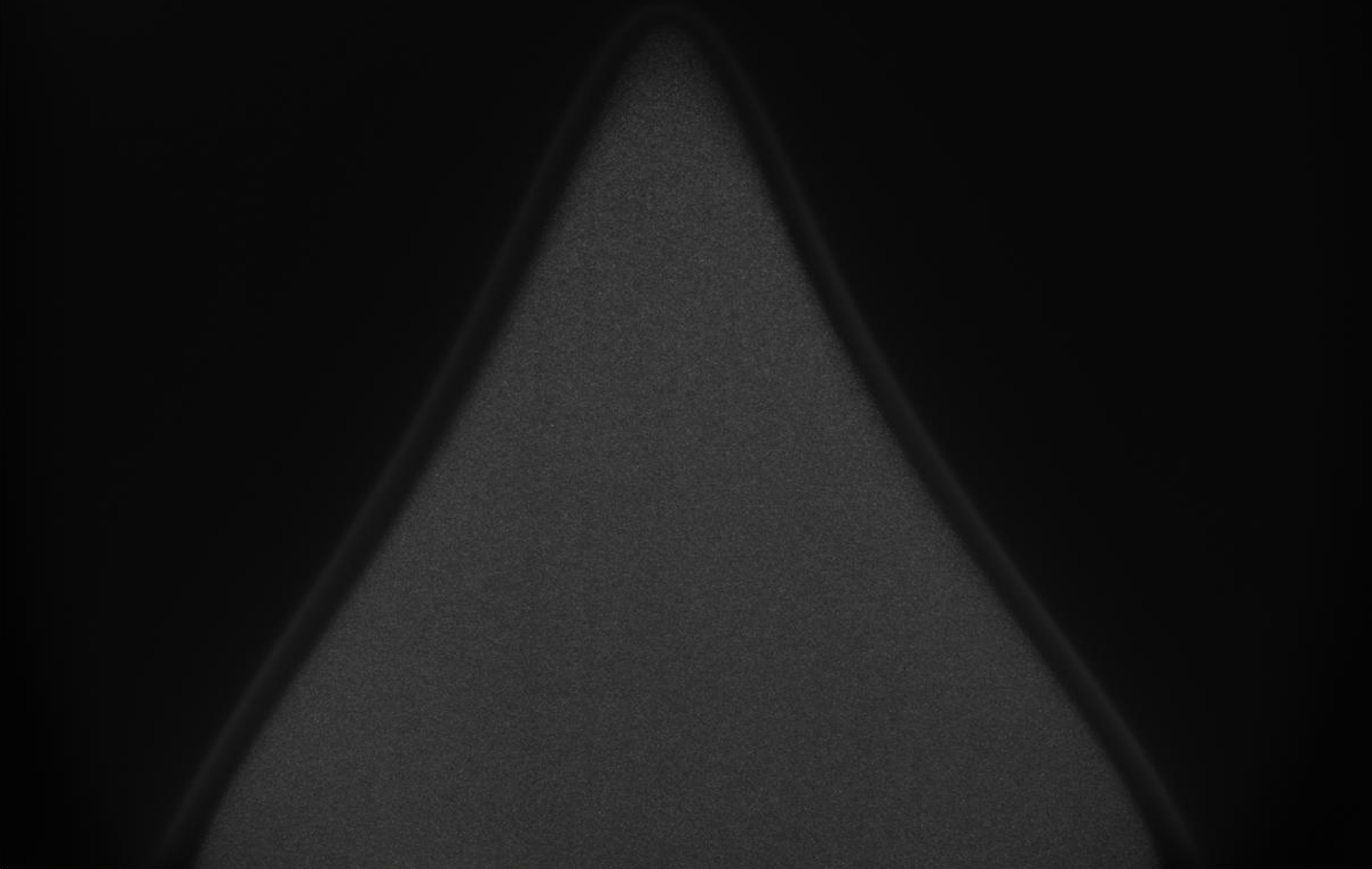

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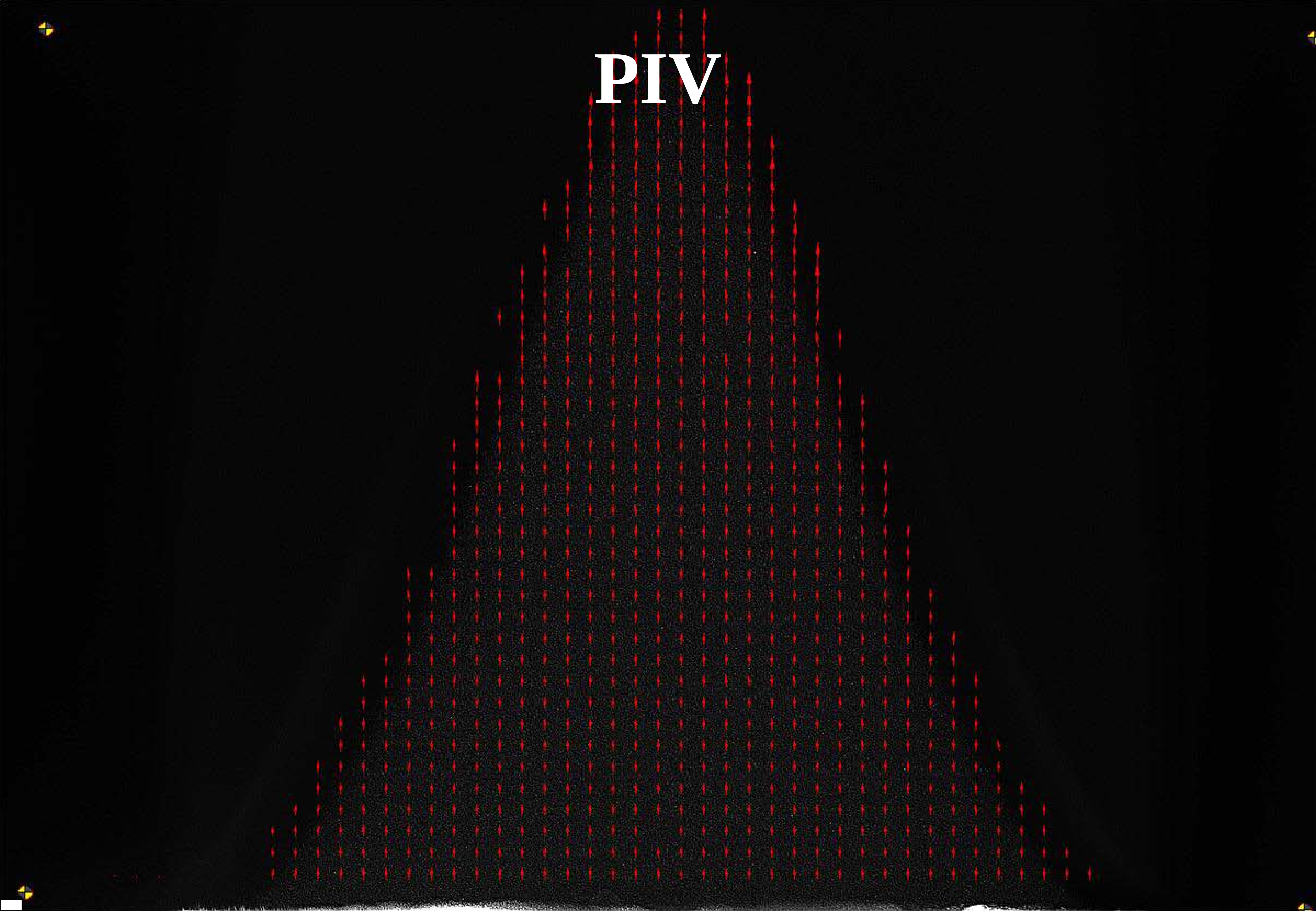
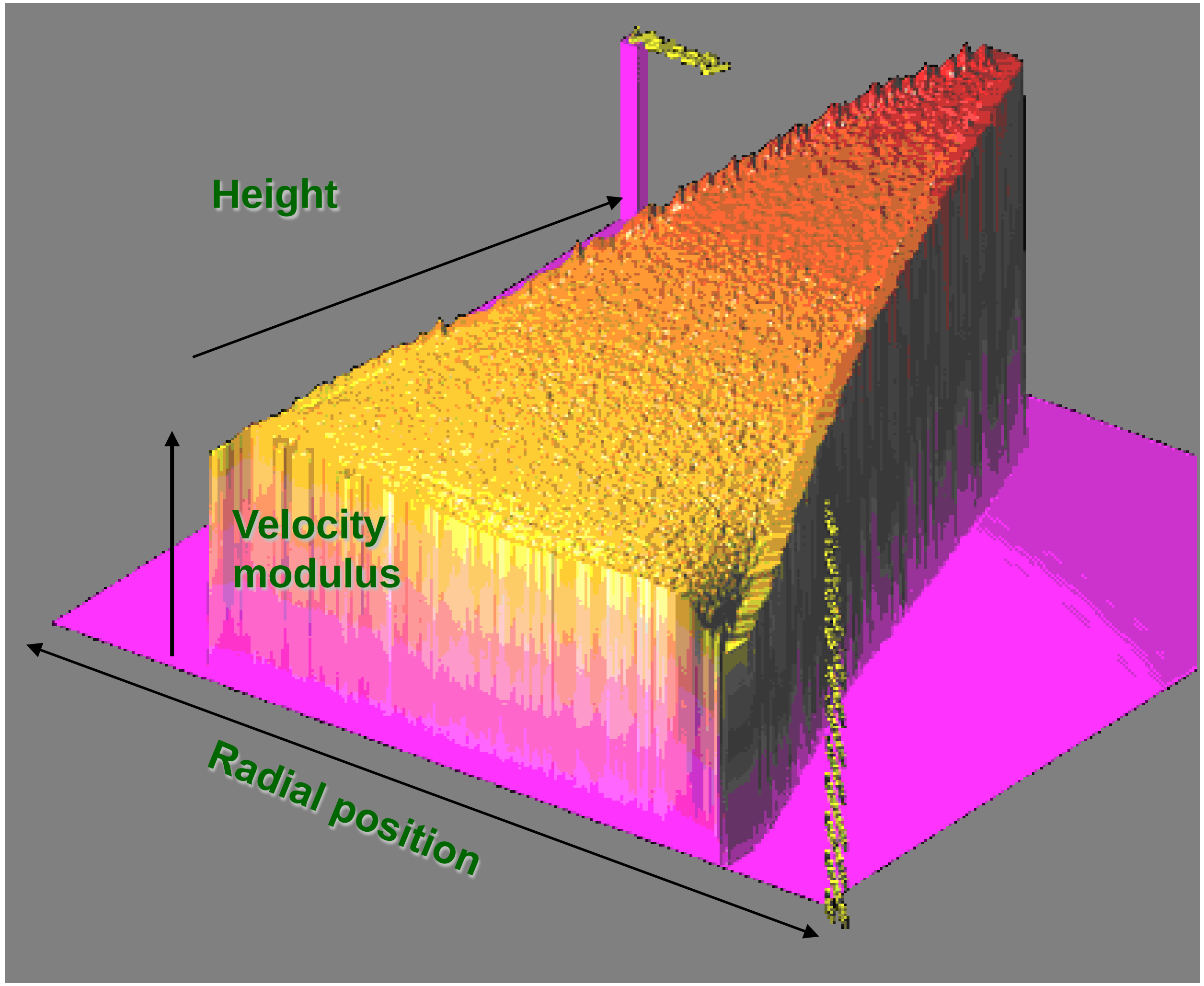
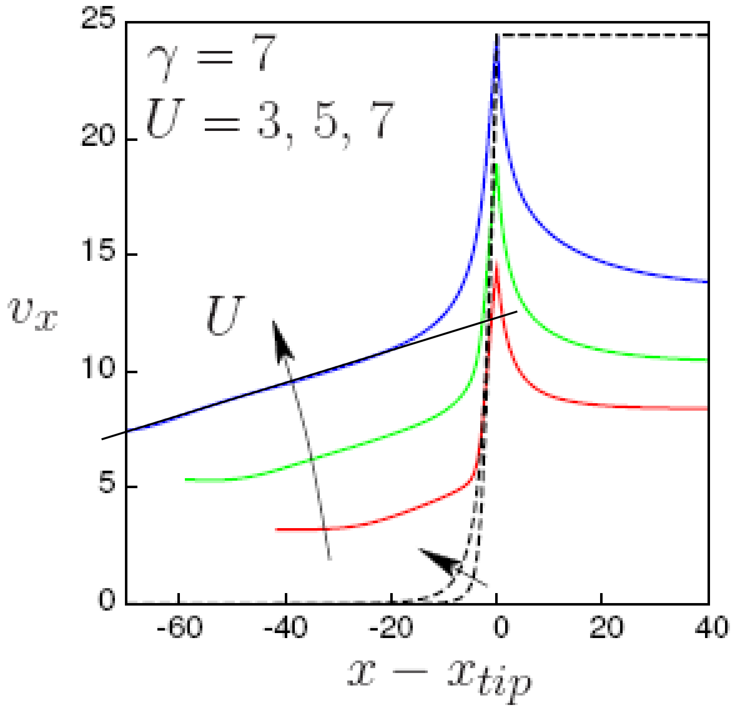

PIV

PIV VELOCITY PROFILES IN A BUNSEN FLAME



VELOCITY ALONG THE SYMMETRY AXIS



$$U \equiv U_n / U_L$$

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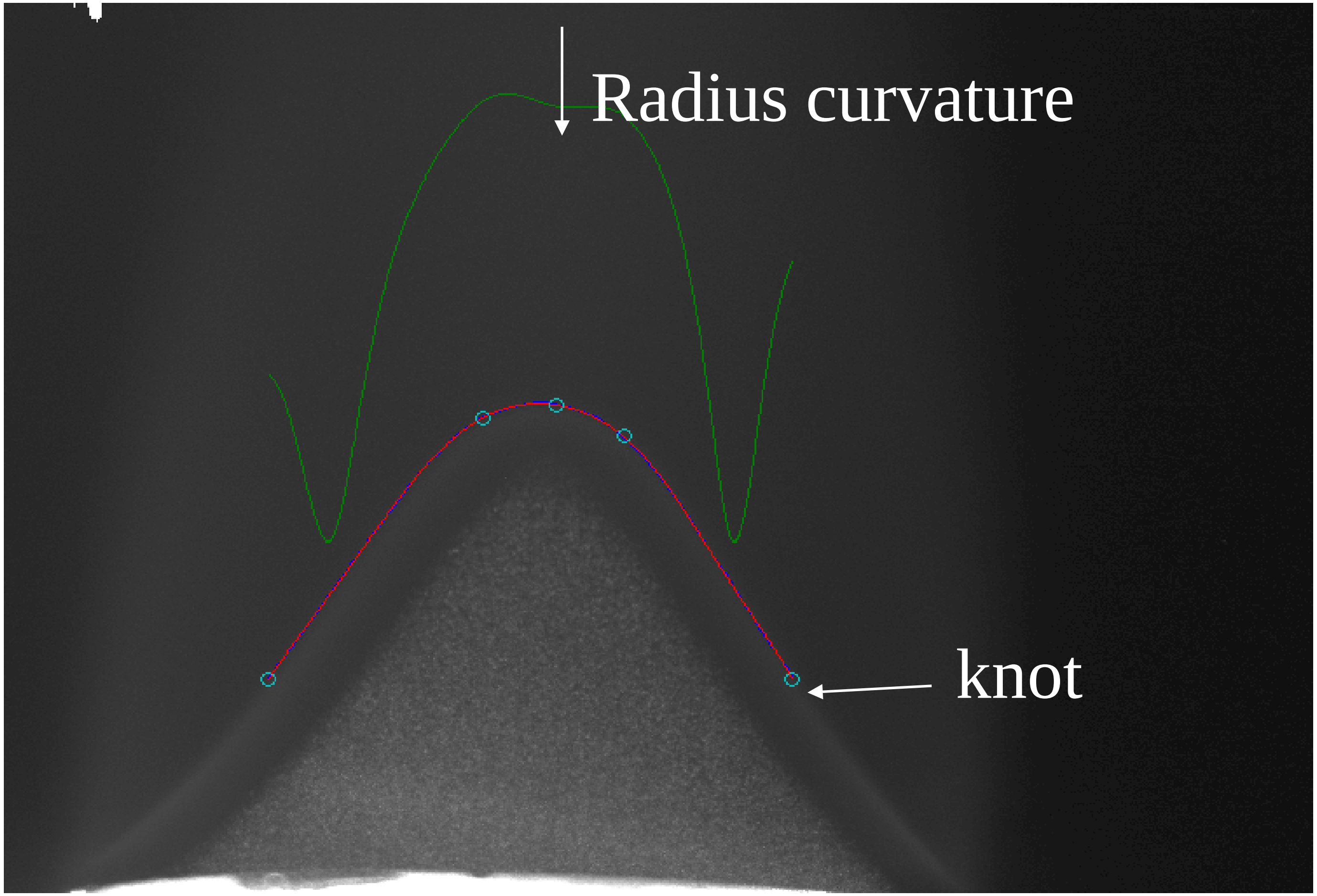
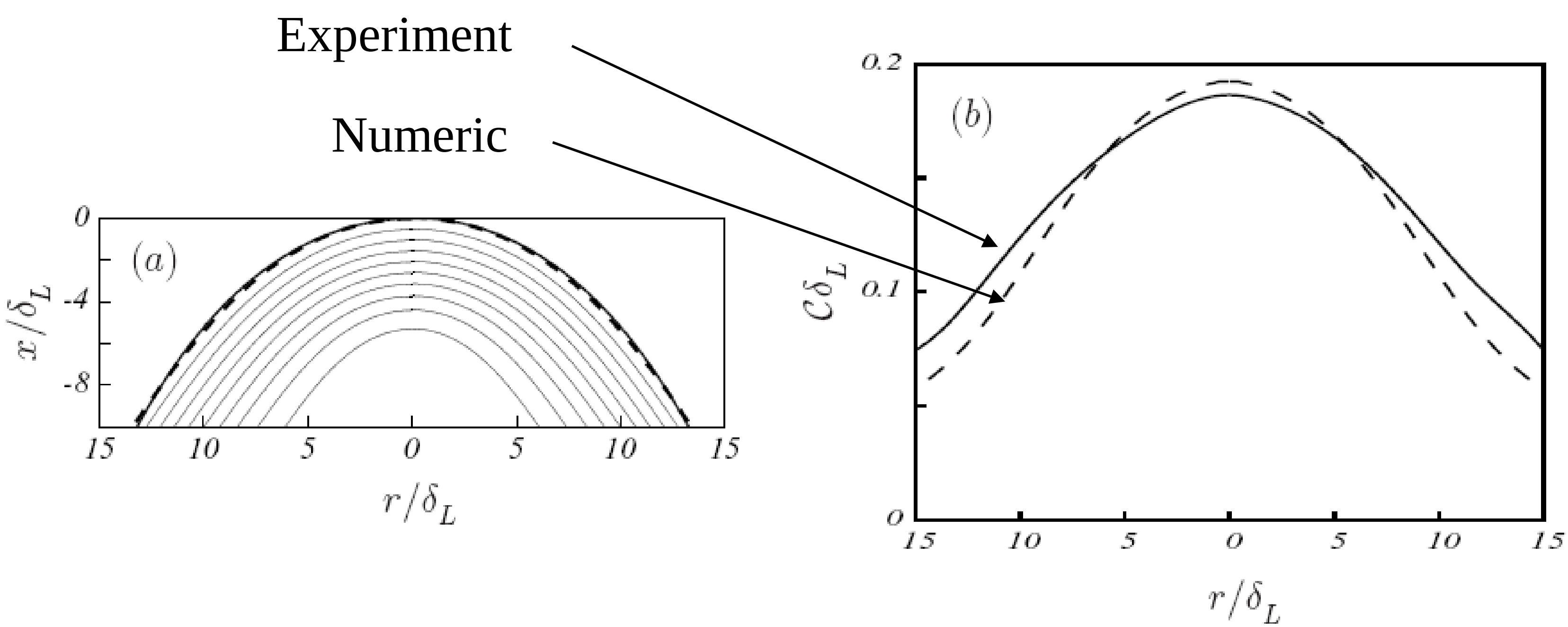
Minimal spline



blue: detected flame front

red: detected flame front

SHAPE OF THE REACTIVE SHEET
($\gamma = 6$, $U_n/U_L = 4.15$)



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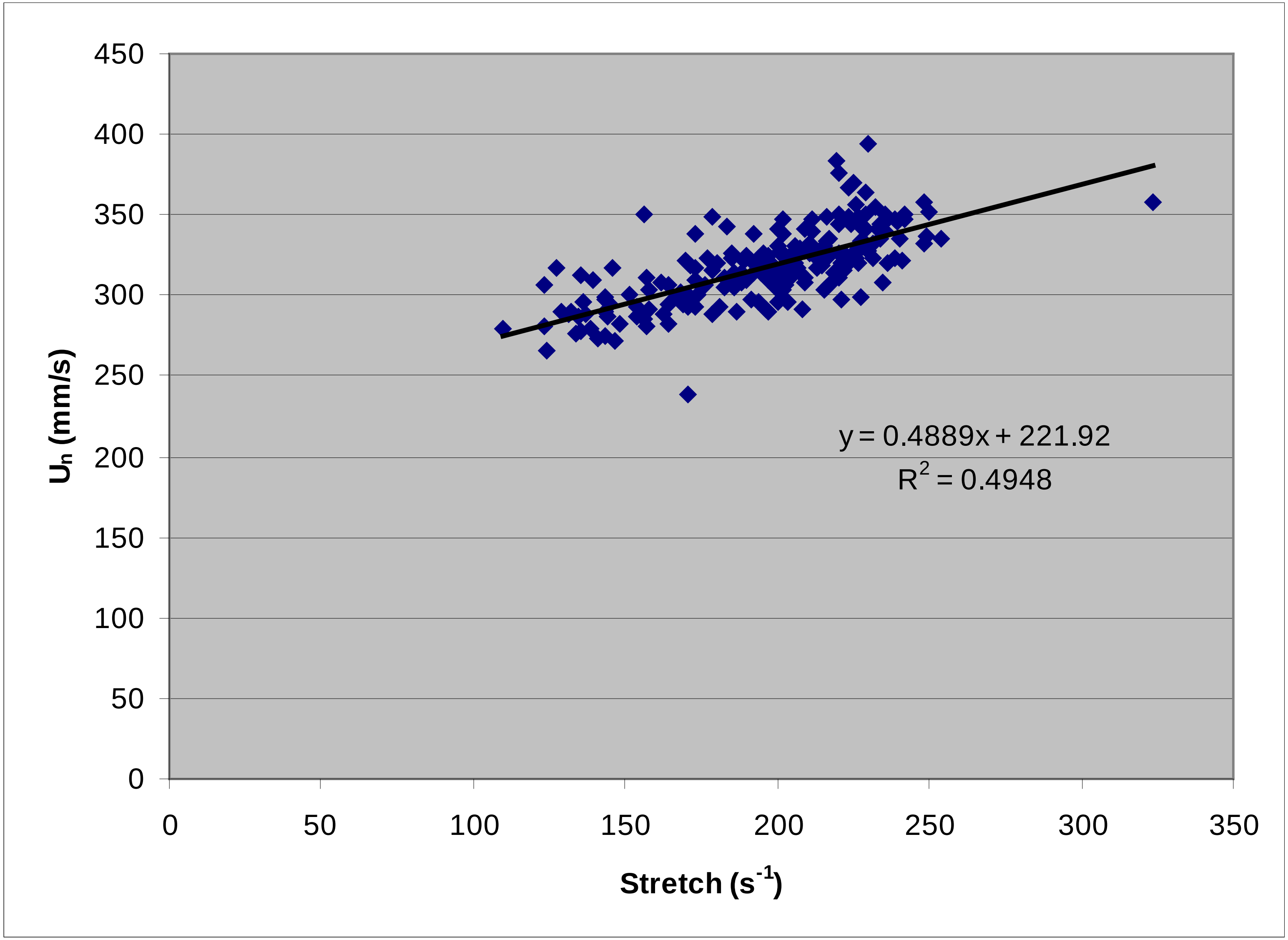
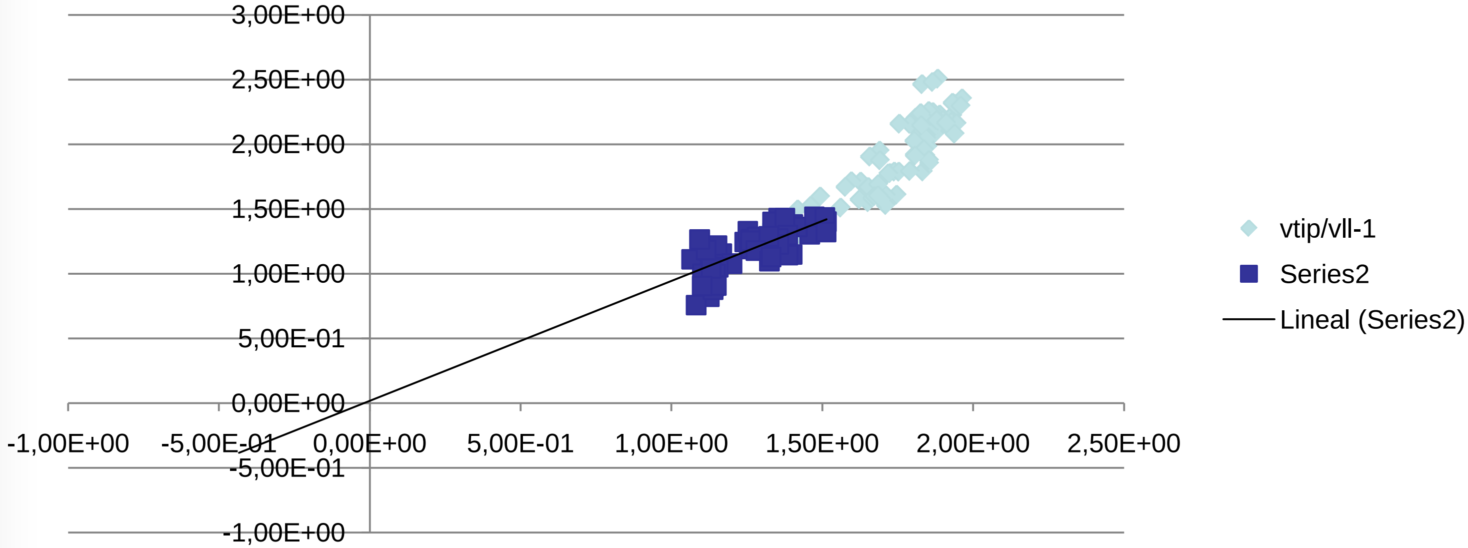
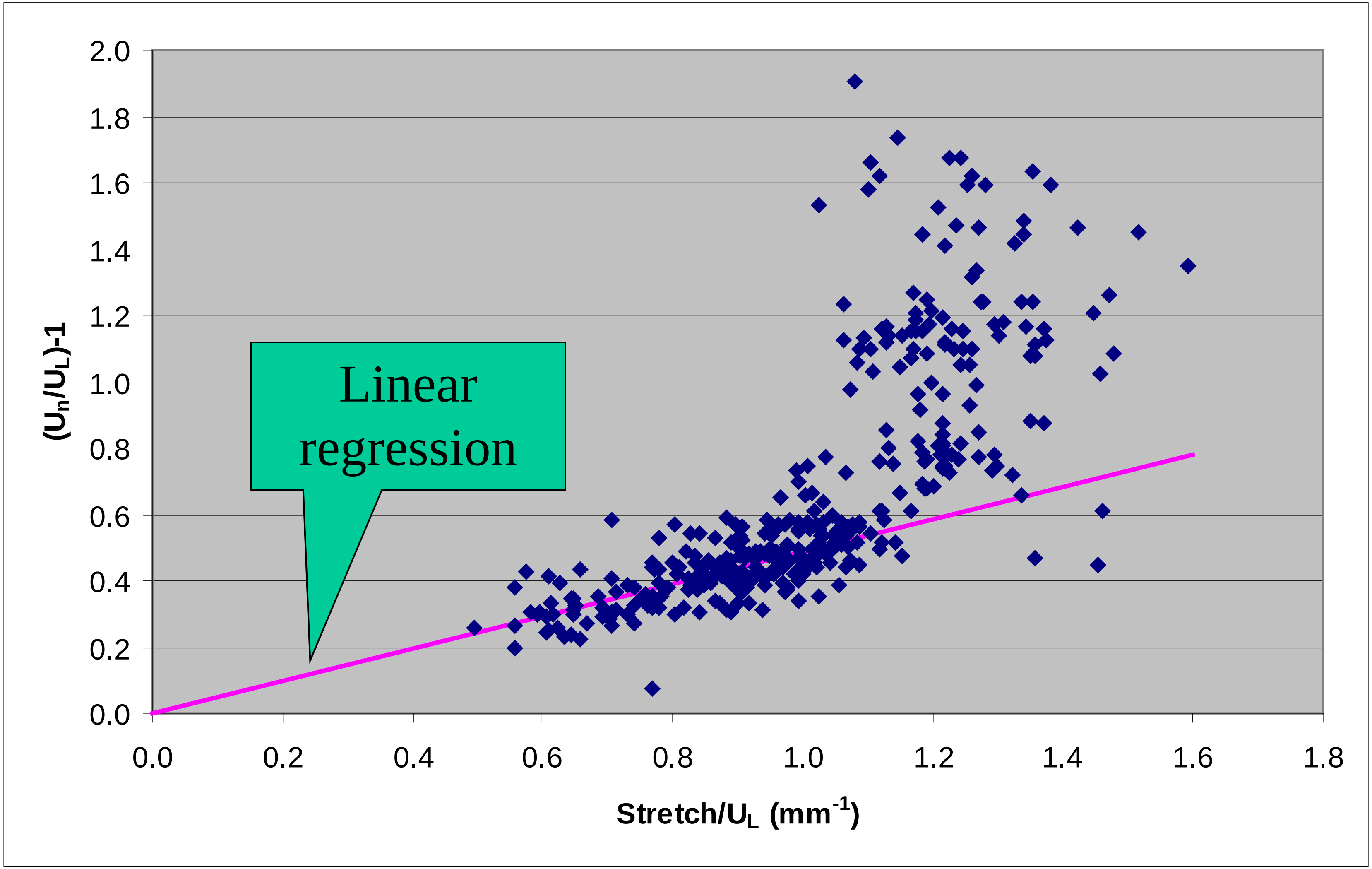
U_n *vs.* S – Linear correlation (flame tip, $\phi = 1.43$)

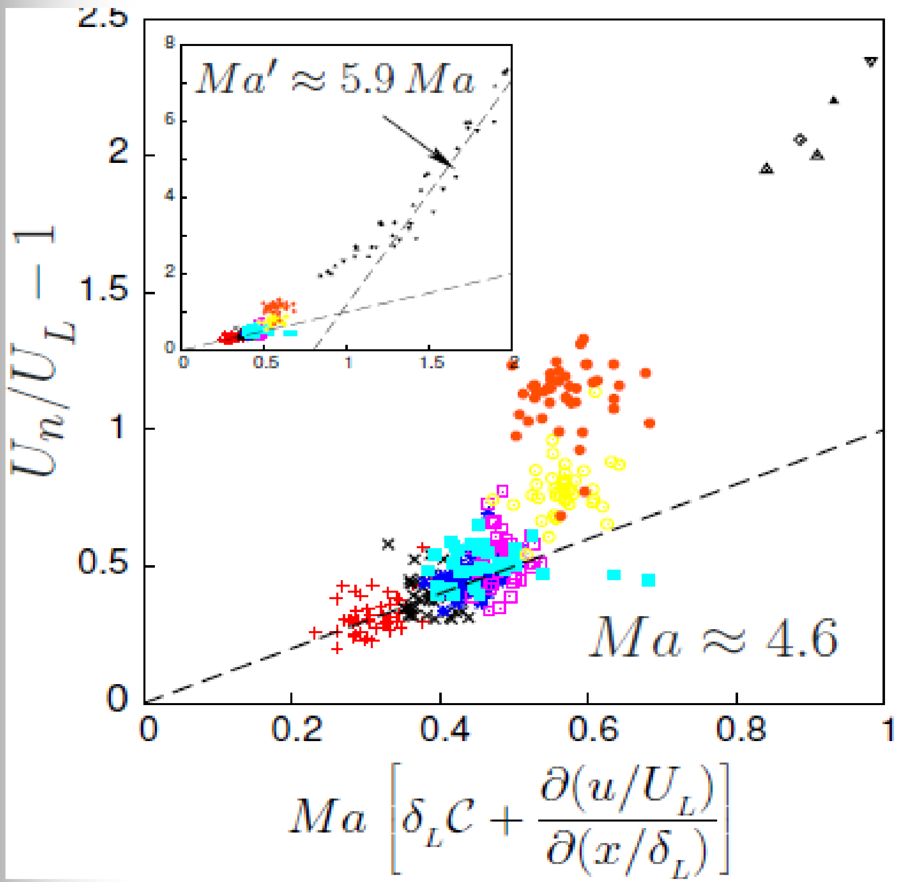


U_n /Ul-1*vs. S/Ul* – Linear correlation (flame tip, $\phi = 1.40$)



$(U_n/U_L\text{-}1)$ *vs.* S/U_L (flame tip, $\phi = 1.43$)





γ

△ = 3

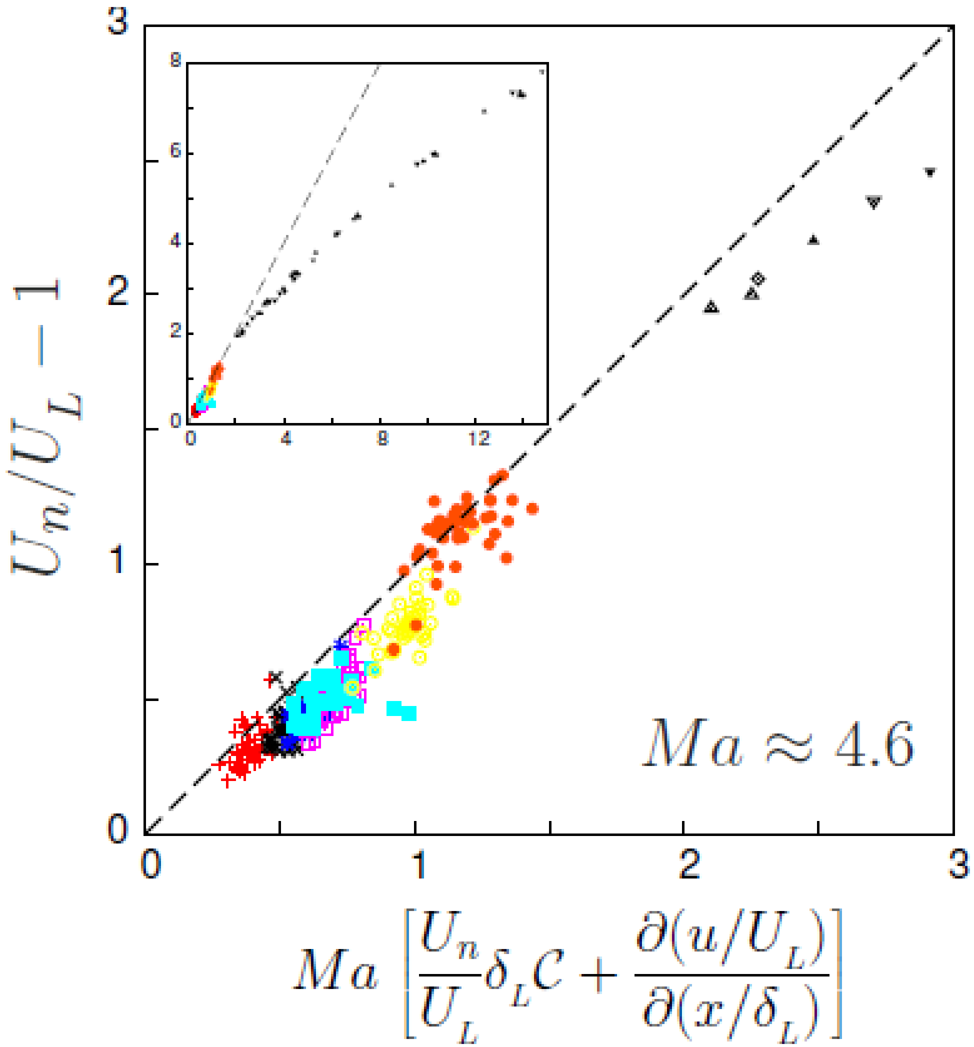
▽ = 5

○ = 6

□ = 7

Color= Experiments

EXTENDED MARKSTEIN RELATION



γ

△ = 3

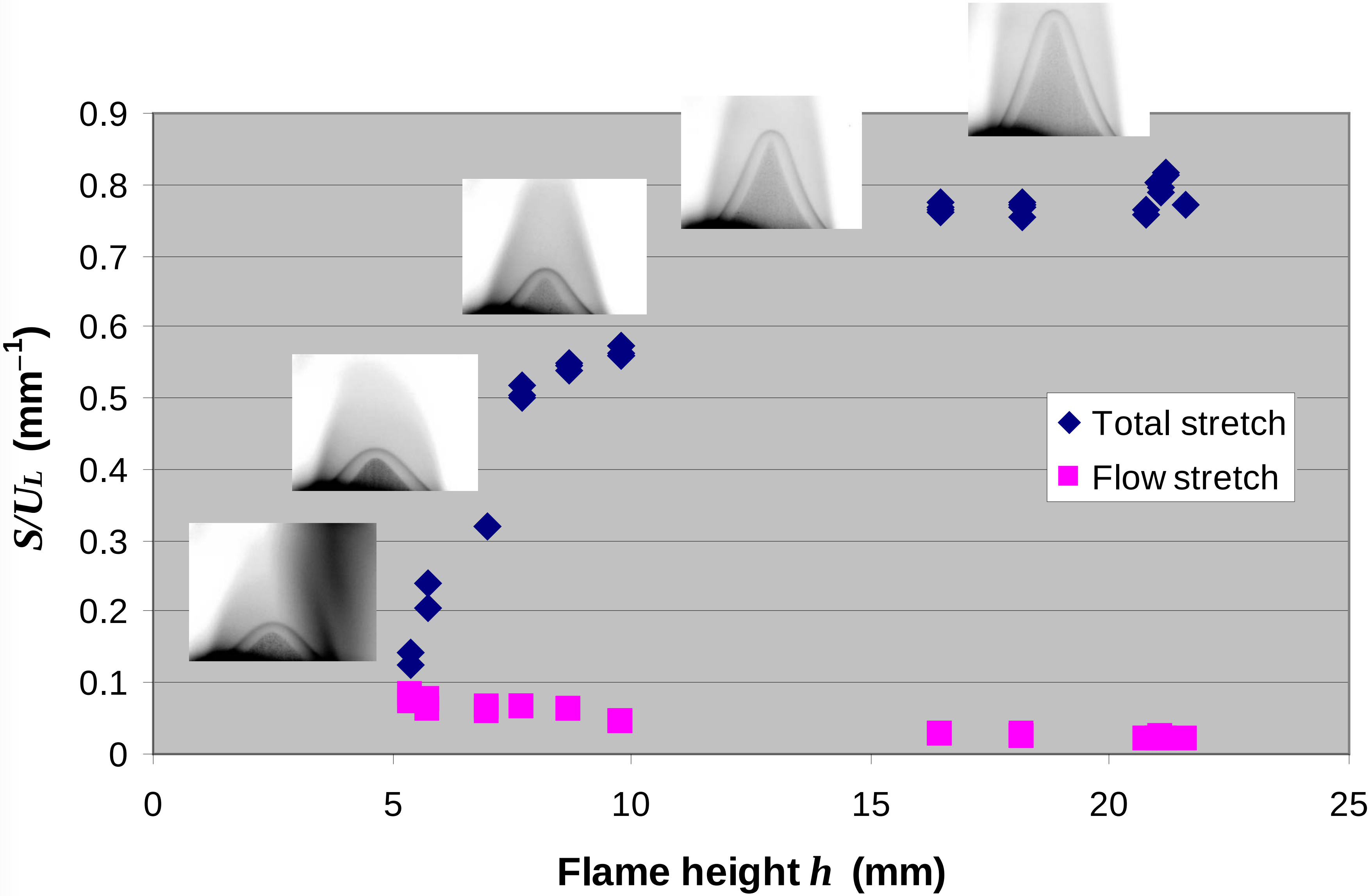
▽ = 5

○ = 6

□ = 7

Color= Experiments

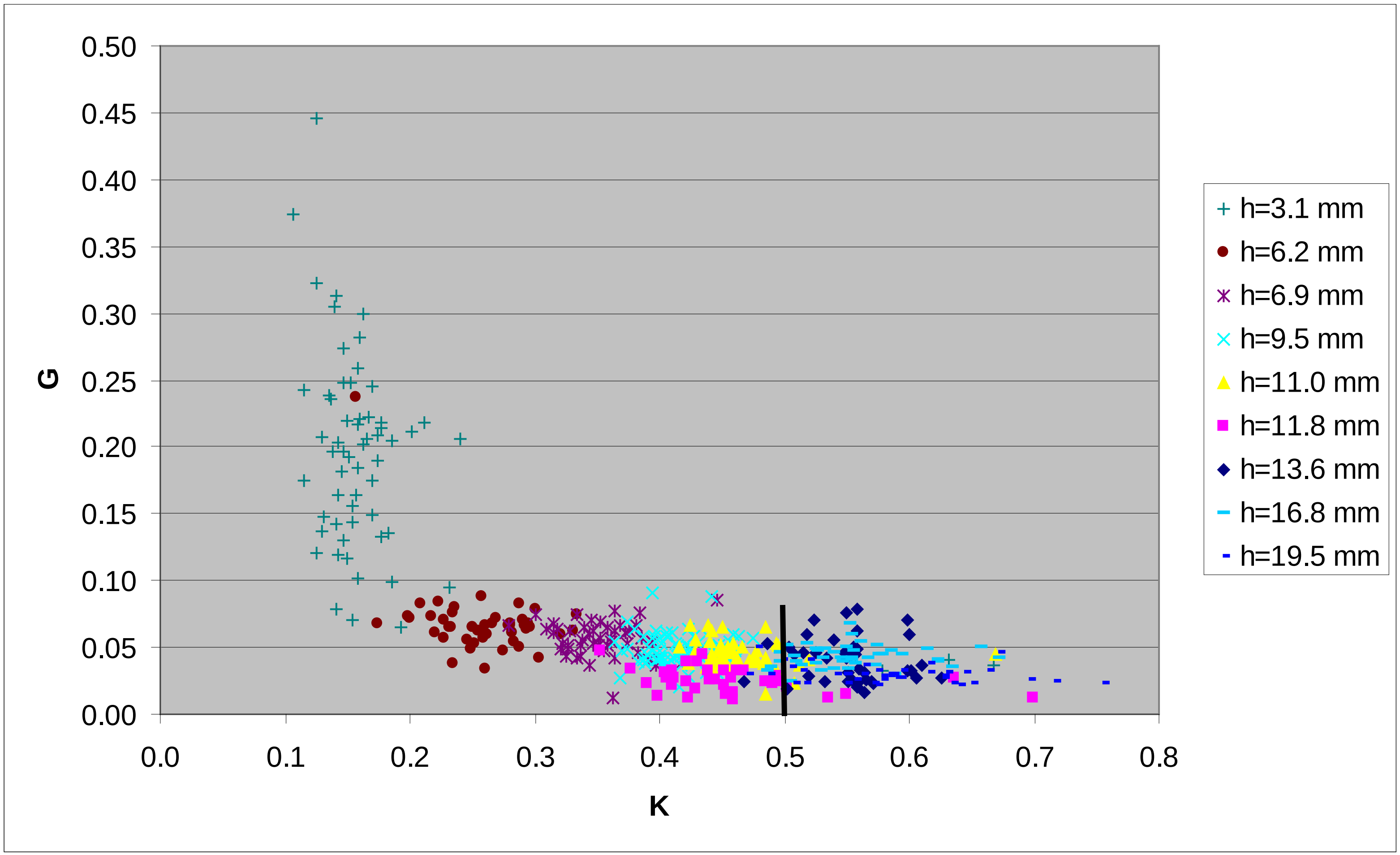
FLAME STRETCH *vs.* FLAME HEIGHT ($\phi = 1.46$)



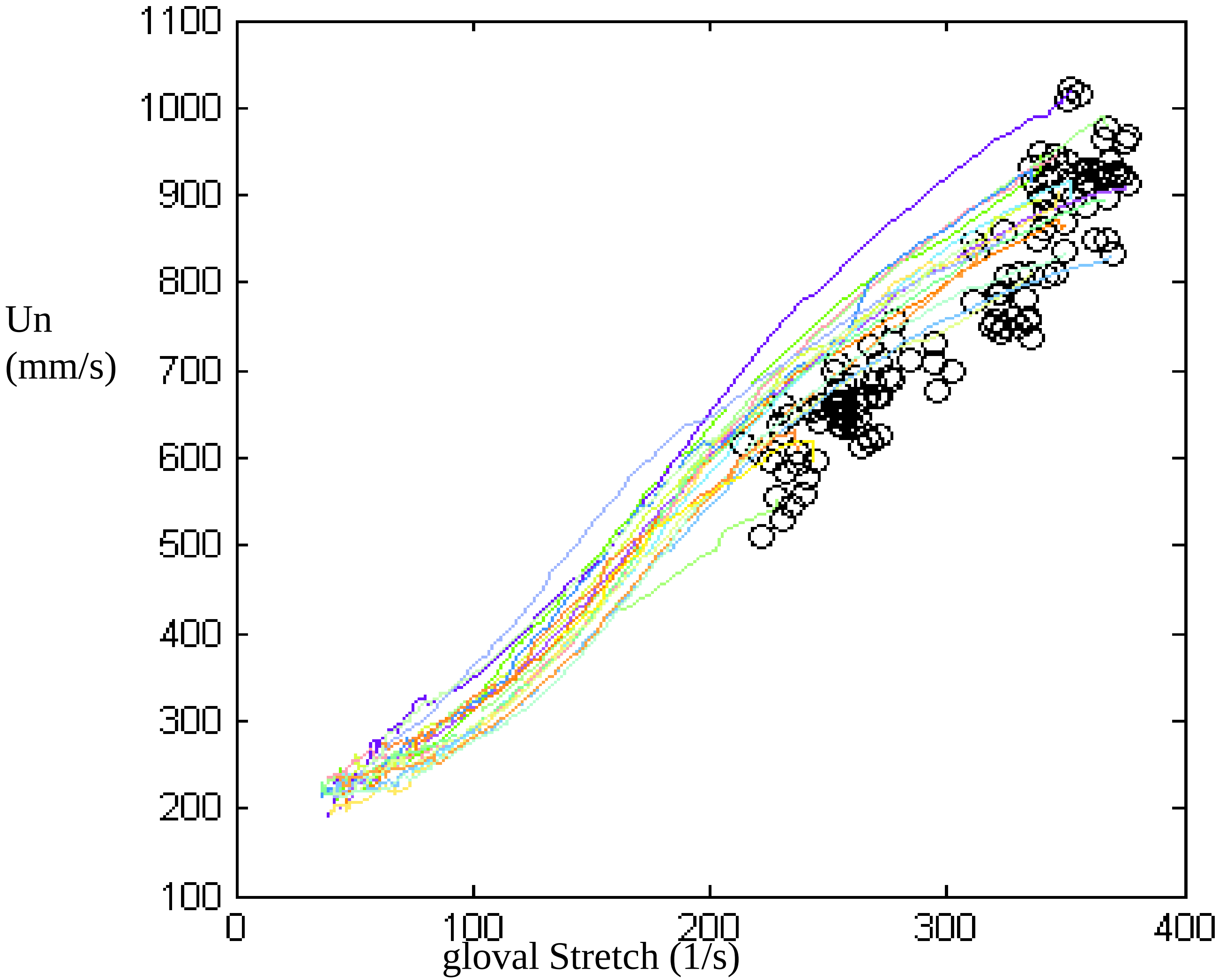
BURNING VELOCITY *vs.* CURVATURE & STRAIN RATE (flame tip, $\phi = 1.43$)

Two-variable regression:

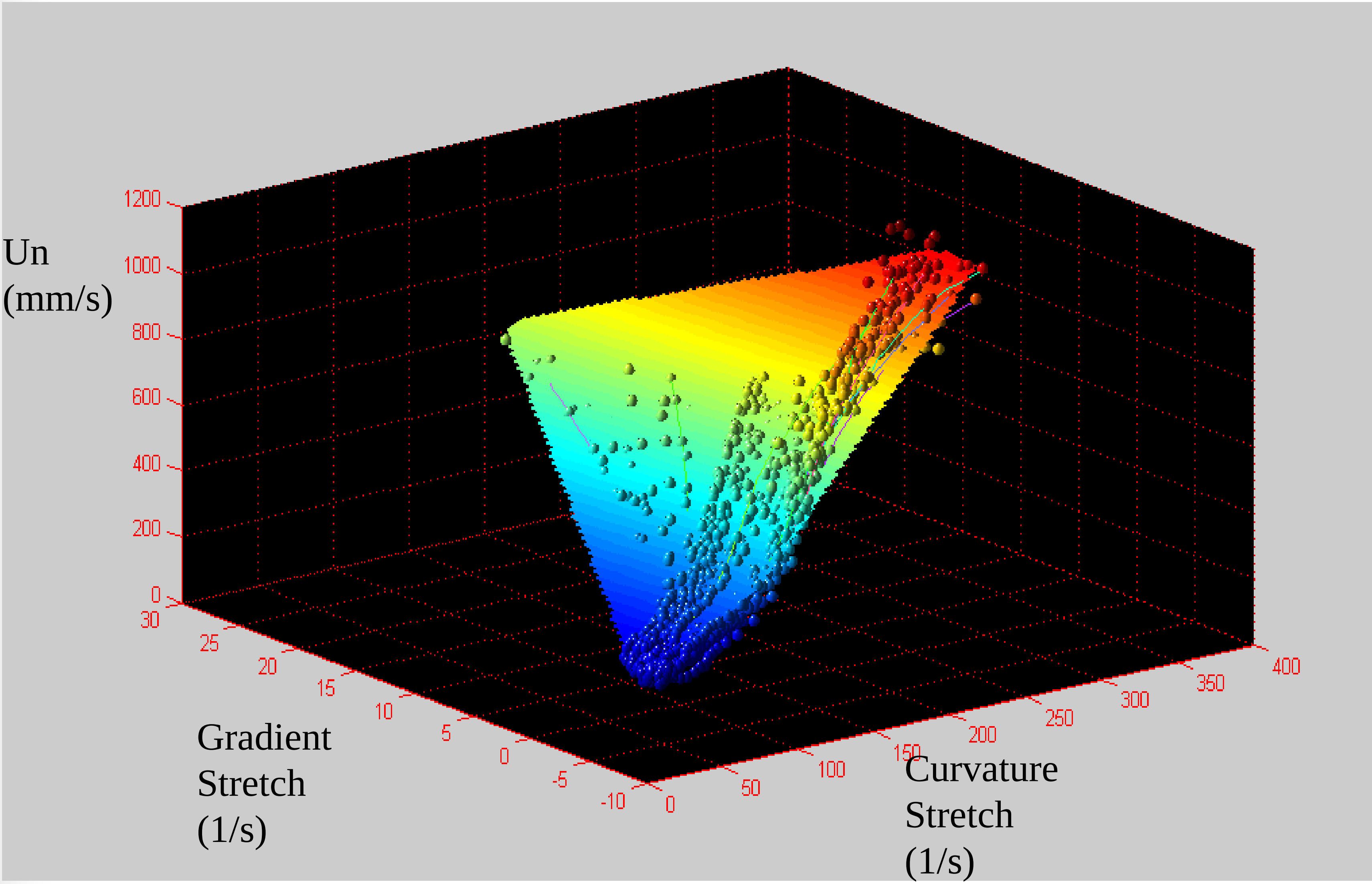
$$\frac{U_n}{U_L} - 1 = \mathscr{L}_K (\nabla \cdot \boldsymbol{n}) + \mathscr{L}_G \left(\frac{1}{U_L} \boldsymbol{n} \cdot \nabla \boldsymbol{u} \cdot \boldsymbol{n} \right)$$



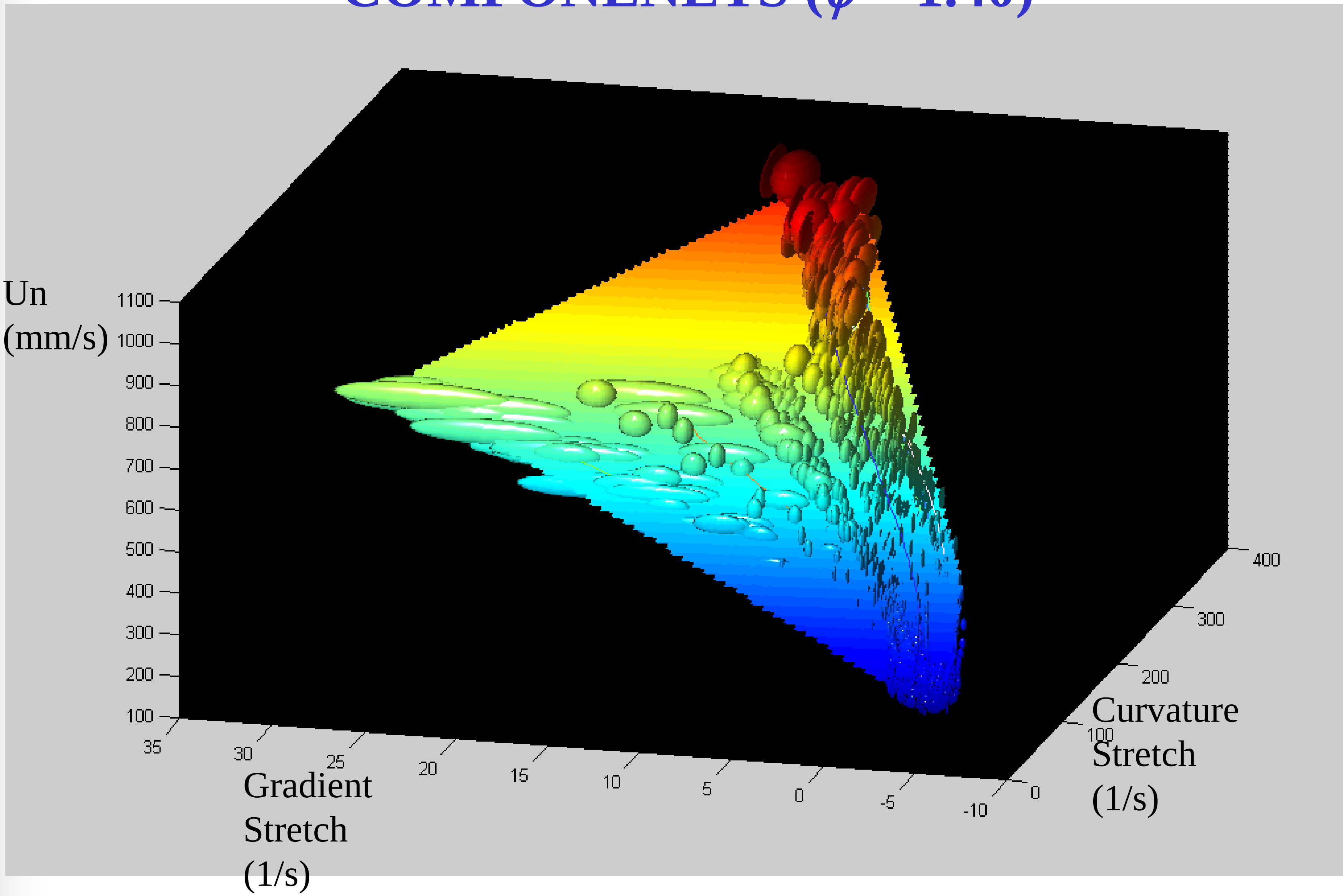
BURNING VELOCITY *vs.* FLAME STRETCH
($\phi = 1.40$)



BURNING VELOCITY *vs.* STRETCH COMPONENETS ($\phi = 1.40$)



BURNING VELOCITY *vs.* STRETCH COMPONENETS ($\phi = 1.40$)



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- Discussion of results
- Conclusions.

CONCLUSIONS

- A PIV-based system has been set-up for the simultaneous measurement of the local burning velocity of premixed flames and the flame stretch due to the flame front curvature and the incoming flow strain rate.

- In Bunsen flame tips, these measurements allow the indirect determination of the Markstein length, according to the linear theory (Clavin & Joulin, 1983).

- The experimental results confirm the existence of two different values of the Markstein length when the flame strain rate becomes large. However, one single value of the Markstein length remains even for moderate values the flame curvature. The linear relation becomes less accurate when the stretch is very large, and a break down is observed, probably related to the transition rounded-tip to slender-tip.