Consumption speed from spherically expanding flame

Towards the true value?

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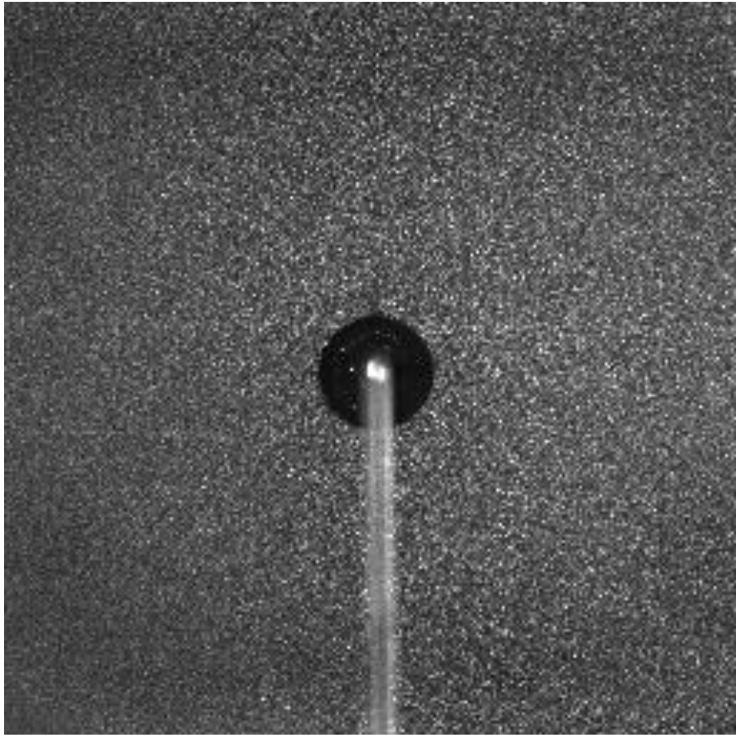
Laminar Burning Velocity Workshop 2019
Lisbon| PORTUGAL

Context

Measuring Burning Velocity from Spherically Expanding Flames



Consistency in definitions

→Kinematic definition

Groodt and De Goey, Combust. Flame (2002)
Balusamy et al., Exp. Fluids (2011)
Varea et al., Combust. Flame (2012)
Varea et al., Proc. Combust. Inst (2014)

Generalized through the Density Weighted Flame Displacement Speed - DWFDS

Giannakopolos et al. Combust. Flame (2015)

→Kinetic definition – Consumption speed

Fiock and Marvin, Chem. Reviews (1937)
Linnett, Lectures (1954)
Bradley and Mitcheson, Combust. Flame (1976)
Varea, PhD Thesis (2013)
Bonhomme et al. Combust. Flame (2013)
Lefebvre et al. Combust. Flame (2016)

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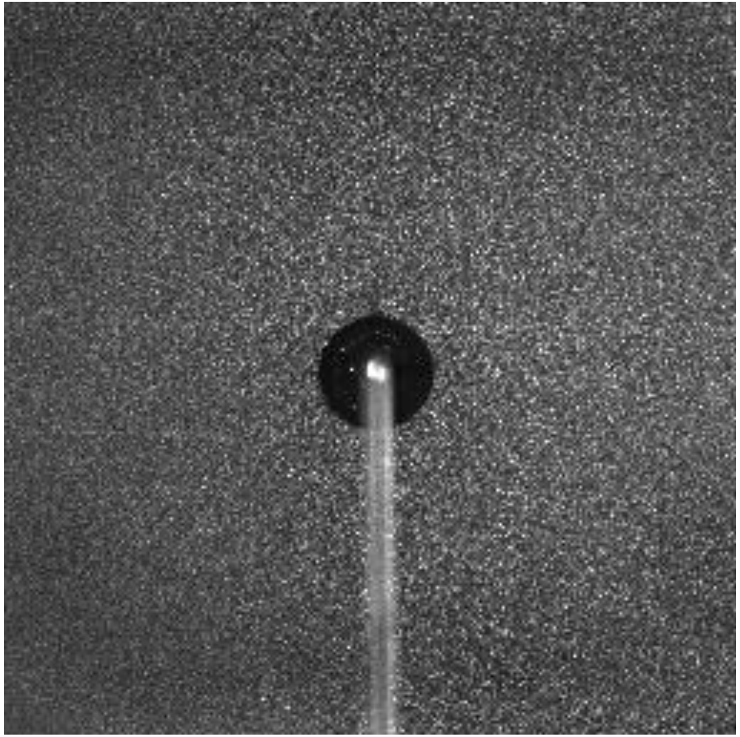

→Extrapolation to zero stretch

Chen and Ju, Combust. Flame (2008)
Kelley and Law, *Combust. Flame (2009)*
Halter et aL., Combust. Flame (2010)
Kelley at al., J. Fluid. Mech (2012)
Wu et al., Proc. Combust. Inst. (2015)
Chen, Combust. Flame (2015)

→Radiation and compression effects

Chen et al., Combust. Flame (2010)
Jayachandran et al., Combust. Flame (2014)
Jayachandran et al., Proc. Combust. Inst. (2014)
Hao et al. Proc. Combust. Inst. (2016)
Chen, Proc. Combust. Inst. (2016)
Chen, Combust.Flame (2017)

→Stretch and Lewis number effect

Chen, Proc. Combust. Inst (2009)
Chen, *Combust. Flame (2011)*
Faghih et al. Proc. Combust. Inst (2018)

Context

Density Weighted Flame Displacement Speed - DWFDS

$$S_d^* = \frac{\rho^*}{\rho_u}(S_f - u_g^*)$$

Fresh gas side

$$S_{d,u} = S_f - U_{g(T=T_u)}$$

Difficulty:

- Measurement of the fresh gas velocity at T=Tu

Groodt and De Goey, Combust. Flame (2002)
Balusamy et al., Exp. Fluids (2011)
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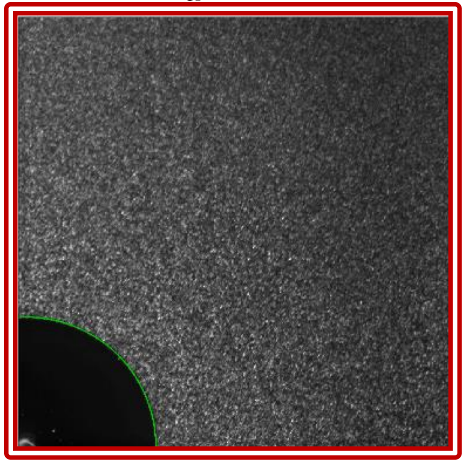

Burned gas side

$$S_{d,b} = \frac{\rho_b^{eq}}{\rho_u} S_f$$

Assumptions:

- Burned gases are motionless
- $\delta_f/r(t) << 1$
- ρ_b constant - equilibrated

Are these DWFDS formalisms relevant from a kinetic point of view?

Rate at which reactants are consumed….

Context

Density Weighted Flame Displacement Speed - DWFDS

$$S_d^* = \frac{\rho^*}{\rho_u}(S_f - u_g^*)$$

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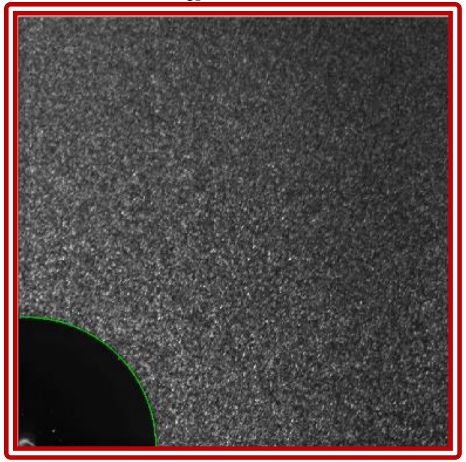

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Rate at which reactants are consumed….

Consumption speed

Consumption Speed

$$S_c = \frac{1}{R_f^2 \rho_u (Y_k^b - Y_k^u)} \int_0^\infty r^2 \dot{w}_k dr$$

Infinitely thin flame

Finite flame thickness

Fiock and Marvin, Chem. Reviews (1937)

$$S_c = \frac{dR_f}{dt} - \frac{R_0^3 - R_f^3}{3R_f^2} \frac{1}{\gamma_u P} \frac{dP}{dt}$$

Bonhomme et al. Combust. Flame (2013)

$$S_c = \frac{dR_{eq}}{dt} - \frac{R_0^3 - R_{eq}^3}{3R_{eq}^2} \frac{1}{\gamma_u P} \frac{dP}{dt}$$

Lefebvre et al. Combust. Flame (2016)

$$S_c = \frac{dR_{eq,1}}{dt} - \frac{R_0^3 - R_{eq,2}^3}{3R_{eq,2}^2} \frac{1}{\rho_u} \frac{d\rho_u}{dt}$$

Models

Bradley 1996

$$S_c = -\frac{\rho_b^{eq}}{\rho_b^{eq} - \rho_u} U_g$$

Poinsot & Veynante

2001

$$S_c = \frac{\rho_b^{eq}}{\rho_u} \frac{dR_f}{dt} \left[1 + \frac{\delta}{2R_f} \left(1 + \frac{\rho_u}{\rho_b^{eq}} \right) \right]$$

2011

$$S_c = \frac{\rho_b^{eq}}{\rho_u} \frac{dR_f}{dt} \left[1 + \frac{\delta}{R_f} \right]$$

Varea et al., ECM 2013, Lund

Consumption Speed

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Fiock and Marvin, Chem. Re

$$S_c = \frac{dR_f}{dt} - \frac{R_0^3 - R_f^3}{3R_f^2} \frac{1}{\gamma_u P}$$

Flame (2013)

$$\frac{dP}{dt}$$

Lefebvre et al. Combust. Flame (2016)

Derived from first principle

$$S_c = \frac{dR_{eq,1}}{dt} - \frac{R_0^3 - R_{eq,2}^3}{3R_{eq,2}^2} \frac{1}{\rho_u} \frac{d\rho_u}{dt}$$

. Combust. Flame (2016)

$$= \frac{dR_{eq,1}}{dt} - \frac{R_0^3 - R_{eq,2}^3}{3R_{eq,2}^2} \frac{1}{\rho_u} \frac{d\rho_u}{dt}$$

$$S_c = -\frac{\rho_b^{eq}}{\rho_b^{eq} - \rho_u} U_g$$

2001

2011

$$S_c = \frac{\rho_b^{eq}}{\rho_u} \frac{dR_f}{dt} \left[1 + \frac{\delta}{2R_f} \left(1 + \frac{\rho_u}{\rho_b^{eq}} \right) \right]$$

$$S_c = \frac{\rho_b^{eq}}{\rho_u} \frac{dR_f}{dt} \left[1 + \frac{\delta}{R_f} \right]$$

Varea et al., ECM 2013, Lund

Objectives

→Hypothesis or Assumptions involved in Sc derivation

→ Validation of the assumptions thanks to DNS data

→Experimental procedure to measure the fresh gas density field and report Sc values

→Compare and validate with DNS for CH_4/Air flame (YALES2)

Assumptions

Lefebvre et al. Combust. Flame (2016)

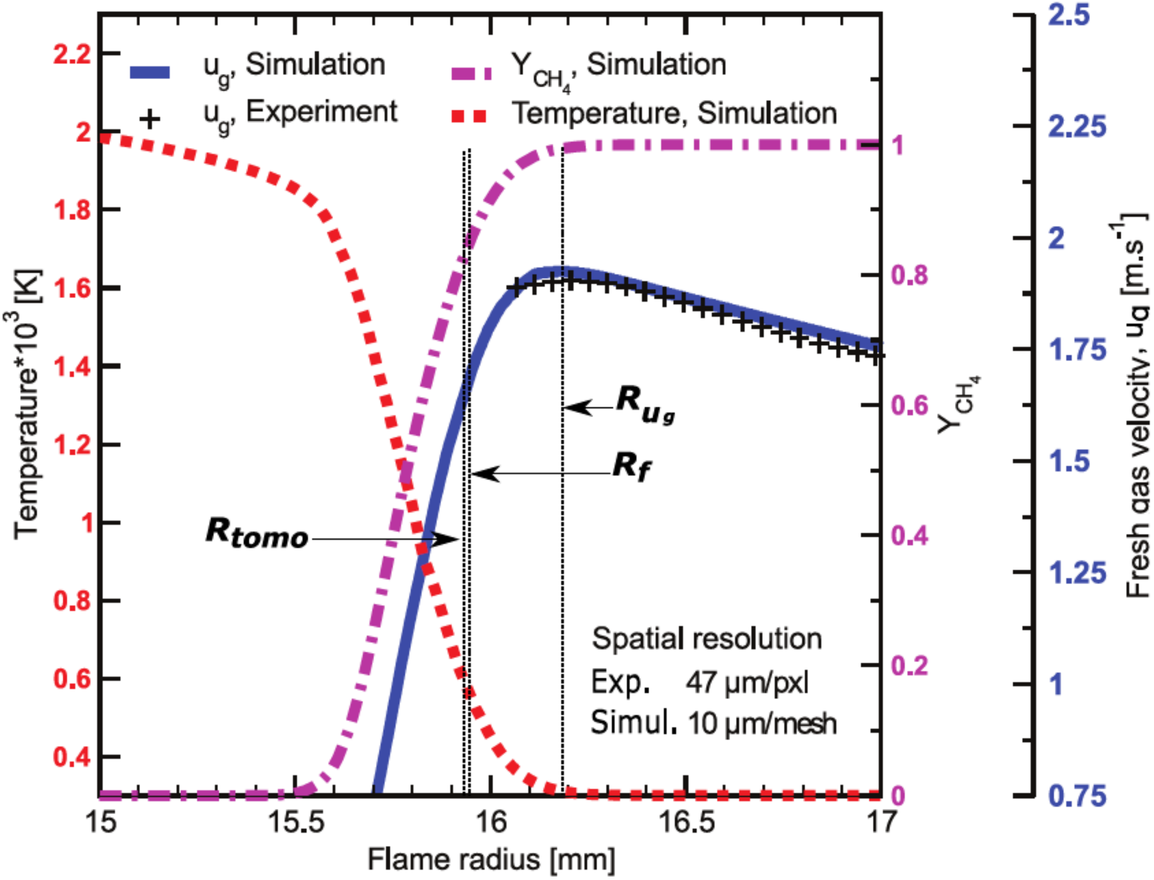
$$S_c = \frac{dR_{eq,1}}{dt} - \frac{R_0^3 - R_{eq,2}^3}{3R_{eq,2}^2} \frac{1}{\rho_u} \frac{d\rho_u}{dt}$$

→ $R_{eq,1}$ **comes from the integral of a progress variable of a species *k*, here reactant**

→ $R_{eq,2}$ **comes from the total mass of species *k* contained into the sphere of radius** $R_{eq,2}$

Do these radii correspond to a flame radius measured in the experiments?

Validation – CH4 Air Flame



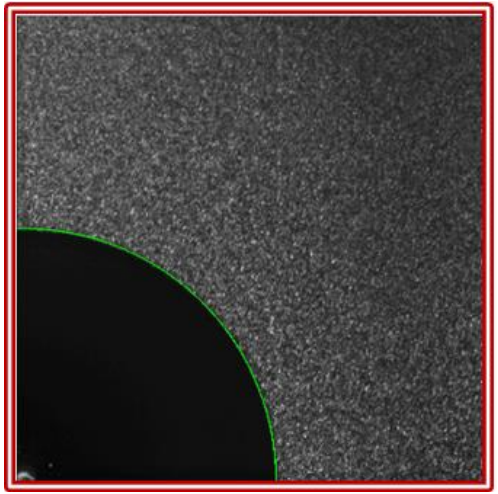
$$R_{eq,1} = R_{eq,2} \rightarrow R_f$$

$$R_f \approx R_{tomo}$$

$$S_c = \frac{dR_{tomo}}{dt} - \frac{R_0^3 - R_{tomo}^3}{3R_{tomo}^2} \frac{1}{\rho_u} \frac{d\rho_u}{dt}$$

Varea et al. Int. Symp. Combust. (2018)

Exp. Procedure



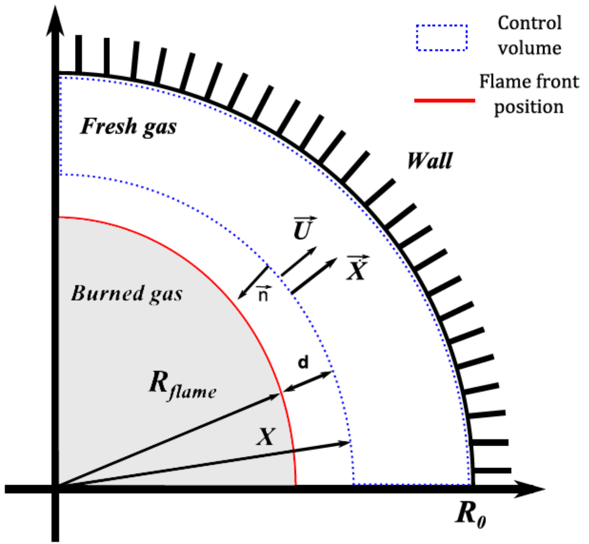
Go back to Fluid Mechanics

Mass conservation

$$\frac{d}{dt}\int_{V_m(t)} \rho \, dV = 0.$$

$V_m(t)$ **is a Material Volume (system) moving at the flow velocity U**

Exp. Procedure



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$V_m(t)$ **is a Material Volume (system) moving at the flow velocity U**

$V_a(t)$ **Control Volume CV moving with the flame through which fluid might flow**

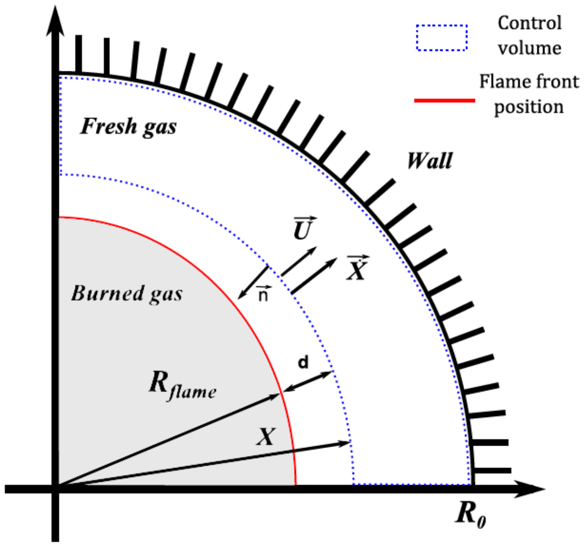
$$\frac{d}{dt}\int_{V_m(t)} \rho \, dV = \frac{d}{dt}\int_{V_a(t)} \rho \, dV - \oint_{A_a(t)} \rho \left(U - \dot{X}\right) dA = 0$$

Rate of change of the density in the Material Volume

Rate of change of the density in the Control Volume

Net flux through the control surface : boundary

Exp. Procedure



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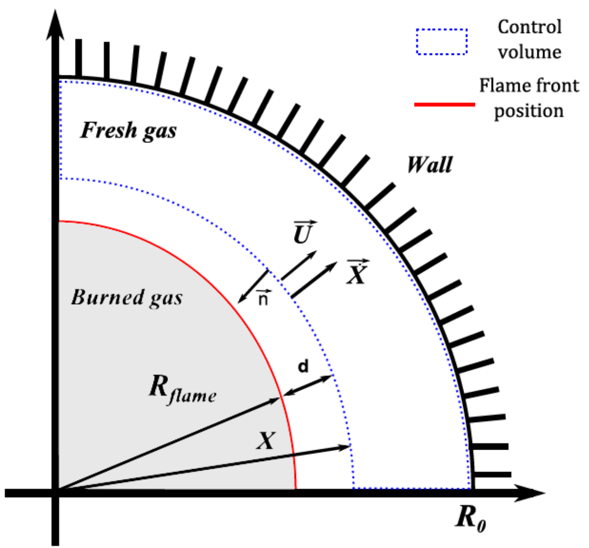
Time integration between time t and t+dt yields

$$\frac{d}{dt}\int_{V_a(t)} \rho \, dV - \oint_{A_a(t)} \rho \left(U - \dot{X}\right) dA = 0 \rightarrow \rho_u^{t+1} = f(\rho_u^t, \dot{X}, U)$$

Exp. Procedure



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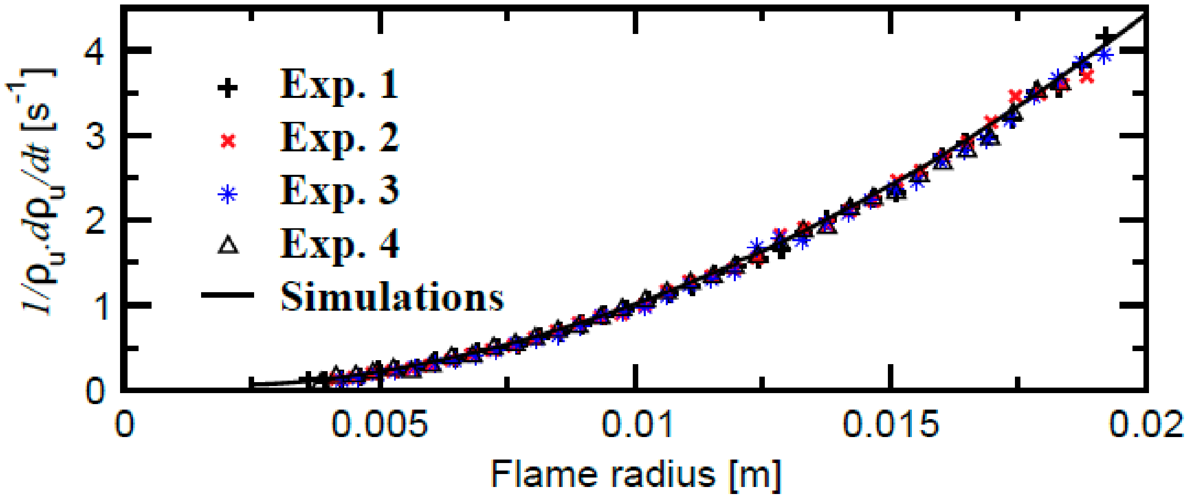
Consumption speed can be experimentally determined

$$S_c = \frac{dR_{tomo}}{dt} - \frac{R_0^3 - R_{tomo}^3}{3R_{tomo}^2}\frac{1}{\rho_u}\frac{d\rho_u}{dt}$$

Exp. Procedure

Evaluation of the compression term



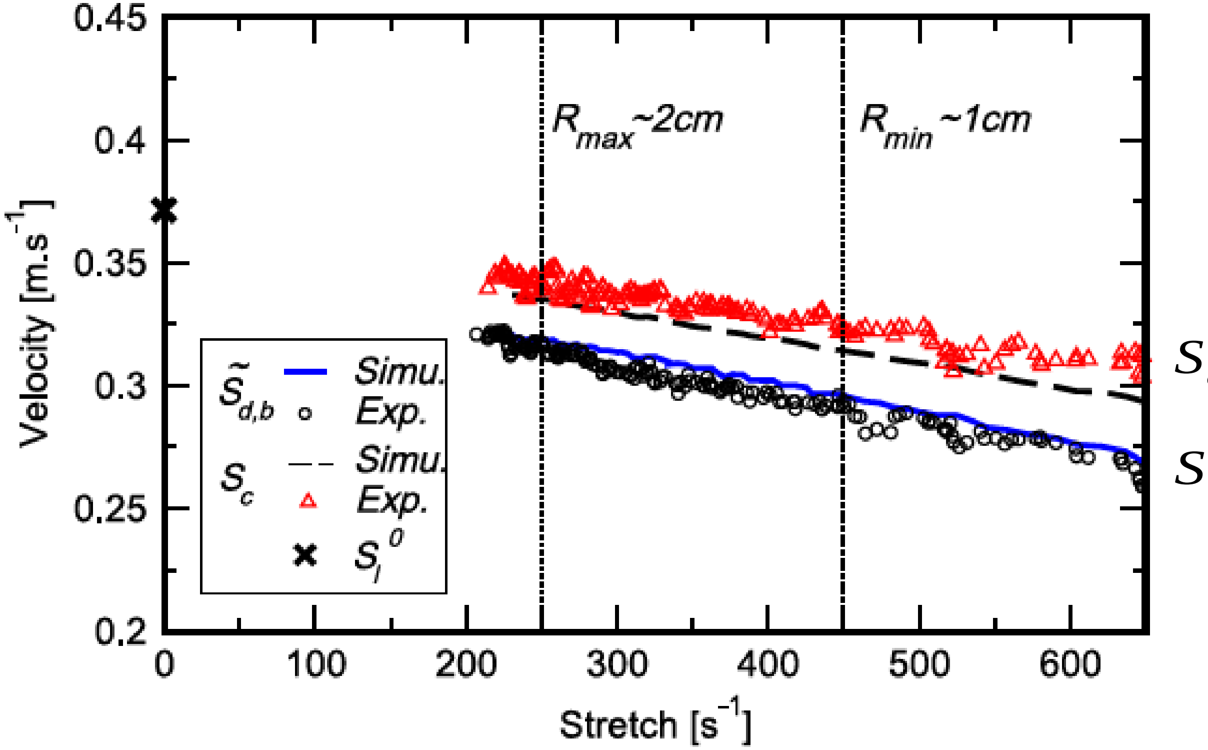
Experiments ***VS*** **DNS**

$$\frac{1}{\rho_u}\frac{d\rho_u}{dt}$$

Excellent agreement

Results

Evaluation of burning quantities for CH4/Air Flame (Stoichiometric)



S_c

$$S_{d,b} = \frac{\rho_b^{eq}}{\rho_u} S_f$$

- **Good agreement between Exp. And DNS**
- **Different slopes**
- **→which one should be used for LES simulations?**
- **Same pointing value?...**

Conclusion

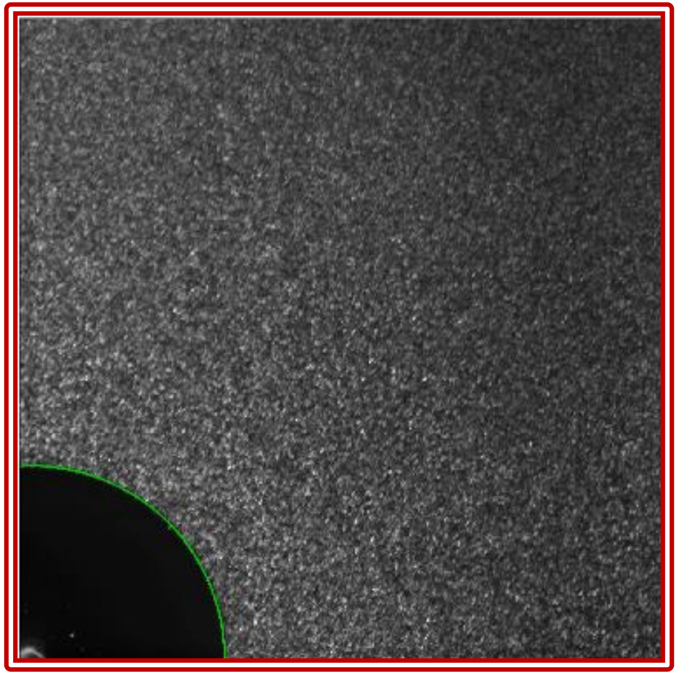
Development of a new methodology for the consumption speed

→More related to kinetics

→From Tomo PIV techniques

→Validated using DNS data

→Needs to be validated for other fluels



Conclusion

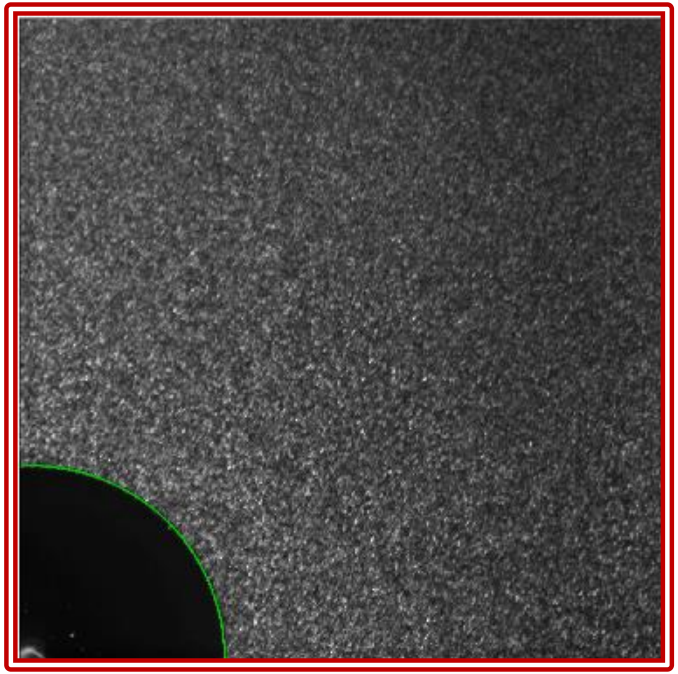
Development of a new methodology for the consumption speed

→Identify the influence of the flame radius for normalization

Consumption Speed

$$S_c = \frac{1}{R_f^2 \rho_u (Y_k^b - Y_k^u)} \int_0^\infty r^2 \dot{w}_k dr$$

$$S_c = \frac{1}{\rho_u (Y_k^b - Y_k^u)} \int_V \dot{w}_k dV$$

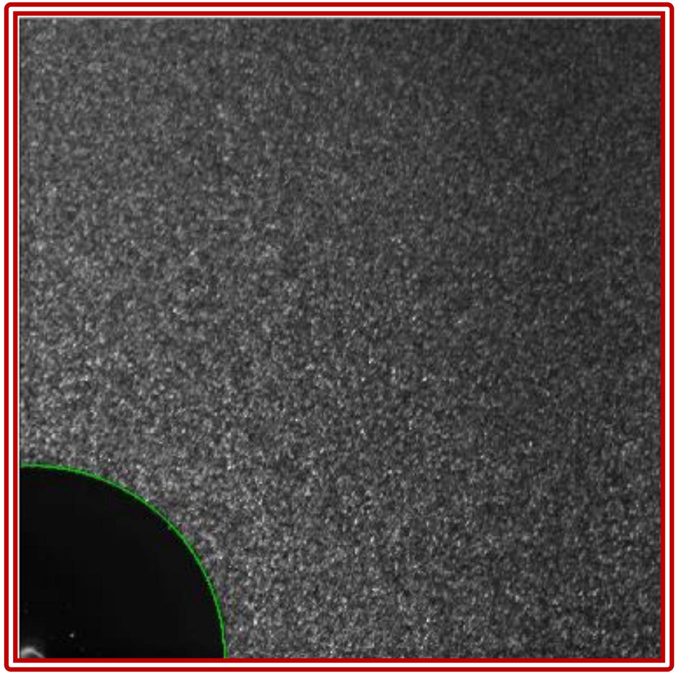


Collaboration with Zheng Chen

1D-Spherically Expanding Flames

A-Surf Code

Conclusion



Thank you for your attention

Financial support from the French National Research Agency, under the project 'EMCO2Re' is gratefully acknowledged.

Context

For 1D planar case

Kinematic definitions ←→ Kinetic definition

$$S_l = S_f - U_g \Leftrightarrow \frac{\rho_b^{eq}}{\rho_u} S_f \Leftrightarrow S_c = -\frac{1}{\rho_u Y_k^u} \int_{-\infty}^{+\infty} \dot{w}_k dx$$

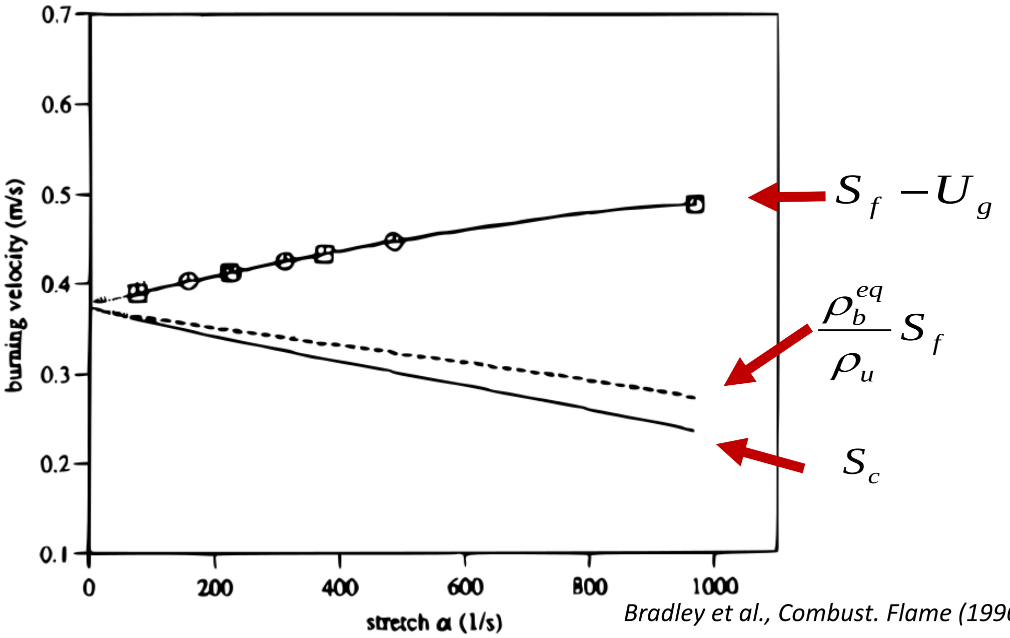
For spherical configuration

…

Kinematic definitions

≠

Kinetic definition



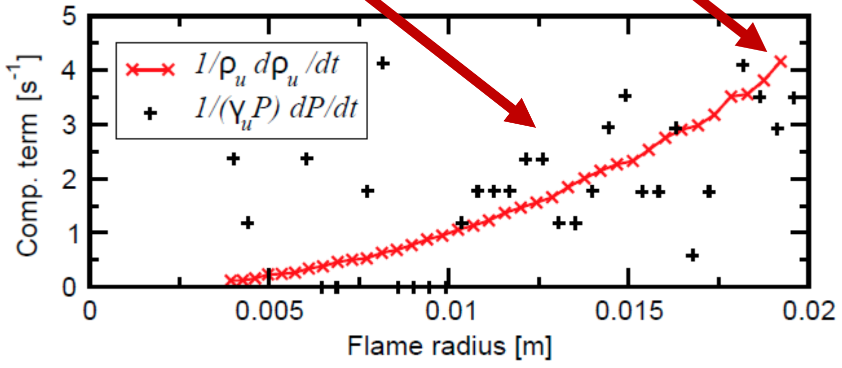
Bradley et al., Combust. Flame (1996)

Results

Evaluation of the compression term

$$S_c = \frac{dR_f}{dt} - \frac{R_0^3 - R_f^3}{3R_f^2}\frac{1}{\rho_u}\frac{d\rho_u}{dt}$$

$$\frac{1}{\gamma_u P}\frac{dP}{dt} \quad \textbf{VS} \quad \frac{1}{\rho_u}\frac{d\rho_u}{dt}$$



(b) Experiments

Results

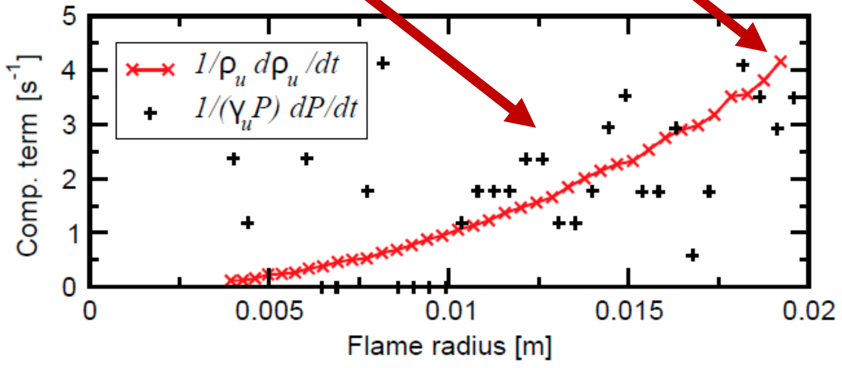
Evaluation of the compression term

$$S_c = \frac{dR_f}{dt} - \frac{R_0^3 - R_f^3}{3R_f^2}\frac{1}{\rho_u}\frac{d\rho_u}{dt}$$

$\frac{1}{\gamma_u P}\frac{dP}{dt}$ **VS** $\frac{1}{\rho_u}\frac{d\rho_u}{dt}$

Experiments ***VS*** **DNS**

$$\frac{1}{\rho_u}\frac{d\rho_u}{dt}$$



(b) Experiments