The temperature and pressure dependences of the laminar burning velocity: experiments and modeling

A.A. Konnov

Division of Combustion Physics, Dept. of Physics,
Lund University, Lund, Sweden

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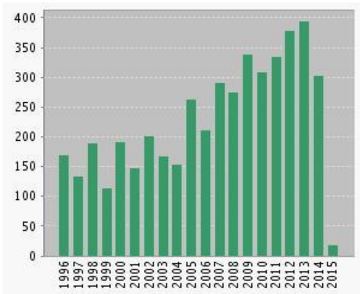
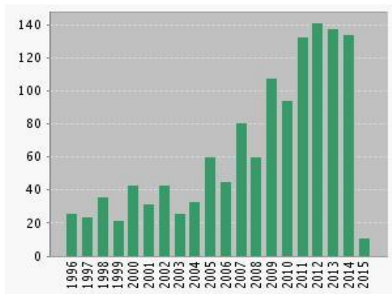
Keywords WoSci





Burning velocity

Laminar flame speed

Terminology

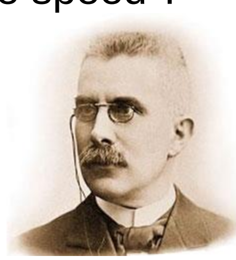
Burning velocity or Laminar flame speed ?

“la vitesse normale”

↓

“fundamental flame speed” or “burning velocity”

NOT “laminar flame speed”



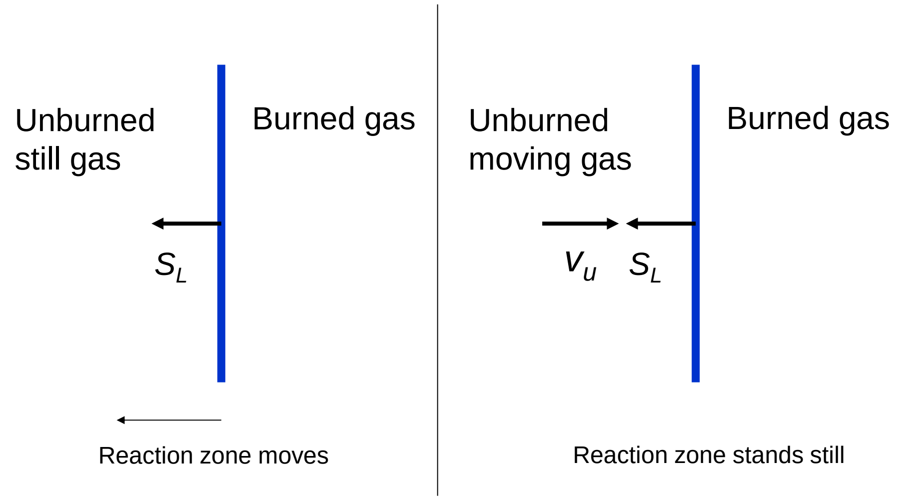
E.F. Mallard and H.L. Le Chatelier

“Sur la vitesse de propagation de la flamme”, Ann. des Mines, Ser. 8, IV (1883)

Definition

The laminar burning velocity, S_L, is the velocity of a steady one-dimensional adiabatic free flame propagating in the doubly infinite domain.

Definition



Definition

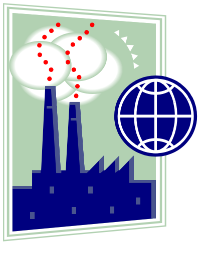
The laminar burning velocity, S_L, is the velocity of a steady one-dimensional adiabatic free flame propagating in the doubly infinite domain.

The laminar burning velocity is, therefore, **not a measurable quantity**; it is derived from other observables using different assumptions or theoretical models.

Importance

In labs P = 1 atm, T = 25 C = 298 K.

In general applications, from domestic appliances to engines and gas turbines, pressure and initial temperature of the mixture are often higher than standard ones.



Focus of this lecture

Adiabatic burning velocity, S_L:

– Fundamental characteristic of the mixture, function of equivalence ratio, pressure, and initial temperature
– Invaluable for validation of kinetic models
– Major parameter in calibration of turbulent flame speeds

- Typical presentation in CFD and engineering models

$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p},$$

- Reliable data are available only for gaseous fuels and some reference liquid fuels, because stretch correction was not implemented until 80's of XX century

Empirical correlations P $S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p}$

History: Mallard and Le Chatelier (1883), Jouguet (1913), Crussard (1914), Nusselt (1915), Daniell (1930).

Zeldovich and Frank-Kamenetsky (1938) showed that the mass burning rate

m = ρ S_L

is proportional to the square root of the overall reaction rate *W.*

Since *W* is proportional to P^n exp(-Ea/RT), where n is the overall reaction order, the mass burning rate shows a power exponent dependence of n/2. The power exponent β is therefore

β = n/2 -1,

0 for bimolecular reactions,

-0.5 for the first order reactions.

Empirical correlations T

$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p}$$

Origin?

G.L. Dugger, D.D. Graab, Proc. Combust. Inst. 4 (1953) 302-310.

~~M. Metghalchi, J.C. Keck, Combust. Flame, 38 (1980) 143–154.~~

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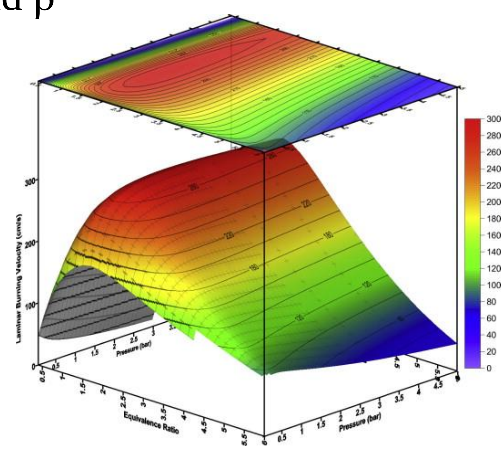
Data consistency – role of α and β

Laminar burning velocity of hydrogen/air mixtures according to the pressure and the equivalence ratio calculated at *T* u = 303 K with the mechanism of Keromnès et al.



G. Dayma, F. Halter, P. Dagaut

Combustion and Flame, Volume 161, Issue 9, 2014, 2235 - 2241

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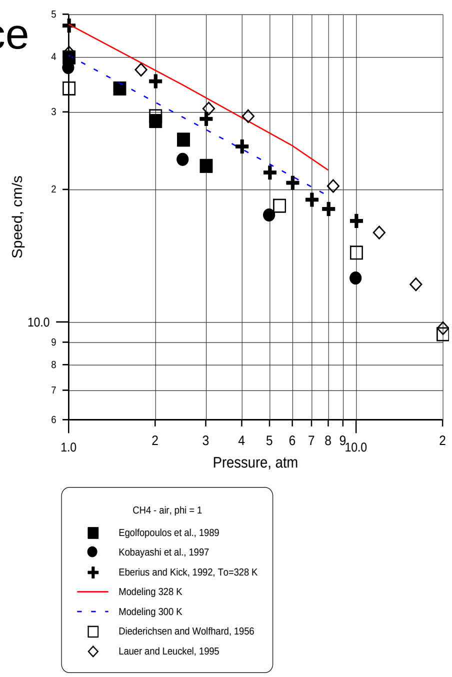
Pressure dependence for CH4

$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p},$$

Adiabatic burning velocities of stoichiometric CH4 + air flames as a function of pressure.

Lines: modeling.



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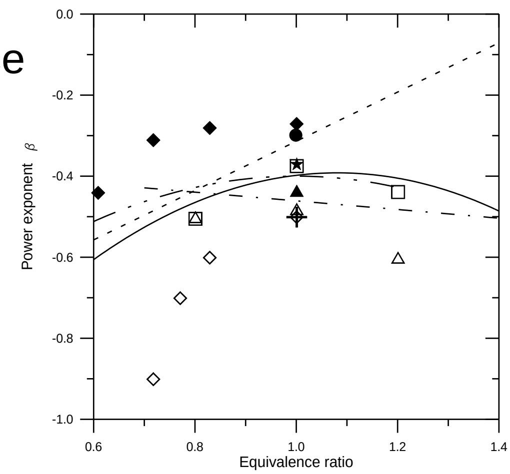
Pressure dependence for CH4

- Variation of the power exponent β with equivalence ratio at elevated pressures.

- Solid diamonds: [19],
- squares: [27],
- circle: [25],
- open triangles: [30],
- solid triangle: [28],
- cross: [20],
- open diamonds: [32],
- star: [43],
- solid line: [29],
- dashed line: [26],
- dash-dot line: [16],
- dash-double dot line: [33].



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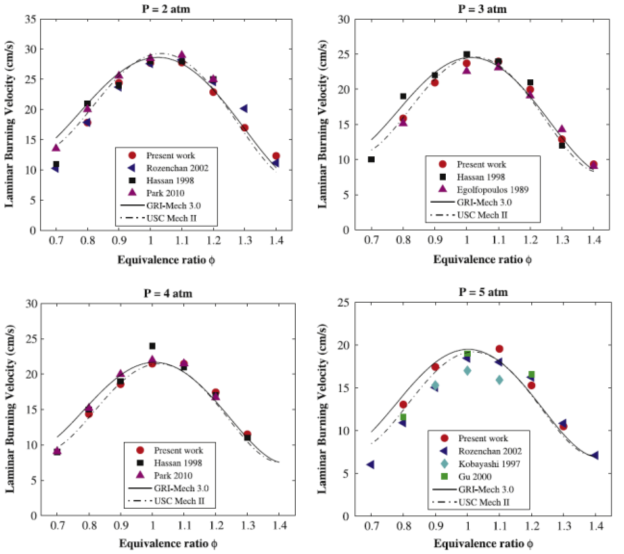
Pressure dependence for CH4

Comparison of the burning velocities of methane + air flames from experimental (symbols) and simulation (lines) results for 2, 3, 4 and 5 atm as functions of equivalence ratio.

M. Goswami, S. Derks, K. Coumans, W.J. Slikker, M.H. de Andrade Oliveira, R.J.M. Bastiaans, C.C.M. Luijten, L.P.H. de Goey, A.A. Konnov, *Combust. Flame* 160 (2013) 1627-1635.



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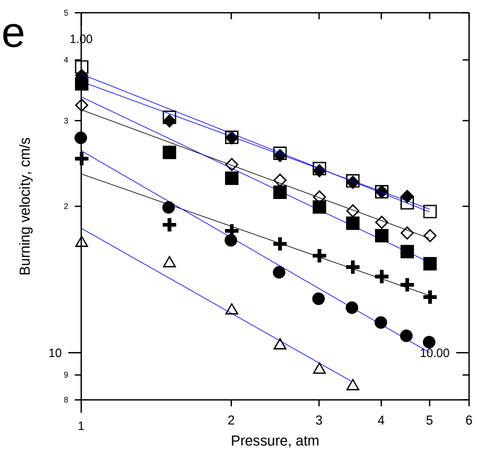
Pressure dependence for CH4

Laminar burning velocities of methane + air mixture at different equivalence ratios. Crosses: 0.8, open diamonds: 0.9, solid diamonds: 1.0, open squares: 1.1, solid squares: 1.2, circles: 1.3, triangles: 1.4.



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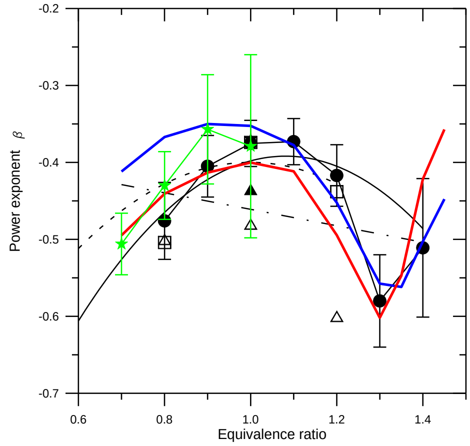
Pressure dependence for CH4

Variation of the power exponent β_1 (Eq. (4)) with equivalence ratio at elevated pressures. Open squares: [36], open triangles: [42], solid triangle: [43], star: [44], solid line: [45], dash-dot line: [31], dashed line: [46], circles: [34], green stars: [41].

Red line: GRI-mech.,

blue line: USC Mech II.



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[36] X.J. Gu, M.Z. Haq, M. Lawes, R. Woolley, Combust. Flame, 121 (2000) 41-58.
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[42] F. Halter, C. Chauveau, N. Djebaili-Chaumeix, , I. Gokalp, Proc. Combust. Inst. 30 (2005) 201-208.
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[45] S.Y. Liao, D.M. Jiang, Q. Cheng, Fuel, 83 (2004) 1247-1250.
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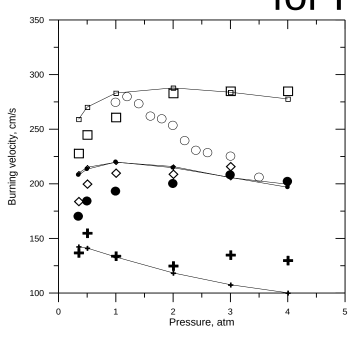
Pressure dependence for H2



Unstretched laminar burning velocities for hydrogen + air flames at standard temperature as a function of initial pressure. Measurements: symbols; calculations: lines with corresponding small symbols. Equivalence ratios: crosses: 0.75; diamonds: 1.05; squares: 1.8; [56]; solid circles: 3 [56]; open circles: 3 [12].

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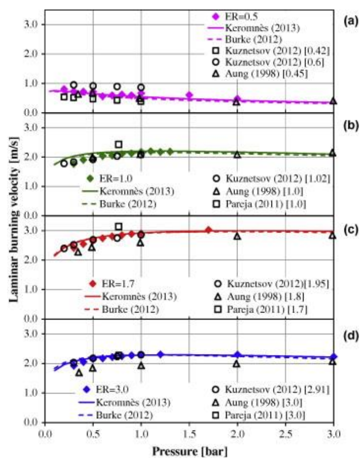
from: A.A. Konnov, Combust. Flame 152 (2008) 507-528.



Laminar burning velocity of hydrogen/air mixtures according to the initial pressure at T u = 303 K and (a) φ = 0.5, (b) φ = 1.0, (c) φ = 1.7, and (d) φ = 3.0.

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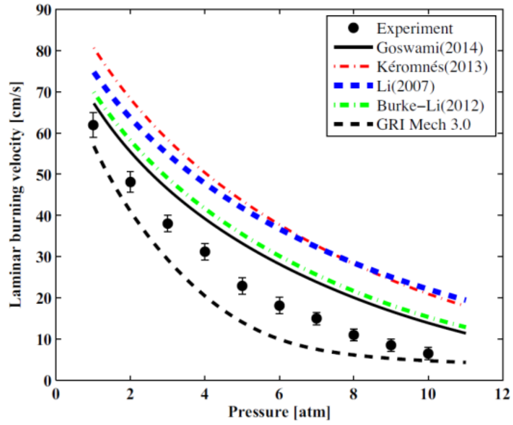
Pressure dependence for H2

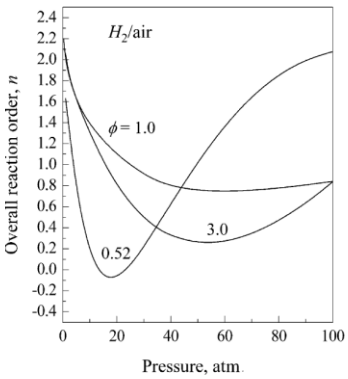
Problem in lean H2 flames



Laminar burning velocity of 85:15 % H_2 + N_2 with 1:7 O_2:He oxidizer at ϕ = 0.6 and 298 K.

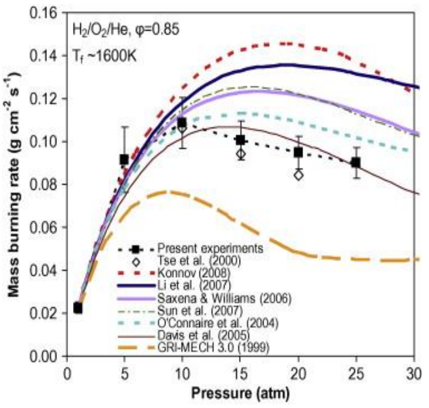
M. Goswami, J.G.H. van Griensven, R.J.M. Bastiaans, A.A. Konnov, L.P.H. de Goey, Proc. Combust. Inst. 35 (2015) 655-662.

Pressure dependence for H2



Extracted overall reaction order for H2 + air flames.

C.K. Law, CST 178 (2006) 335.



Mass burning rate measurements for various pressures for H2 /O2 /He flames of equivalence ratio 0.85 and flame temperature of ~1600 K.

Michael P. Burke , Marcos Chaos , Frederick L. Dryer , Yiguang Ju
Combustion and Flame, Volume 157, 2010, 618 - 631

$m = \rho S_L \sim W^{1/2}$ *W* is proportional to $P^n \exp(-Ea/RT)$,

Intermediate conclusions (P)

- The power exponents β show large scattering both in experiments and in model predictions
- The power exponents β are sensitive to the rate constants implemented, yet the sensitivity spectra are different from those for the laminar burning velocity
- The pressure dependence is therefore and independent parameter for kinetic model validation
- The burning velocity of lean hydrogen flames is often far from the model predictions

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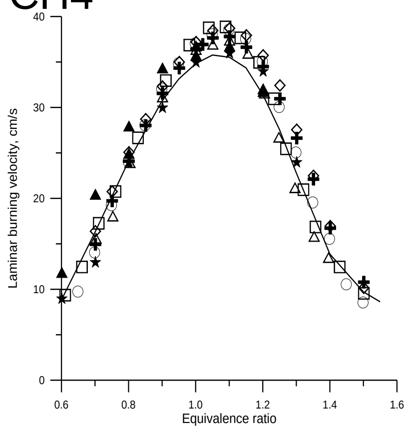
Temperature dependence for CH4



Adiabatic burning velocity in methane – air mixtures. Diamonds: present measurements in CH4 - air mixtures; crosses: present measurements in CH4 - O2 - N2 mixtures; squares: Vagelopoulos et al. (1994); open triangles: Vagelopoulos and Egolfopoulos (1998); circles: van Maaren et al. (1994b); stars: Hassan et al. (1998); solid triangles: Gu et al. (2000); solid line: modeling.

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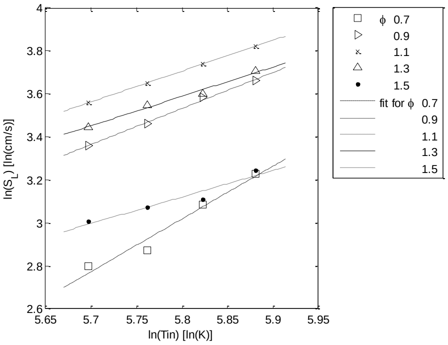
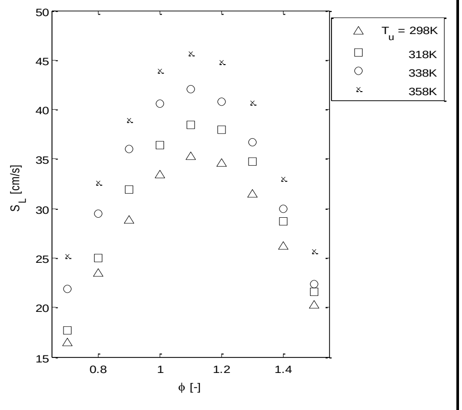
Temperature dependence for CH4

- Temperature correlation





$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p},$$

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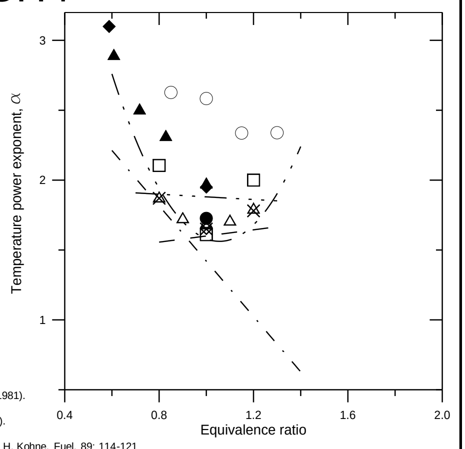
Temperature dependence for CH4

Power exponent coefficient, α, for methane + air flames.

Crosses: [25], open diamonds: [34], solid diamonds: [22], open circles: [28], solid circle: [30, 31], open squares: [23], solid triangles: [3], open triangles: [6], long-dash line: [27], dash-dot line: [35], dash- double dot line: [24], dash-triple dot line: [29]



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35. R. Stone, A. Clarke, P. Beckwith, Combust. Flame, 114 (1998) 546-555.

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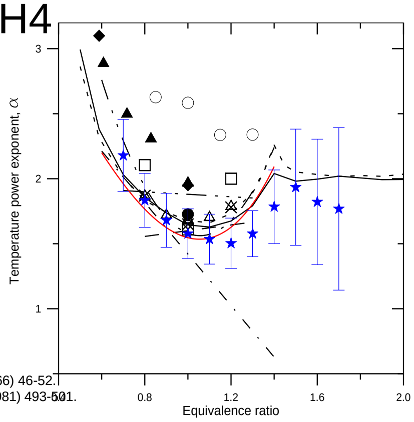
Temperature dependence for CH4

Power exponent coefficient, α, for methane + air flames. Crosses: [74], open diamonds: [44], solid diamonds: [73], open circles: [29], solid circle: [75], open squares: [36], solid triangles: [17], open triangles: [18], long-dash line: [30], dash-dot line: [76], dash-double dot line: [45], dash-triple dot line: [77], red solid line: [78], blue stars: [41]. Solid line: modeling using the Konnov mech.,

short-dash line: modeling using the GRI-mech. 3.0.



[17] V.S. Babkin, L.S. Kozachenko, Combust. Expl. Shock Waves, 2 (1966) 46-52.
[18] S.P. Sharma, D.D. Agrawal, C.P. Gupta, Proc. Combust. Inst. 18 (1981) 493-501.
[30] T. Iijima, T. Takeno, Combust. Flame 65 (1986) 35-43.
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Temperature dependence for H2

Power exponent coefficient, α, for hydrogen + air flames.

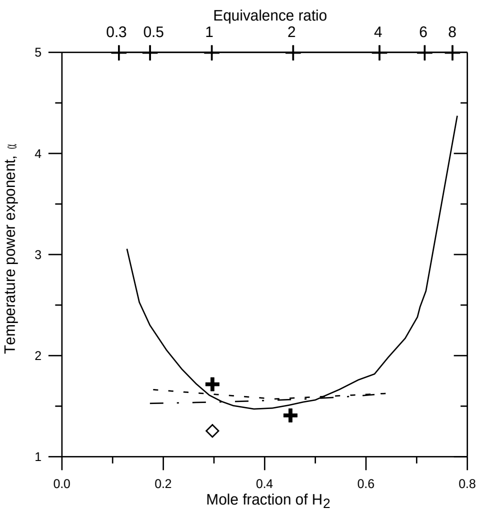
Crosses:
S. Heimel, Effects of initial mixture temperature on burning velocity of hydrogen-air mixtures with preheating and simulated preburning. NACA Technical Note 4156, Lewis Flight Propulsion Lab., 1957.

diamond:
B.E. Milton, J.C. Keck, Combust. Flame, 58: 13-22 (1984)

dashed line:
D.D.S. Liu, R. MacFarlane, Combust. Flame, 49: 59-71 (1983)

dash-dot line:
T. Iijima, T. Takeno, Combust. Flame, 65: 35-43 (1986).

solid line: modeling.



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Temperature dependence for H2

Power exponent α for H_2 + air flames at standard conditions. Solid symbols and thick lines: experiments [16, 30, 80, 81, 89], open symbols: fit to experimental data [82, 83, 84, 85, 86, 87], made by Alekseev et al. [88]; thin lines: modeling.

[16] S. Heimel, Effect of initial mixture-temperature on burning velocity of hydrogen-air mixtures with preheating and simulated preburning, NACA Technical Note 4156, Lewis Flight Propulsion Laboratory, 1957.
[30] T. Iijima, T. Takeno, Combust. Flame 65 (1986) 35-43.
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[84] D. Bradley, M. Lawes, K. Liu, S. Verhelst, R. Woolley, Combust. Flame 149 (2007) 162-172.
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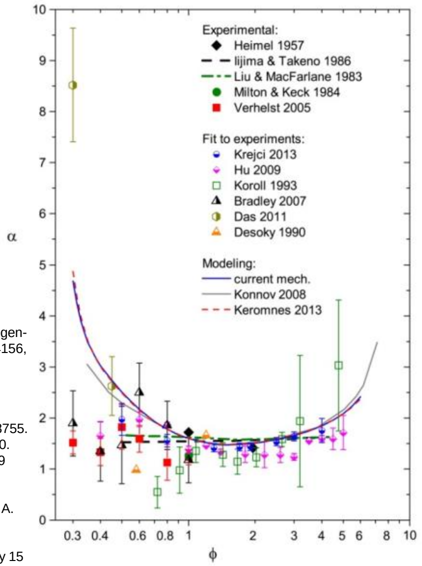

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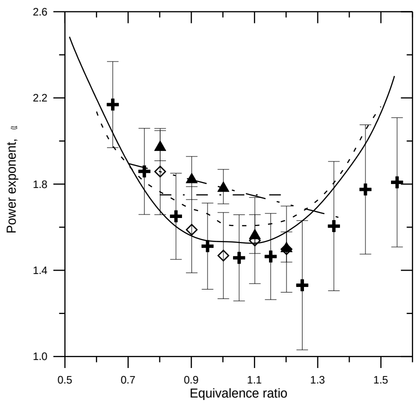
Temperature dependence - general



Konnov, A.A., Meuwissen, R.J., de Goey, L.P.H. *Proceed. Combustion Institute,* 33: 1011-1019 (2011)

Power exponent coefficient, α, for ethanol + air flames. Dash-dot line: [19]; dash-double dot line: [20]; solid triangles: [22]; diamonds and crosses: present work. Solid line and dashed line: modeling using the Konnov mechanism and that of Saxena and Williams [9], respectively.

9. P. Saxena, F.A. Williams, Proc. Combust. Inst. 31 (2007) 1149-1156.
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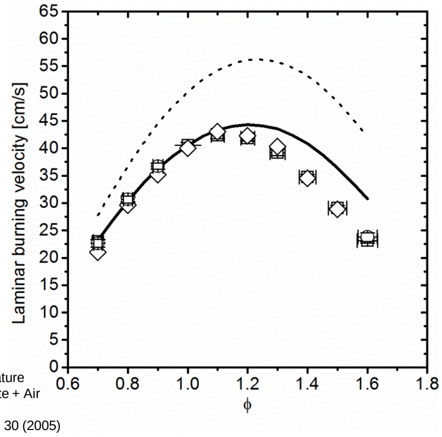
Temperature dependence - general

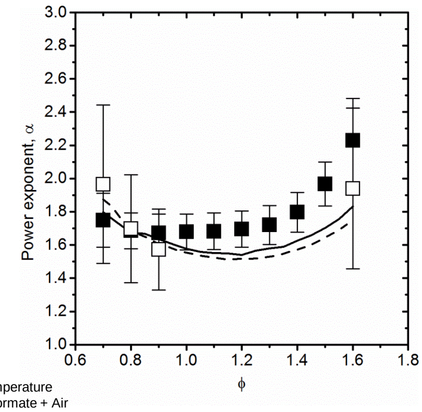
- Laminar burning velocities of MF+air as a function of ϕ at 338 K. Symbols: experimental data and lines: modelling. Squares and circles: Christensen et al. [91]; diamonds: Wang et al. [94] at 333 K.
- Solid line: model of Dievart et al. [93] and dotted line: model of Glaude et al. [92].



[91] M. Christensen, E.J.K. Nilsson, Konnov, A.A.. The Temperature Dependence of the Laminar Burning Velocities of Methyl Formate + Air Flames. Fuel, submitted.
[92] P.A. Glaude, W.J. Pitz, M.J. Thomson, Proc. Combust. Inst. 30 (2005) 1111-1118.
[93] P. Diévart, S.H. Won, J. Gong, S. Dooley, Y. Ju, Proc. Combust Inst. 34 (2013) 821-829.
[94] Y.L. Wang, D.J. Lee, C.K. Westbrook, F.N. Egolfopoulos, T.T. Tsotsis, Combust. Flame. 161 (2014) 810-817.

Temperature dependence - general

Power exponent, α, as a function of ϕ. Symbols: experiments [91] and lines: modelling. Dashed line: model of Glaude et al. [92], solid line: model of Dievart et al. [93].



[91] M. Christensen, E.J.K. Nilsson, Konnov, A.A.. The Temperature Dependence of the Laminar Burning Velocities of Methyl Formate + Air Flames. Fuel, submitted.
[92] P.A. Glaude, W.J. Pitz, M.J. Thomson, Proc. Combust. Inst. 30 (2005) 1111-1118.
[93] P. Diévart, S.H. Won, J. Gong, S. Dooley, Y. Ju, Proc. Combust Inst. 34 (2013) 821-829.

Temperature dependence - sensitivity

$$Sens(SL,k) = \frac{\partial SL}{\partial k}\frac{k}{SL}$$

$$Sens(a,k) = \frac{\partial a}{\partial k}\frac{k}{a} \qquad S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{p_u}{p_0}\right)^{\beta_p},$$

$$Sens(a,k) = \frac{Sens(SL,k) - Sens(SL_0,k)}{ln\left(\frac{T}{T_0}\right)\,\alpha}$$

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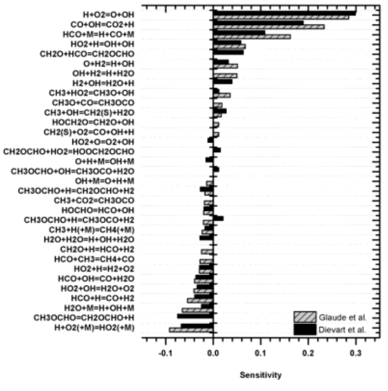
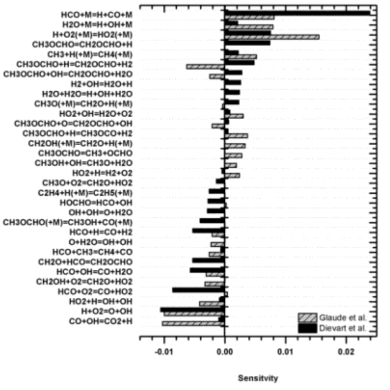
Temperature dependence - sensitivity



Normalized sensitivity coefficients for the laminar burning velocity of MF+air flames at ϕ = 1.0



Normalized sensitivity coefficients for the power exponent α of MF+air flames at ϕ = 1.0.

M. Christensen, E.J.K. Nilsson, Konnov, A.A.. The Temperature Dependence of the Laminar Burning Velocities of Methyl Formate + Air Flames. *Fuel*, submitted.

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Data consistency – role of α and β

- Experimental power exponents α and β show large scattering => more experiments are needed
- Calculated power exponents β are sensitive to the rate constants implemented => useful for model validation
- Calculated power exponents α are not sensitive => useful for analysis of experimental data consistency

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Experimental uncertainties

Progress in Energy and Combustion Science 43 (2014) 36–67

Contents lists available at ScienceDirect

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Progress in Energy and Combustion Science

journal homepage: www.elsevier.com/locate/pecs

Review

Advances and challenges in laminar flame experiments and implications for combustion chemistry

CrossMark

F.N. Egolfopoulos [a,*], N. Hansen [b], Y. Ju [c], K. Kohse-Höinghaus [d], C.K. Law [c], F. Qi [e]

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Outdated methods

Simple tube

Disadvantage: interaction with walls (E. Mallard, H.L. Le Chatelier, 1883).

Development: divergent channels

Bunsen burner, slot burner

Advantage: simple, disadvantage: curvature + stabilization

Soap bubble

Advantage: constant P, disadvantage: saturation by water

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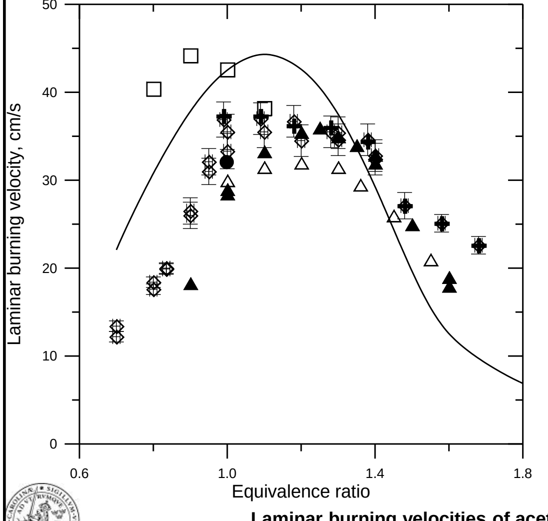
Acetone nightmare



Squares: G.J. Gibbs, H.F. Calcote. J. Chem. Eng. Data. 3 (1959) 226–235.

open triangles: L.N. Khitrin "Physics of Combustion and Explosion", Israel Program for Scientific Translation, Jerusalem, 1962, p. 448.

solid circle: V.V. Molkov, V.P. Nekrasov. Comb. Explosion, Shock Waves, 17 (1981) 280-283.

solid triangles: G. Black, S. Pichon, H. Curran, J. Simmie, R. Donohue, N. Djebaili-Chaumeix, An experimental and modeling study of the combustion of acetone. Third European Combustion Meeting, Greece, 2007.

crosses: spark ignition;
diamonds: laser ignition;
line: modeling

Burluka, A.A., Osman, H., Harker, M., Lawes, M., Sheppard, C.G.W., Konnov, A.A. *Fuel* 89: 2864-2872 (2010)

Laminar burning velocities of acetone + air mixtures at atmospheric pressure and room temperature (298 K).

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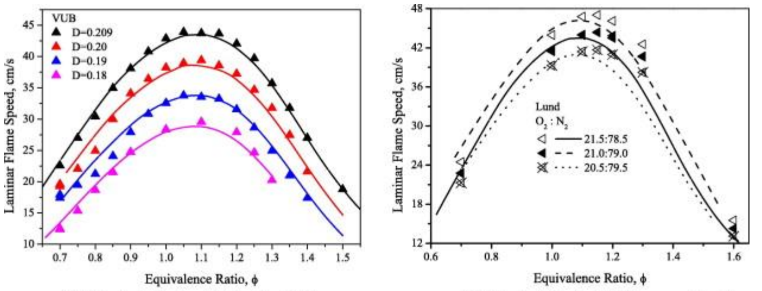
What do we burn ?



(a) Effect of altering dilution levels D = $O_2/(O_2+N_2)$.

(b) Effect of altering "air" composition by ± 0.5%

MFC

ΔU=0.5% (reading) + 0.1% (full scale)

Buffering vessels !

Vibrations !

Calibration !

Sinéad M. Burke , Ultan Burke , Reuben Mc Donagh , Olivier Mathieu , Irmis Osorio , Charles Keesee , Anibal Moron...

Combustion and Flame, Volume 162, 2015, 296 - 314

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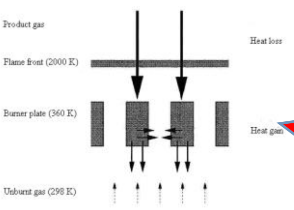
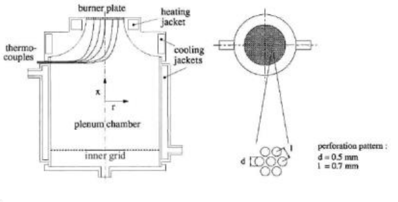
Buffering vessel

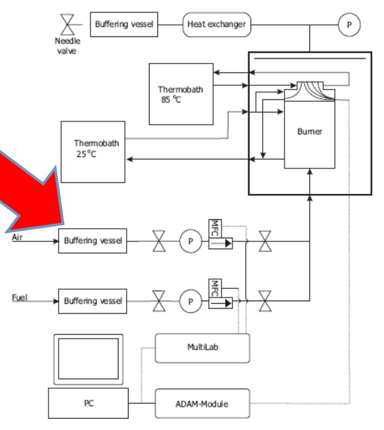
Heat flux balance



Heat flux burner



Experimental setup



Remember to preheat MFCs !

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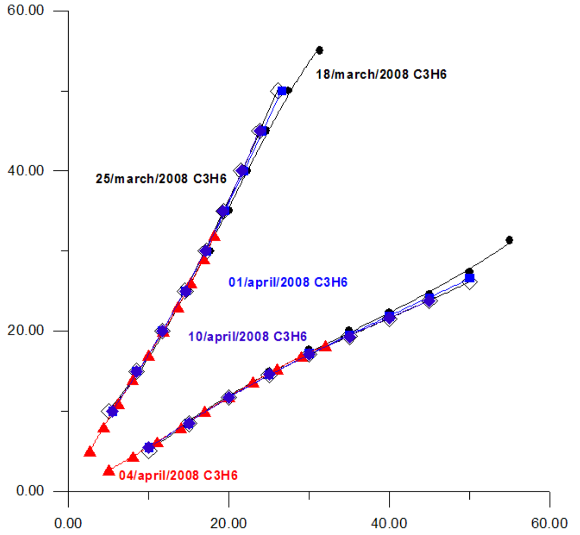
Calibration



Calibration curves of the MFC for C3H6

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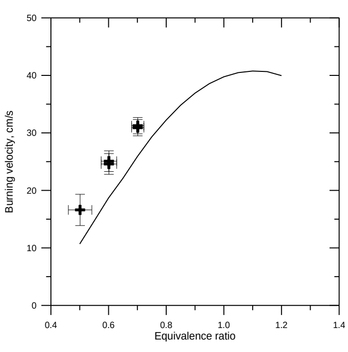
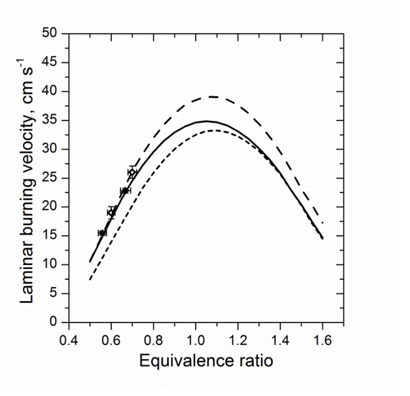
MFC calibration vs. fluidat





Laminar burning velocity vs. equivalence ratio for ethanol + O_2 + CO_2 at 298 K. Symbols: Open diamonds represent first set of experimental data, filled diamonds second set of experimental data. Lines represent modeling; solid line (-): Marinov's model, long dash line (--): the San Diego model; short dash line (..): the LDTV model.

Naucler, J.D., Christensen, M., Nilsson, E.J.K., Konnov, A.A. Oxy-fuel combustion of ethanol in premixed flames . *Energy and Fuels* 26: 4269-4276 (2012).

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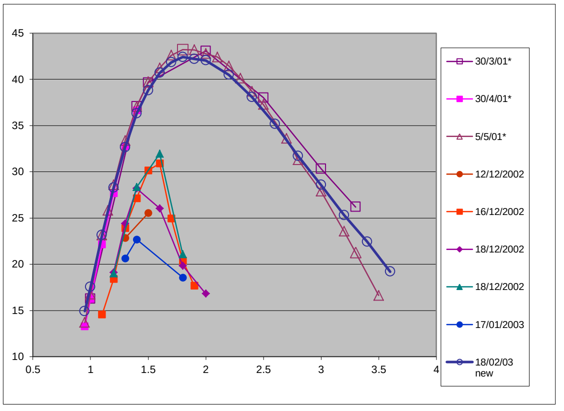
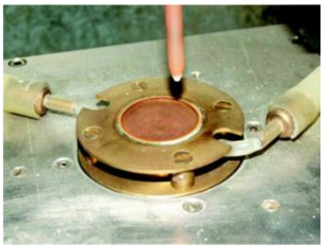
What do we burn ?



Fuel: 50%CO+50%H_2

Oxidizer: 9% O_2 + 91% N_2



Konnov et al. CST 181 (2009) 117

Fe $(CO)_5$!!!

Williams, T.C., Shaddix C.R. CST 179 (2007) 1225

Kaskan W.E. Proc. Comb. Inst., 6 (1956) 134

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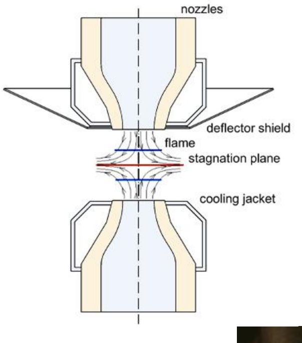
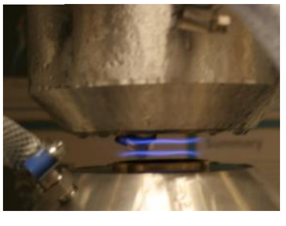
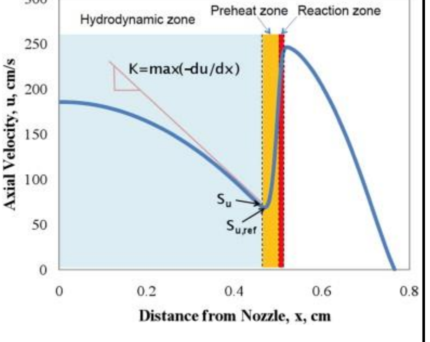
Counterflow





Counterflow flames in Lund



F.N. Egolfopoulos , N. Hansen , Y. Ju , K. Kohse-Höinghaus , C.K. Law , F. Qi

Progress in Energy and Combustion Science, Volume 43, 2014, 36 - 67

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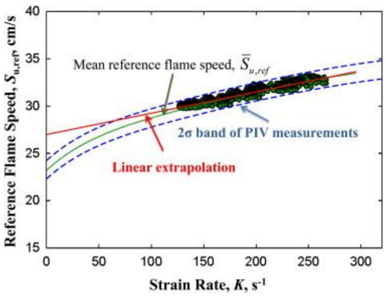
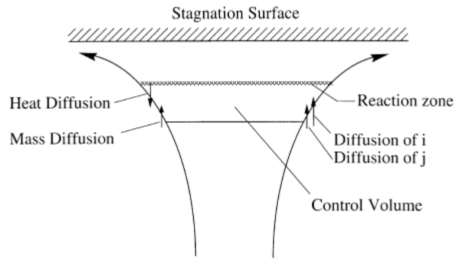
Counterflow





Conceptual demonstration of the nonconcervative nature of stretched flame response in the presence of equidiffusion.

F.N. Egolfopoulos, N. Hansen, Y. Ju, K. Kohse-Höinghaus, C.K. Law, F. Qi

Progress in Energy and Combustion Science, Volume 43, 2014, 36 - 67

Law C.K., Sung C.J. Prog. Energy Comb. Sci., 26 (2000) 459

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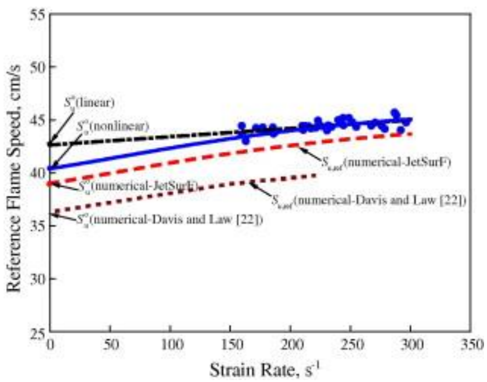
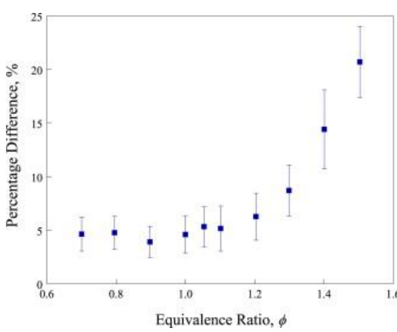
Counterflow





Percentage difference of SL obtained with linear and computationally-assisted extrapolation for C5 – C12 alkanes

Chunsheng Ji, Enoch Dames, Yang L. Wang, Hai Wang, Fokion N. Egolfopoulos

Combustion and Flame, Volume 157, 2010, 277 - 287

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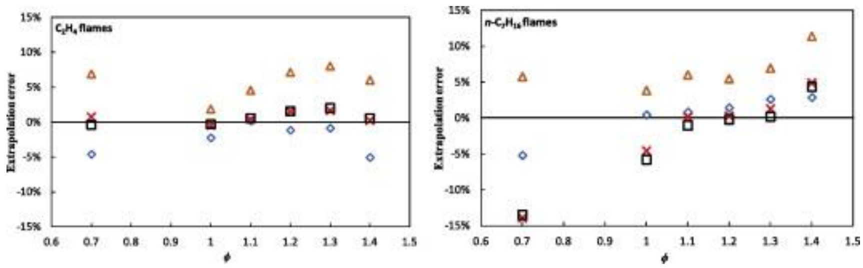

Deviation of experiment-based extrapolated SL values from computed ones as function of equivalence ratio. Differences represented by symbols: (diamond) non-linear method for $S_{u,ref}$ from CFF's; (cross) linear method for S_b; (□) non-linear method for S_b; and (triangle) non-linear method for U_n from SEF's.

Jagannath Jayachandran , Alexandre Lefebvre , Runhua Zhao , Fabien Halter , Emilien Varea , Bruno Renou , Fokion N. Egolfopoulos

Proceedings of the Combustion Institute, Volume 35, 2015, 695 - 702

Clearly, in steady state experiments like those of CFF's the directly measured $S_{u,ref}$'s can be optimized so that the uncertainties are minimized. In carefully performed CFF experiments, the uncertainty based on 2σ, where σ is the standard deviation, can be as low as 5%.

However, the uncertainty of CFF experiments can be 10% or higher if issues related to the quality of the flow, reactant concentrations especially for $\phi > 1.0$ flames of liquid fuels, flow tracer seeding density, the implementation of particle image velocimetry (PIV) or laser Doppler velocimetry (LDV) to measure flow velocities, and interpretation of the raw data are not addressed carefully and rigorously.

Jagannath Jayachandran , Runhua Zhao , Fokion N. Egolfopoulos

Combustion and Flame, Volume 161, Issue 9, 2014, 2305 - 2316

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Counterflow 1D vs. 2D

Both cold and reactive cases investigated show that the 1D approach fails to give accurate predictions of the corresponding velocity fields. The observed discrepancies between the 1D and 2D results are traced back to the assumption of a constant-pressure-derivative term in the momentum equation of the 1D model.

Nicolas Bouvet, Dmitry Davidenko, Christian Chauveau, Laure Pillier, Youngbin Yoon
Combustion and Flame 161 (2014) 438–452

Based on a normalized error metric, and the diluted hydrogen versus air non-premixed flames considered, it was suggested that nozzle diameters greater than 12 mm will yield errors less than numerical uncertainties and certainly well below current experimental uncertainties.

R. F. Johnson, A. C. VanDine, G. L. Esposito & H. K. Chelliah
CST 187 (2015) 37

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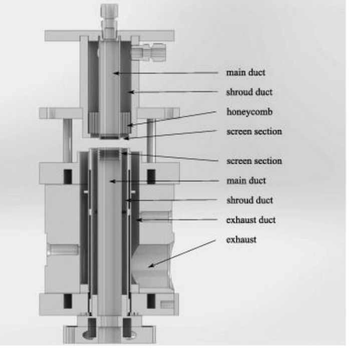
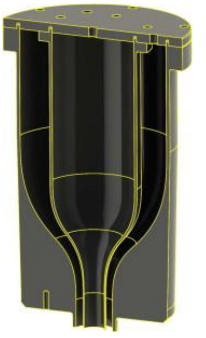
Counterflow



Schematic drawing of a counterflow apparatus employing screened ducts.



It is best to account for the radial gradient of the radial component of the velocity when contoured nozzles are employed, but plug-flow boundary conditions apply with good accuracy for screened ducts. The departures from plug-flow conditions in screened-duct devices generally are too small to be determined accurately enough to justify use of any other boundary condition at the screen exits. Accuracies are such that errors are less than 5% in well-designed screened-duct experiments.

Ulrich Niemann , Kalyanasundaram Seshadri , Forman A. Williams

Combustion and Flame, 162 (2015) 1540-1549

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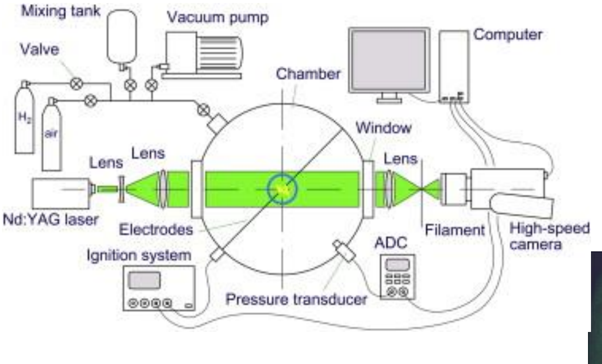
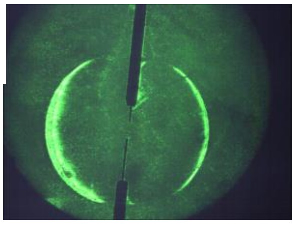
Spherical flames





Zamaschikov, V.V., Alekseev, V.A., Konnov, A.A. *Int. J. Hydrogen Energy,* 39: 1874-1881 (2014).

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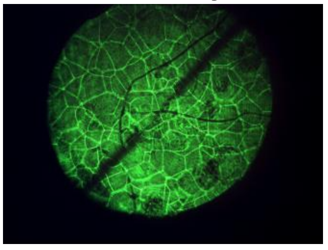
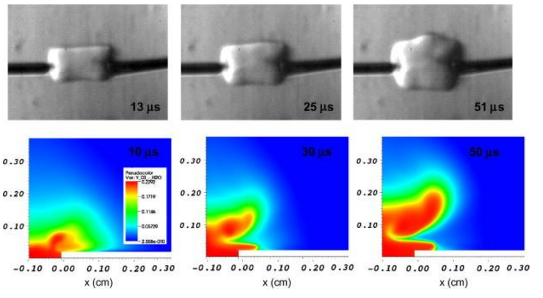
Spherical flames

Cellularity



Electrodes



Images from high-speed schlieren visualization and simulation of ignition with the thin cylindrical electrodes.

Buoyancy

Sally P.M. Bane, Jack L. Ziegler, Joseph E. Shepherd

Investigation of the effect of electrode geometry on spark ignition

Combustion and Flame, Volume 162, 2015, 462 - 469

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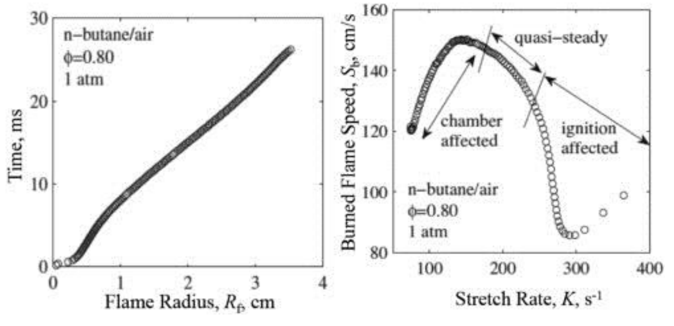
Spherical flames



Variation of the flame radius with time (left) and burned flame speed with stretch for a lean n-C4H10/air mixture at p 1 atm and Tu 298 K.

F.N. Egolfopoulos, N. Hansen, Y. Ju, K. Kohse-Höinghaus, C.K. Law, F. Qi

Progress in Energy and Combustion Science, Volume 43, 2014, 36 - 67

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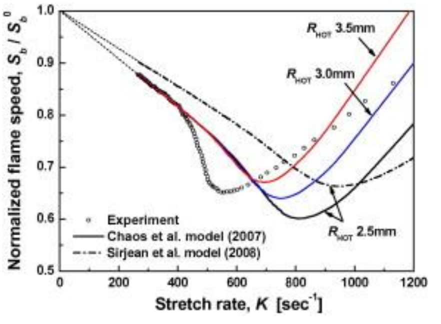
Spherical flames

Critical radius

Models are different !

Cannot use computationally-assisted extrapolation as in CFF



Experimentally and numerically determined normalized flame speed as a function of stretch rate for *n* -C10H22 /air at ϕ = 0.9, *P* = 1 atm, and *T*u = 400 K

Hwan Ho Kim , Sang Hee Won , Jeffrey Santner , Zheng Chen , Yiguang Ju

Measurements of the critical initiation radius and unsteady propagation of n-decane/air premixed flames

Proceedings of the Combustion Institute, Volume 34, 2013, 929 - 936

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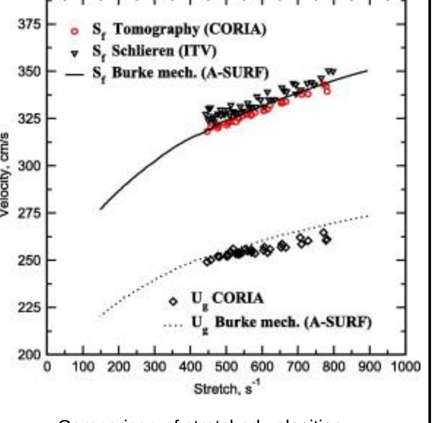
Spherical flames

Confinement and front registration

Tomography (tracer evaporation) or Schlieren



Comparison of stretched velocities obtained from experiments and simulation.

Emilien Varea , Joachim Beeckmann , Heinz Pitsch , Zheng Chen , Bruno Renou

Proceedings of the Combustion Institute, Volume 35, 2015, 711 - 719

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Spherical flames

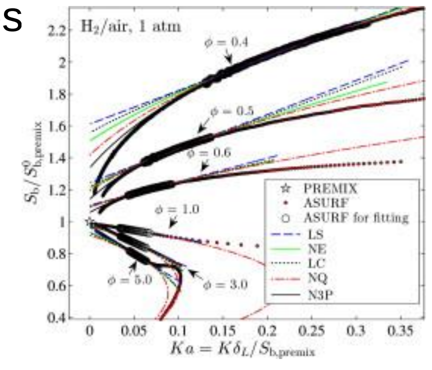
Linear vs. non-linear

$$\frac{S_b}{S_b^0} = 1 - \frac{2L_b}{r} \cdot \frac{S_b}{S_b^0}$$

$$\frac{S_b}{S_b^0} = 1 - \frac{2L_b}{r}$$

$$\frac{S_b}{S_b^0} \, ln\left(\frac{S_b}{S_b^0}\right) = -\frac{2L_b}{r}$$

While the uncertainty is minimized for stoichiometric H_2/air and *n*-heptane/air flames, the uncertainty can be as high as 60% for lean H_2/air mixtures, and 10% for lean and rich *n*-heptane/air mixtures.



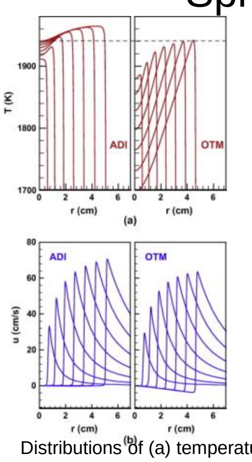
Comparison between results of various extrapolation models with numerical simulation for various equivalence ratios of H 2 /air at 1 atm. Data used for fitting is for flame radius from 1 cm to 2 cm.

Fujia Wu , Wenkai Liang , Zheng Chen , Yiguang Ju , Chung K. Law

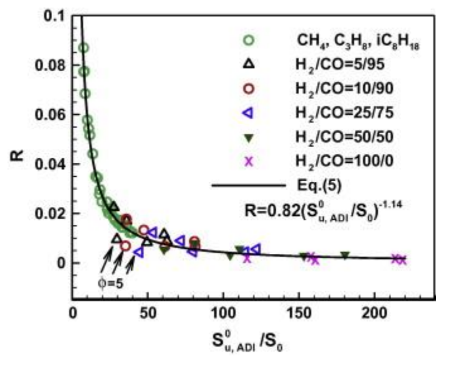
Proceedings of the Combustion Institute, Volume 35, 2015, 663 - 670

LUNDS UNIVERSITET

Spherical flames



Distributions of (a) temperature and (b) flow speed for propagating spherical methane/air (ϕ = 1.4) flames at T u = 298 K and P = 1 atm.



R = 1 – Srad/ Sad

No reflection !

Hao Yu , Wang Han , Jeffrey Santner , Xiaolong Gou , Chae Hoon Sohn , Yiguang Ju , Zheng Chen

Combustion and Flame, Volume 161, Issue 11, 2014, 2815 - 2824

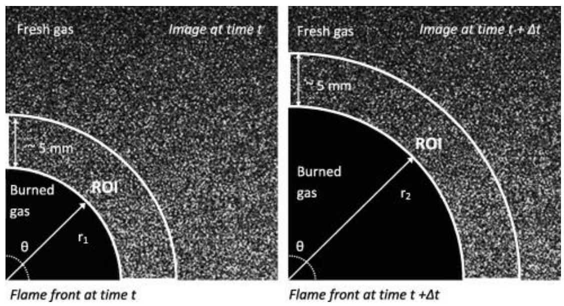
LUNDS UNIVERSITET

Spherical flames

Density ratio problem

$$u_n^0 \cong u_s^0 = \frac{\rho_b}{\rho_u} \cdot S^0$$

$$u_n^0 = \lim_{r\to\infty}(S - u_g).$$



Localization (in polar coordinates) of the region of interest (ROI) for a tomographic image couple.

Emilien Varea , Vincent Modica , Alexis Vandel , Bruno Renou

Combustion and Flame, Volume 159, 2012, 577 - 590

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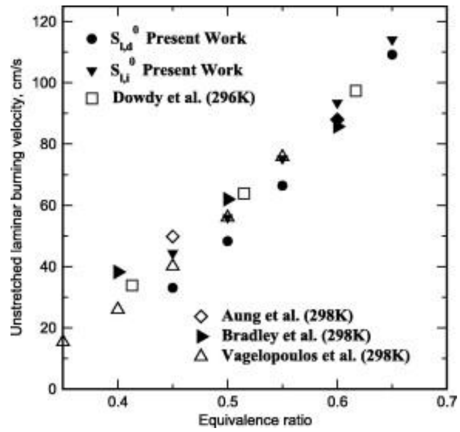
Spherical flames



Comparison with literature of unstretched indirect flame speeds (non-linearly extrapolated)

Emilien Varea , Joachim Beeckmann , Heinz Pitsch , Zheng Chen , Bruno Renou

Proceedings of the Combustion Institute, Volume 35, 2015, 711 - 719

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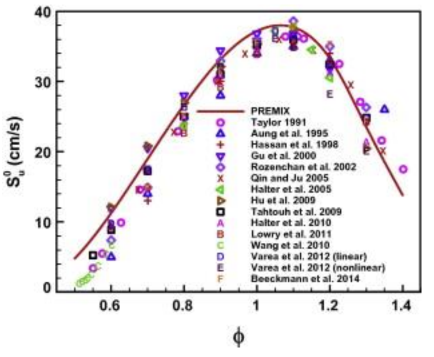
Spherical flames

The present study shows that there are large discrepancies in Su0 measured for CH_4/air at NTP using the OPF method and that these data cannot be used to restrain the uncertainty of chemical models for methane.

However, this does not mean that the laminar flame speed data or the OPF method is useless: they are still useful for conditions at which the uncertainty of chemical model is larger than that of Su0 measurements.



Zheng Chen

Laminar flame speed of CH 4 /air at NTP.

On the accuracy of laminar flame speeds measured from outwardly propagating spherical flames: Methane/air at normal temperature and pressure

Combustion and Flame, 2015

http://dx.doi.org/10.1016/j.combustflame.2015.02.012

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Flat flames

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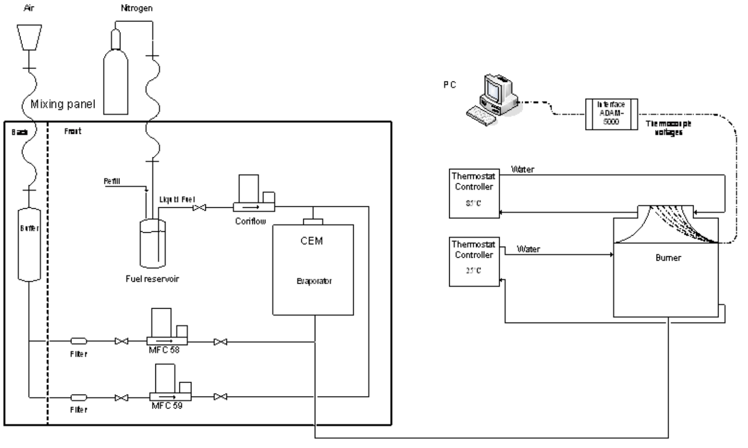
Experimental setup
Overview



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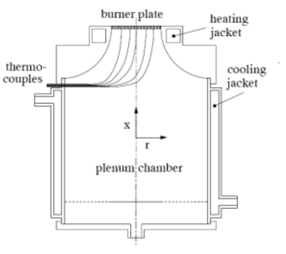
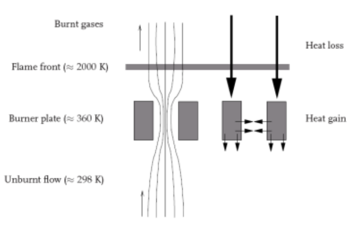
Experimental setup
Perforated plate burner

Schematic overview



Principle



- **Perforated plate burner**
  - **Flow uniformity**
  - **Water circuits**
  - **Thermocouples**

Adiabatic state

heat loss = heat gain

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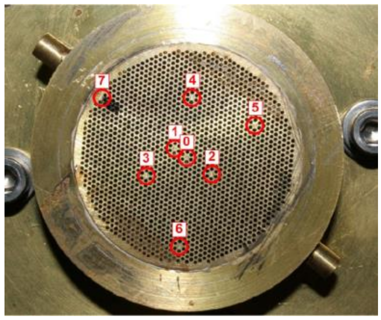
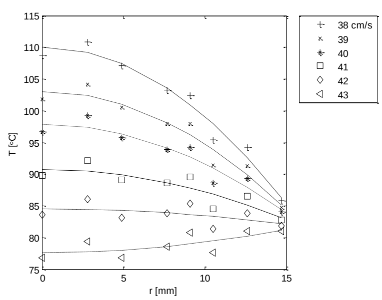


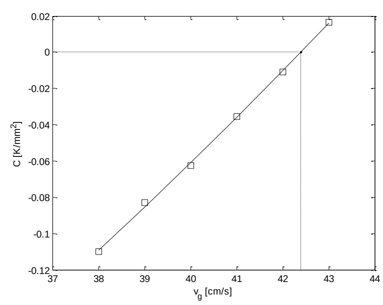
Top view of the perforated plate burner

Experimental setup
Typical measurement

Ethanol / air flame; φ = 1.1, T_u = 298K



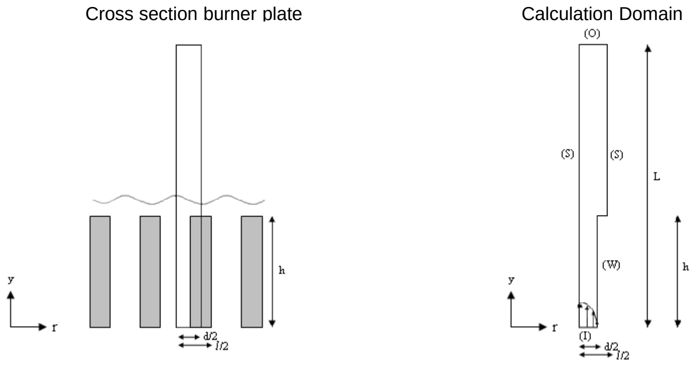
Temperature profile



Parabolic coefficient

$T = T_0 + Cr^2$

Numerical modelling



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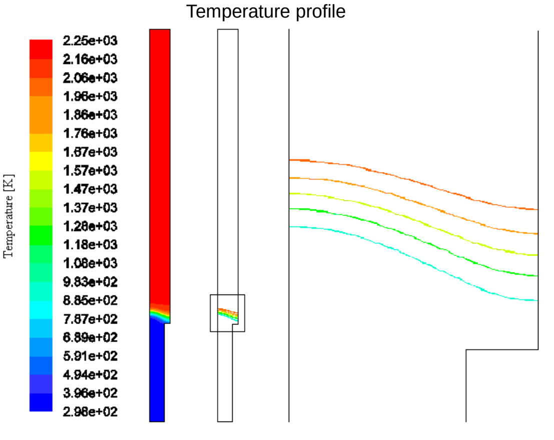
Numerical modelling



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Numerical modelling

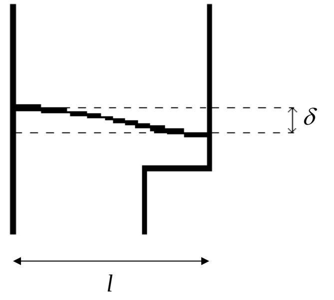
- Flame front surface area increase < 1%

$$S_{increase} = \frac{\pi l\sqrt{l^2+\delta^2}}{\pi l^2} = 1 + \frac{1}{2}\left(\frac{\delta}{l}\right)^2$$

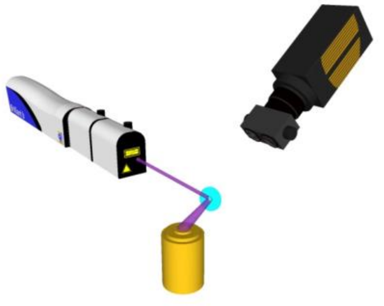
- For 3 bar 0.5/0.7mm can be used

- Up to 10 bar 0.3/0.4mm can be used

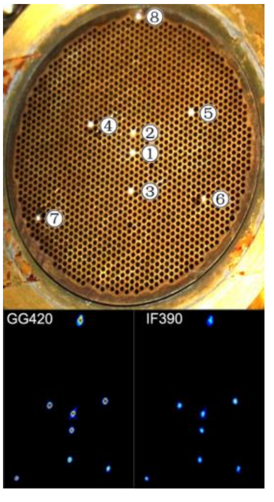
Curvature



Goswami, M., Coumans, K., Bastiaans, R.J.M., Konnov A.A., de Goey L.P.H. Numerical simulations of flat laminar premixed methane-air flames at elevated pressure. *Combust. Sci. Technol.,* 186: 1447-1459 (2014).



setup



Photograph of the perforated burner disc coated with eight thermographic phosphor dots on top of the installed thermocouples installed. Showing beneath are a typical twin laser-induced phosphorescence images collected through two different filters as marked in the corresponding images.

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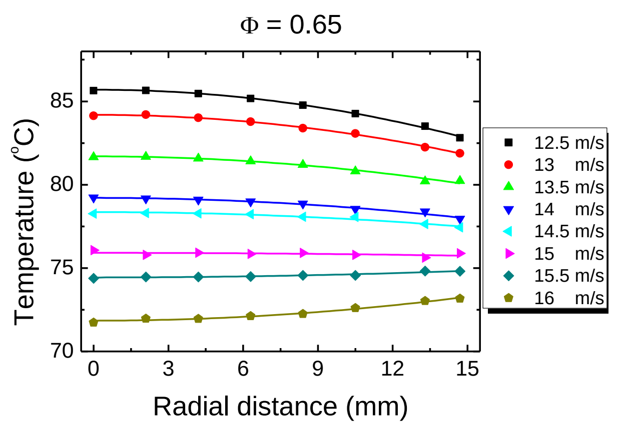

Temperatures measured with thermographic phosphors at different radial distance on top of the burner disc (symbol) at different gas supply speeds and fitting curves (solid lines) for methane/air (Φ=0.65) flame speed evaluation.

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Flat flames

Catalytic surface ?

Radiation ?

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Cellularity

Figure 3.11 *Flat flame*

Figure 3.12 *Non-flat flame*

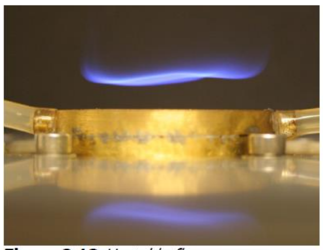

Figure 3.13 *Unstable flame*

Figure 3.14 *Cellular flame*

Take away

- The laminar burning velocity is not a measurable quantity
- Temperature and pressure dependence of SL in terms of α and β – useful for analysis of the data consistency
- Experimental power exponents α and β show large scattering => more experiments are needed
- Calculated power exponents β are <u>sensitive</u> to the rate constants implemented => useful for model validation
- Calculated power exponents α are <u>not sensitive</u> => useful for analysis of experimental data consistency
- Next few years – struggle for uncertainty

Many thanks !

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