11th International Workshop on Premixed Turbulent Flames

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A statistical study on turbulent premixed flames using DNS

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Run of the research

Construction of DNS databases of turbulent premixed flames

different density ratios different Lewis numbers

Statistically analyses using DNS databases

Assessment of some turbulent combustion model

DNS database (1/5)

Governing equations

Mass conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0$$

Momentum conservation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} = \frac{\partial \tau_{ij}}{\partial x_j}$$

Energy conservation

$$\frac{\partial e_t}{\partial t} + \frac{\partial \{(e_t + p) u_j\}}{\partial x_j} = \frac{\partial (u_j \tau_{kj})}{\partial x_k} - \frac{\partial q_j}{\partial x_j}$$

Species conservation

$$\frac{\partial (\rho Y)}{\partial t} + \frac{\partial (\rho Y u_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial Y}{\partial x_j} \right) + W$$

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij} \frac{\partial u_k}{\partial x_k} \right), \quad e_t = \rho Q Y + \frac{\rho R T}{\gamma - 1} + \frac{\rho}{2}\left(u^2 + v^2 + w^2\right),$$

$$q_i = -\lambda \frac{\partial T}{\partial x_i} - \rho D Q \frac{\partial Y}{\partial x_i}, \qquad W = -B \rho Y T^{\beta} \exp\left(-\frac{\theta}{T} \right)$$

DNS database (2/5)

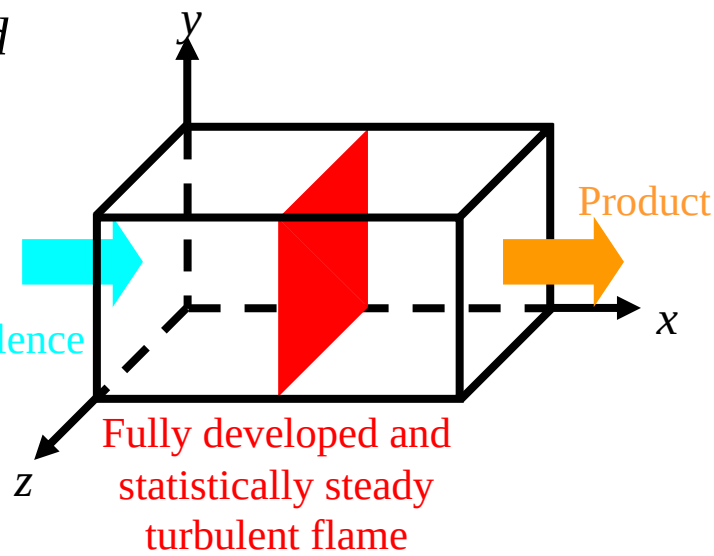
Numerical scheme

Space discretisation: *x (flow) direction:* 6th order central finite difference scheme
y,z directions: Spectral method

Time advancement: *3rd order Runge-Kutta method*

Chemical kinetics: *Single step overall reaction*

Calculation domain: *x: 512 (8 mm)*
y: 128 (4 mm)
z: 128 (4 mm)



Boundary conditions: *upstream:* NSCBC inflow, *downstream:* NSCBC outflow
lateral: Periodic

DNS database (3/5)

Numerical conditions

	Different density ratios			Different Lewis numbers		
ρ_u/ρ_b	2.50	5.00	7.53	5.00	5.00	5.00
Le	1.0	1.0	1.0	0.8	1.0	1.2
u_L^0 (m/s)	0.416	0.523	0.600	0.523	0.523	0.523
δ_f (mm)	0.1572	0.1911	0.2162	0.1913	0.1911	0.1908
u'/u_L^0	1.26	1.01	0.88	1.01	1.01	1.01

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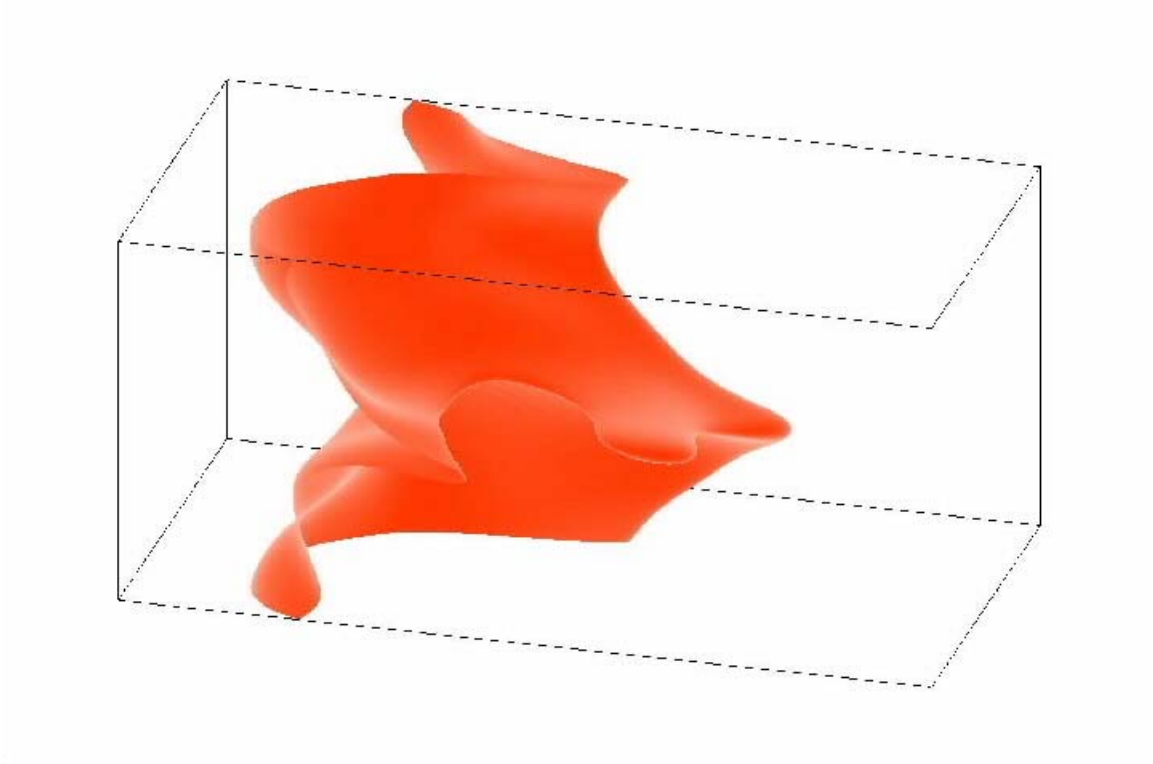
DNS database (4/5)



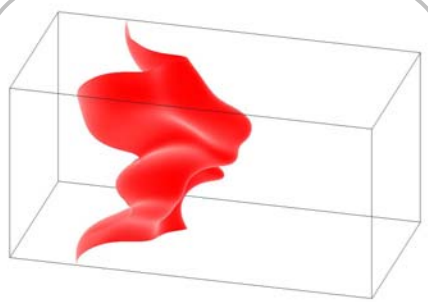
$\rho_b / \rho_u = 5.00$, Le = 0.8

DNS database (5/5)

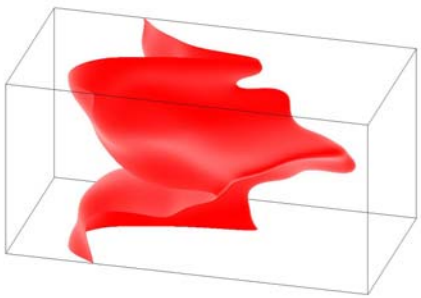
small

flame area

large

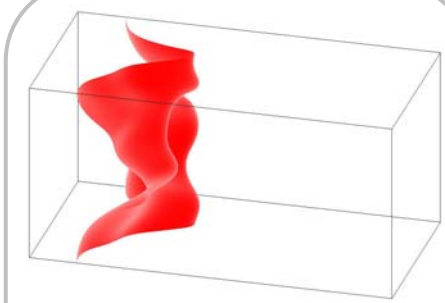


u_t = 1.12637 m/s



u_t = 1.93383 m/s

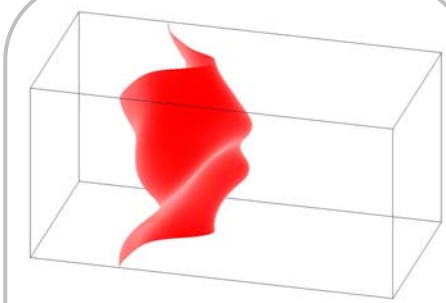
Lewis number: 0.8
progress variable: 0.91



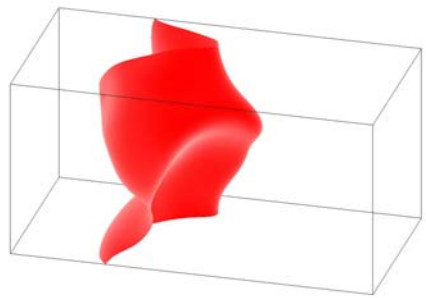
u_t = 0.81642 m/s

u_t = 1.33707 m/s

Lewis number: 1.0
progress variable: 0.89



u_t = 0.76106 m/s



u_t = 0.87856 m/s

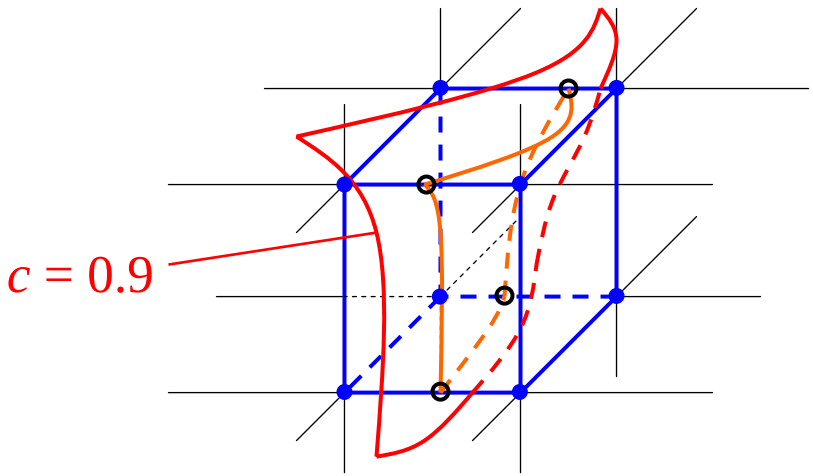
Lewis number: 1.2
progress variable: 0.88

Analysis method (1/4)

1. To identify the surface of turbulent premixed flames

The iso-surface of the prescribed progress variable (c□0.9) is defined as the surface of turbulent premixed flames.

The intersections of computational grids with the surface of turbulent premixed flames are obtained by linear interpolation.



Analysis method (2/4)

2. To evaluate local laminar burning velocities

Local laminar burning velocity

$$u_L = -\frac{1}{A_T \rho_0 Y_0}\int \dot{\omega} \mathrm{d}V = -\frac{1}{\rho_0 Y_0}\int \dot{\omega} \mathrm{d}n$$

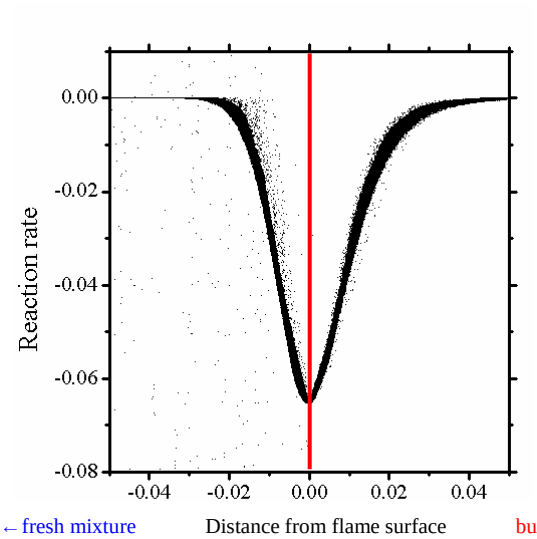
ρ_0：density of the fresh mixture

Y_0：mass fraction of the fresh mixture

$\dot{\omega}$：reaction rate

A_T：total turbulent flame area

n: normal to the flame surface



Distribution of local reaction rates on every normal line to the flame surface (Le = 1.0 ; ρ_u/ρ_b = 5.00; c = 0.89)

Analysis method (4/4)

3. To evaluate local stretch rates (strain rates, flame curvature)

Local stretch rate

$$\kappa = \left(\delta_{ij} - n_i n_j\right)\frac{\partial u_i}{\partial x_j} + u_L\left(\frac{\partial n_i}{\partial x_i}\right)$$

$n_{i,j}$: normal to flame surface

u_i: local flow velocity

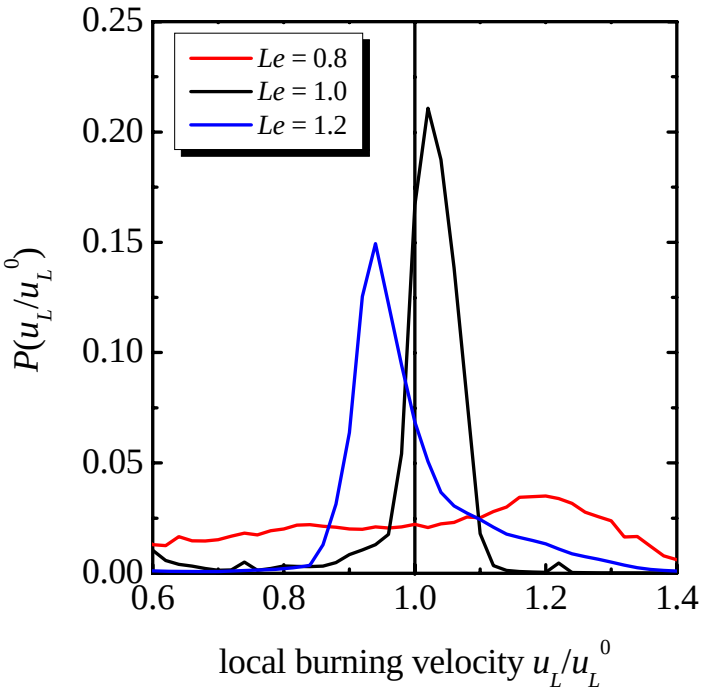
u_L: local burning velocity

δ_{ij}: Kronecker delta

κ: local stretch rate

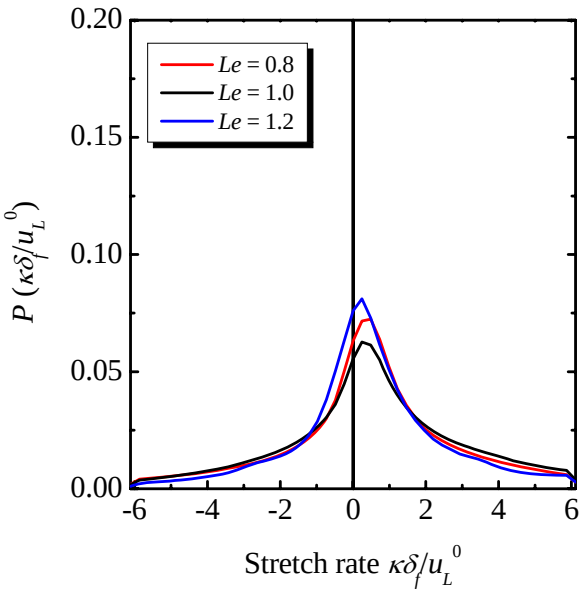
→ Obtain probability density functions (pdfs) for each quantities, and then evaluate joint pdfs among the quantities.

Analysis results (1/6)

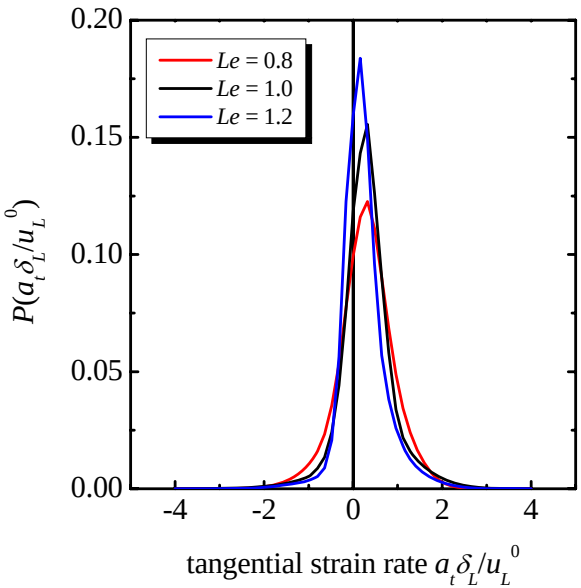


Evaluation of local burning velocities using pdf

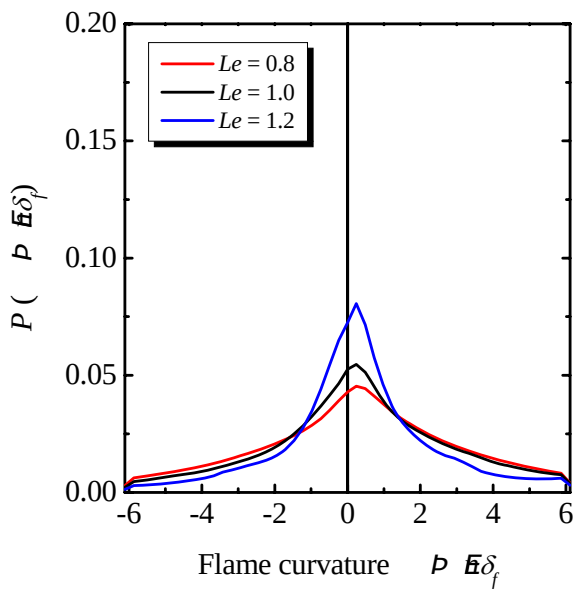
Analysis results (2/6)



stretch rate
(c = 0.91)



tangential strain rate
(c = 0.89)



flame curvature
(c = 0.88)

Evaluation of local stretch rate, tangential strain rate and flame curvature using pdf

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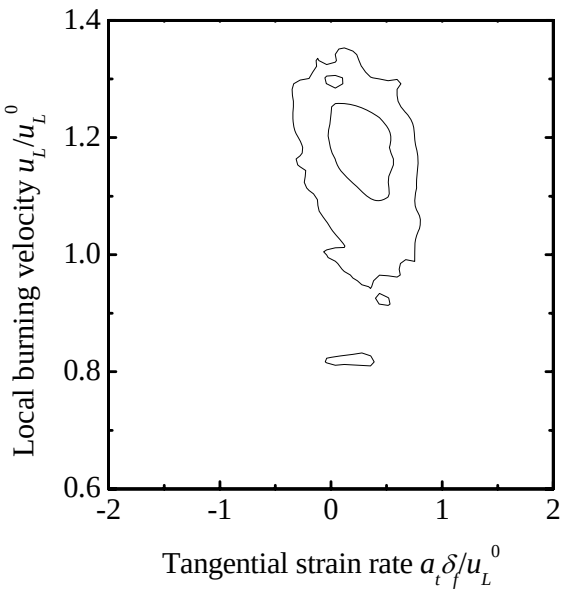
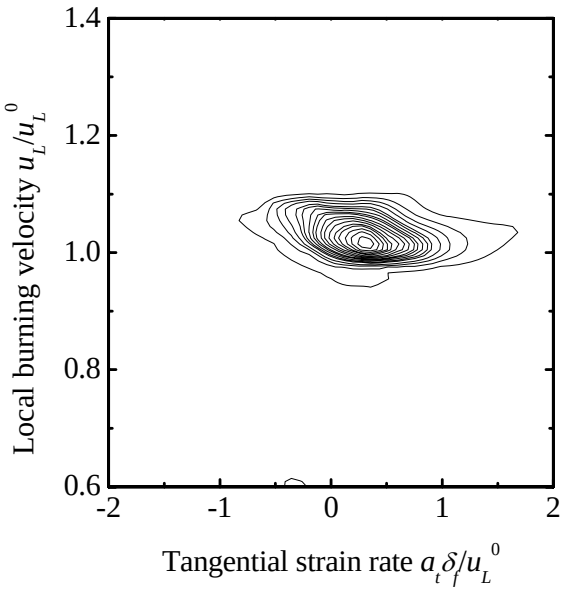
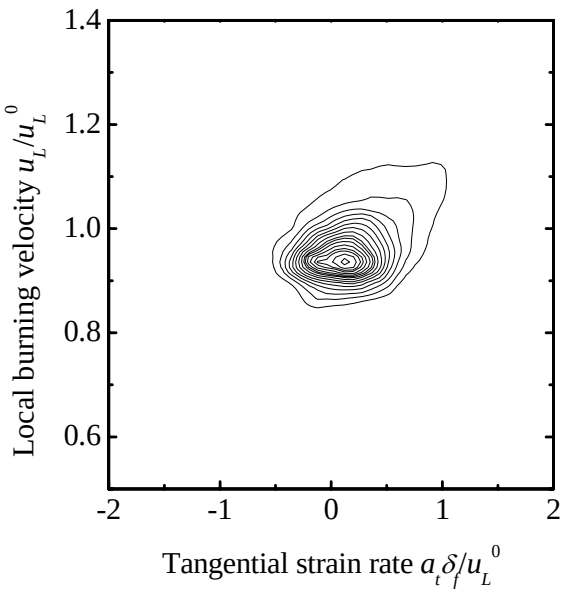
Analysis results (3/6)



Le = 0.8 (c = 0.91)



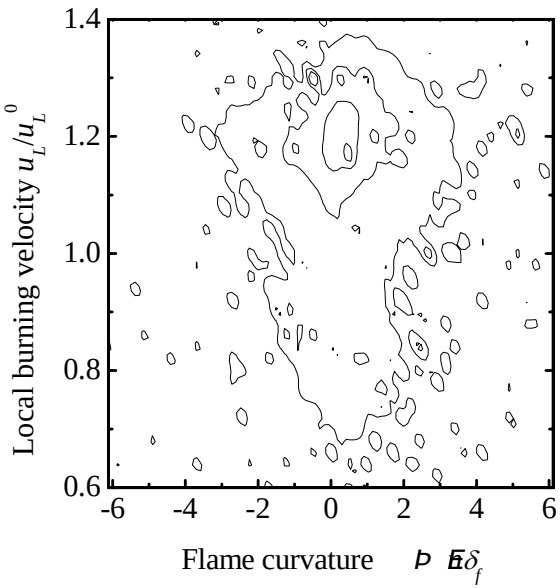
Le = 1.0 (c = 0.89)



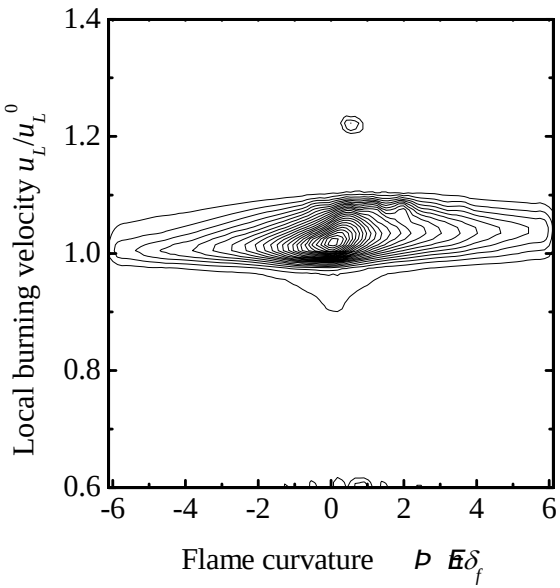
Le = 1.2(c = 0.87)

Correlation between local burning velocity
and local tangential strain rate using joint pdf

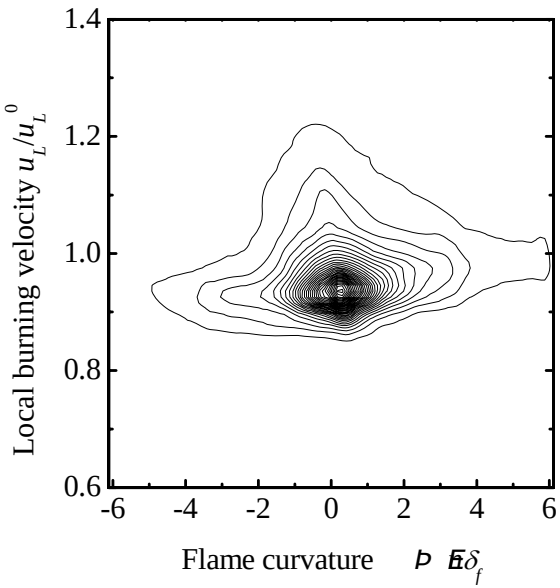
Analysis results (4/6)



Le = 0.8 (c = 0.91)



Le = 1.0 (c = 0.89)



Le = 1.2 (c = 0.87)

Correlation between local burning velocity and local flame curvature using joint pdf

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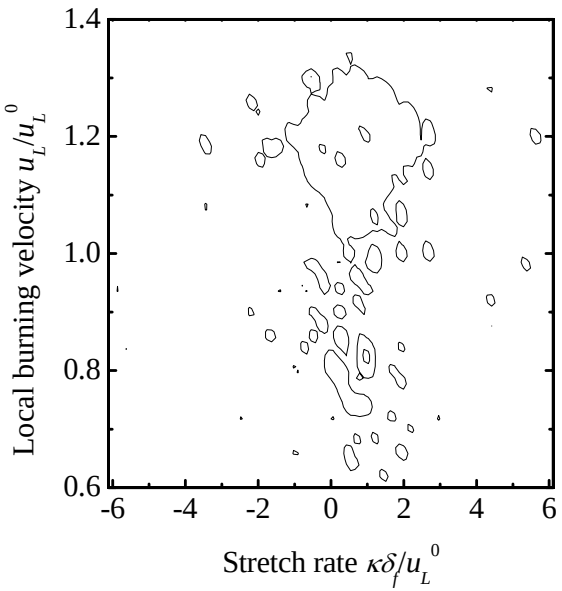
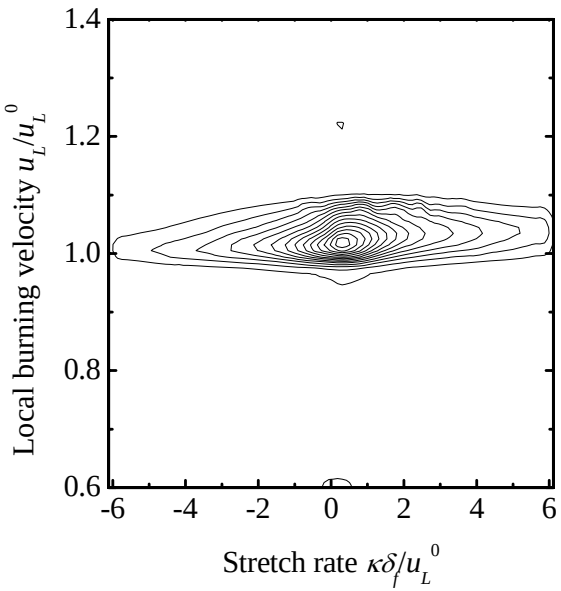
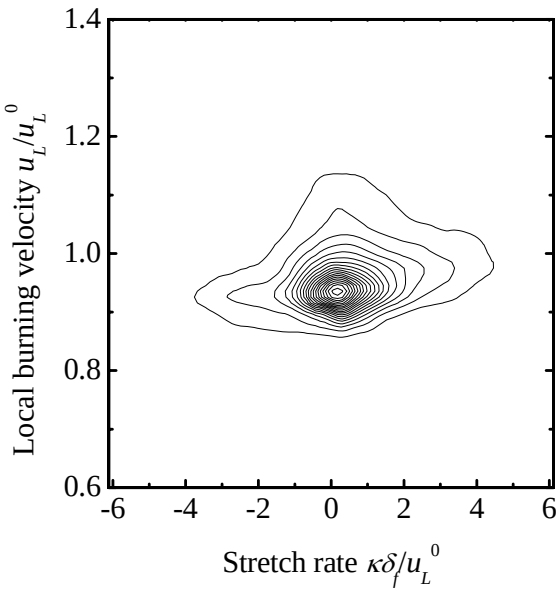
Analysis results (5/6)



Le = 0.8 (c = 0.91)



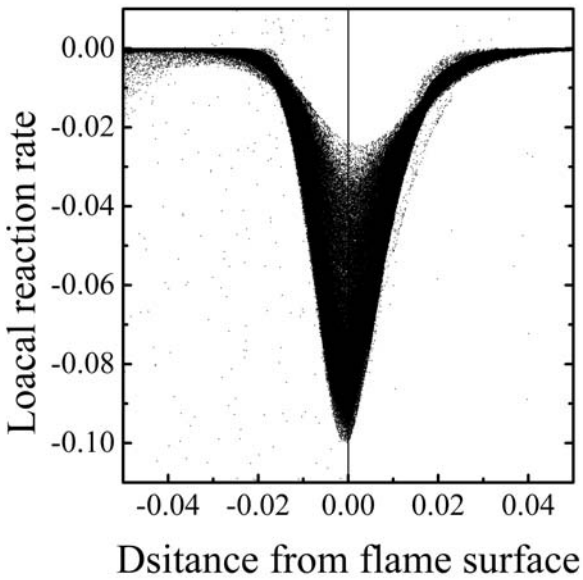
Le = 1.0 (c = 0.89)



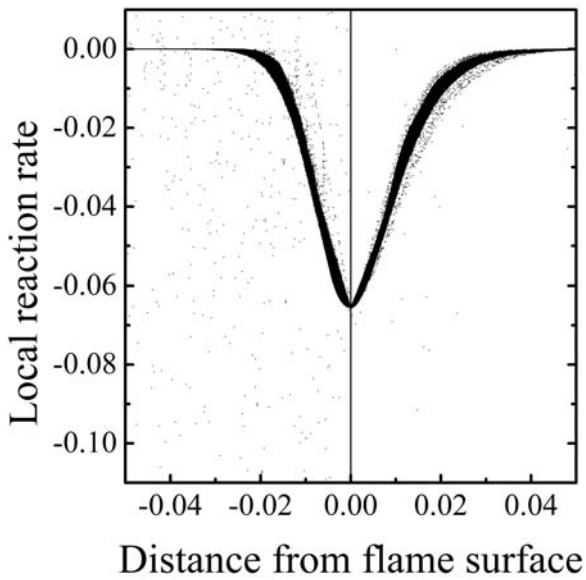
Le = 1.2 (c = 0.87)

Correlation between local burning velocity and local stretch rate using joint pdf

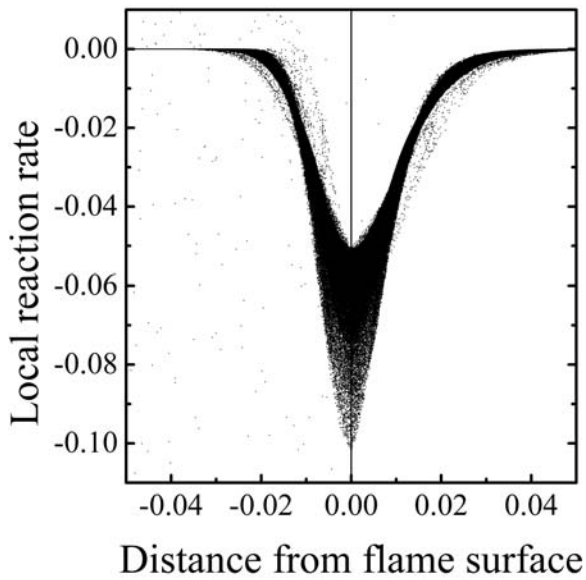
Analysis results (6/6)



Le = 0.8 (c = 0.91)



Le = 1.0 (c = 0.89)



Le = 1.2 (c = 0.87)

Local reaction rates on every normal line to the flame surface

Challenges

1. A value of progress variable to define local stretch rate properly?
2. Is it possible to distinguish strain from expansion?
3. To evaluate local burning velocity precisely…