中国科学技术大学
University of Science and Technology of China

火灾科学国家重点实验室
State Key Laboratory of Fire Science

Effect of wall friction on shock-flame interactions in a hydrogen-air mixture

Ting Shen, Huahua Xiao*

State Key Laboratory of Fire Science, University of Science and Technology of China,
Hefei, Anhui, China
Concordia University, Montreal, Quebec, Canada

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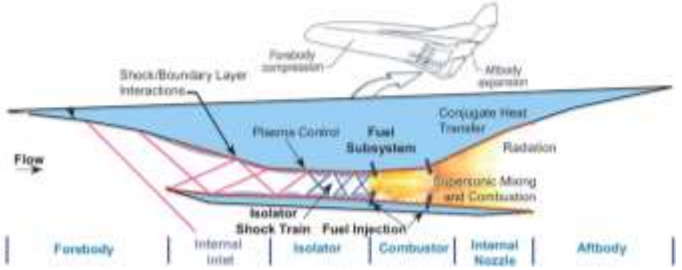
ssharon@mail.ustc.edu.cn
xiaoh@ustc.edu.cn

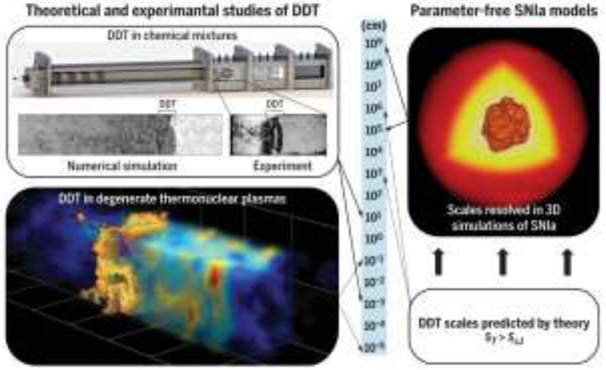
Shock-Flame Interactions and Instability

Shock Flame interactions (SFI)

- **Extend flame surface**
- **Compression**
- **Richtmyer-Meshkov (RM) Instability**
- **The most important process before flame acceleration and DDT**



Hypersonic airbreathing engine



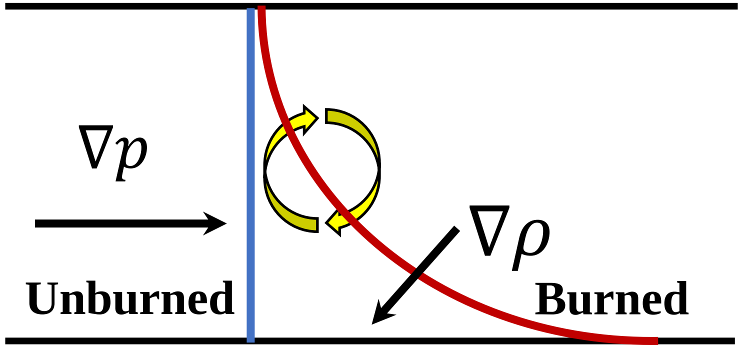
Supernova Explosions
Poludnenko et al., 2019, Science

Power Plant Hydrogen Explosion
Muskingum, Ohio, 2007

Hydrogen Refueling Station Explosion Norway, 2019

Motivation

Shock-flame interactions



- Single flame interacts with shock

  Flame instability (Richtmyer-Meshkov instability)

  Mechanism: Baroclinic torque

  Inert RMI model: Impulsive Model, Zhang & Sohn, Meyer and Blewett, Mikaelian…

  Reactive RMI model [Yang & Radulescu, 2021, JFM]
- Complicated shock-flame interactions

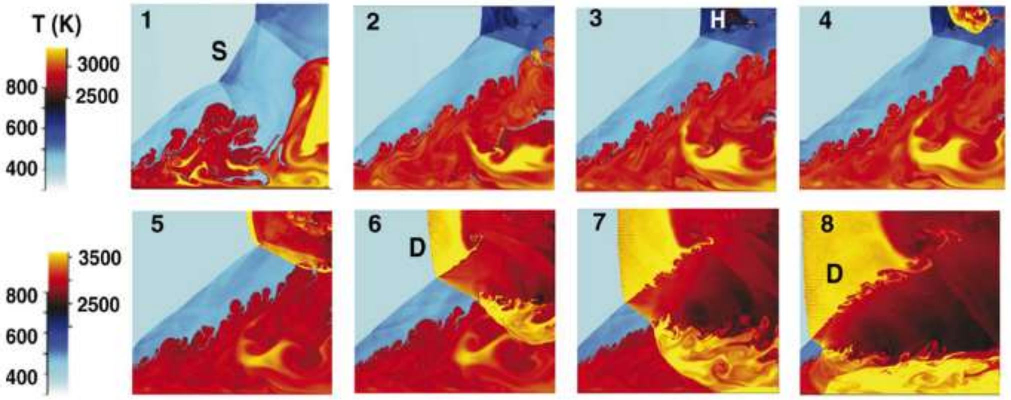
  Shock interacts with multi flames [Bakalis 2021]

  Shock interacts with bubble flame [Haehn 2023, CNF] [Diegelmann 2021, CNF] [Thomas 2007 CTM]

Motivation

Shock-flame interactions

- **Reflected shock, flame and boundary later interactions**
  Shock bifurcation, lambda shock and promotes DDT
  [Gamezo 2001 CNF] [Gamezo 2005 PCI] [Yhuel 2023 PCI]



What if shock-flame interactions occur with the existence of wall friction?

Methodology

Physical Model

- **Initially perturbated flame**

  Unburned region $x < (x_f + L_y) - \sqrt{L_y^2 - y^2}$

  Burned region $x > (x_f + L_y) - \sqrt{L_y^2 - y^2}$

  Flame front $x = (x_f + L_y) - \sqrt{L_y^2 - y^2}$

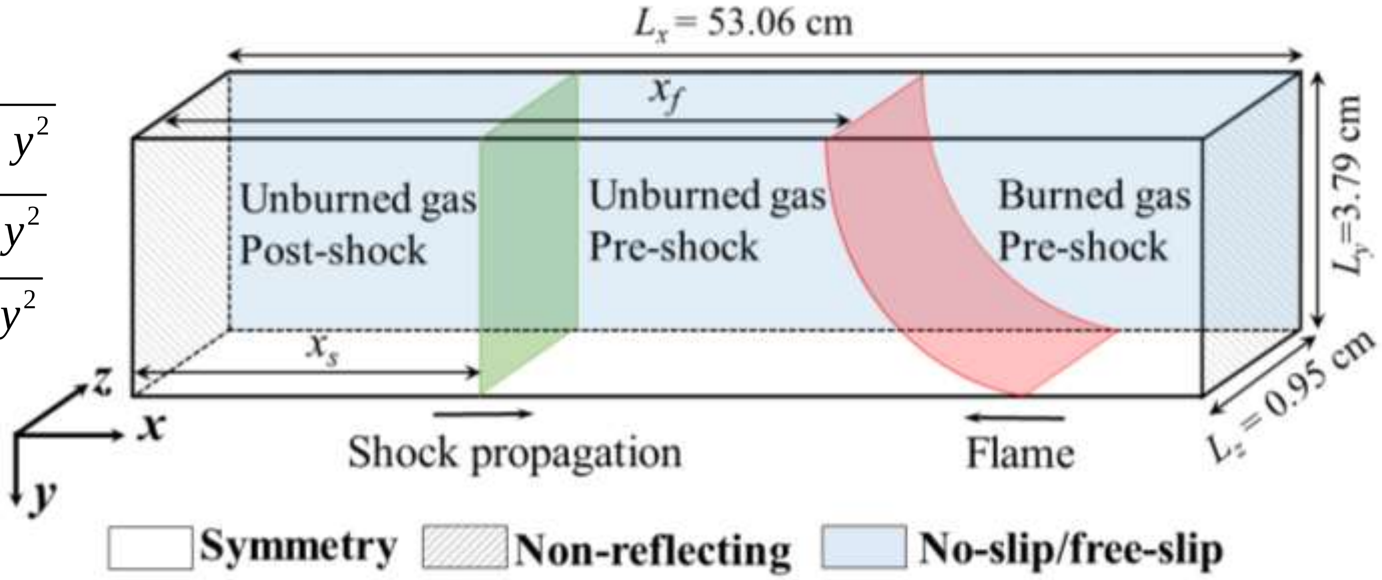
- **Shock wave**

  (Rankine-Hugoniot relations)

$$\frac{\rho_2}{\rho_1} = \left(1 + \frac{\gamma+1}{\gamma-1}\frac{p_2}{p_1}\right) / \left(\frac{\gamma+1}{\gamma-1} + \frac{p_2}{p_1}\right)$$

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}$$

……



Computational domain

Yang & Radulescu, 2021, JFM

Methodology

- **Governing Equations**
  - **Reactive, Navier-Stokes Equation**
  - **Ideal Gas Model**
  - **Chemical-Diffusive Model**
- **Numerical Method**
  - **5th WENO Scheme, HLLC fluxes**
  - **3rd Runge-Kutta**

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

$$\frac{\partial}{\partial t}(\rho Y)+\frac{\partial}{\partial x_i}(\rho Y u_i)=\frac{\partial}{\partial t}(\rho D\frac{\partial Y}{\partial x_i})+\rho\dot{\omega}$$

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial(\rho u_j E+p u_j)}{\partial x_j}=\frac{\partial}{\partial x_j}(K\frac{\partial T}{\partial x_j})+\frac{\partial(\tau_{ij}u_i)}{\partial x_j}-\rho q\dot{\omega}$$

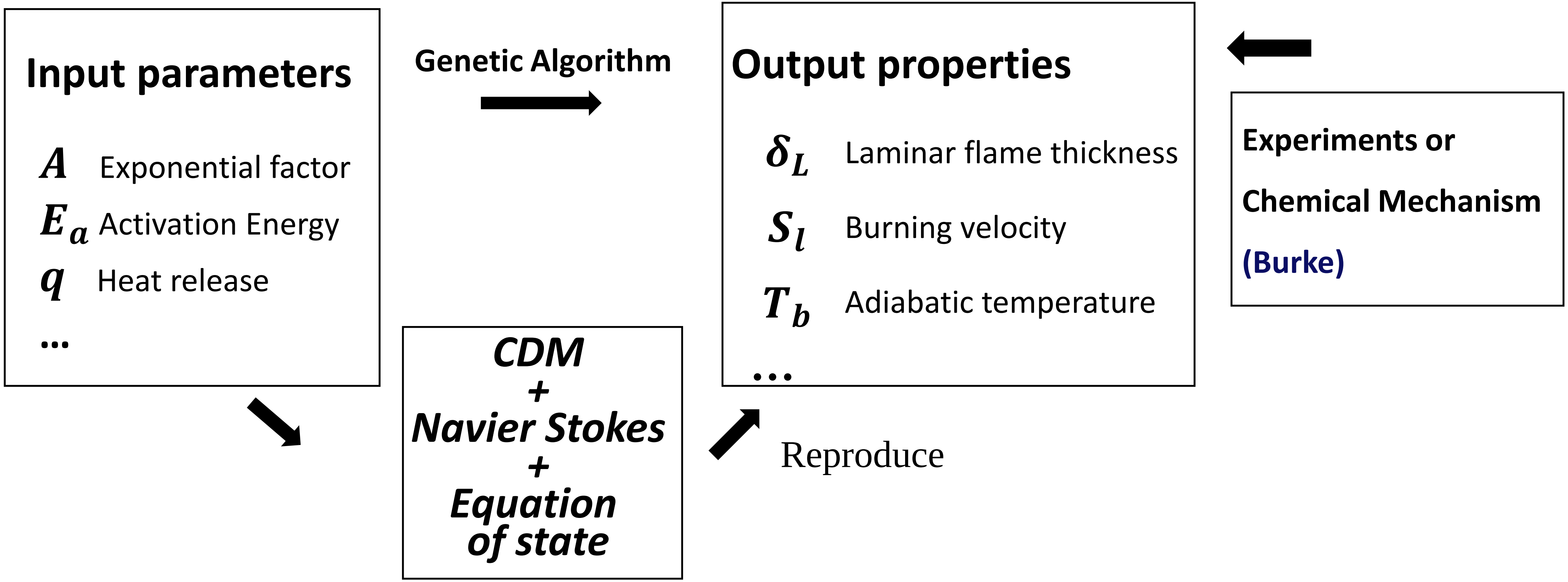
$$p=\rho RT/M$$

$$E=\frac{p}{\rho(\gamma-1)}+\frac{1}{2}u_i^2$$

$$\nu=\frac{\nu_0 T^{0.7}}{\rho},\ D=\frac{D_0 T^{0.7}}{\rho},\ \alpha=\frac{K}{\rho C_p}=\frac{\kappa_0 T^{0.7}}{\rho}$$

Methodology

Arrhenius equation : $\dot{\omega} = \frac{\mathrm{d}Y}{\mathrm{d}t} = A\rho Y \exp(-E_a/RT)$ **Y unburned mass fraction**



Input parameters

A Exponential factor

E_a Activation Energy

q Heat release

…

Genetic Algorithm

CDM
+
Navier Stokes
+
Equation of state

Output properties

δ_L Laminar flame thickness

S_l Burning velocity

T_b Adiabatic temperature

…

Reproduce

Experiments or
Chemical Mechanism
(Burke)

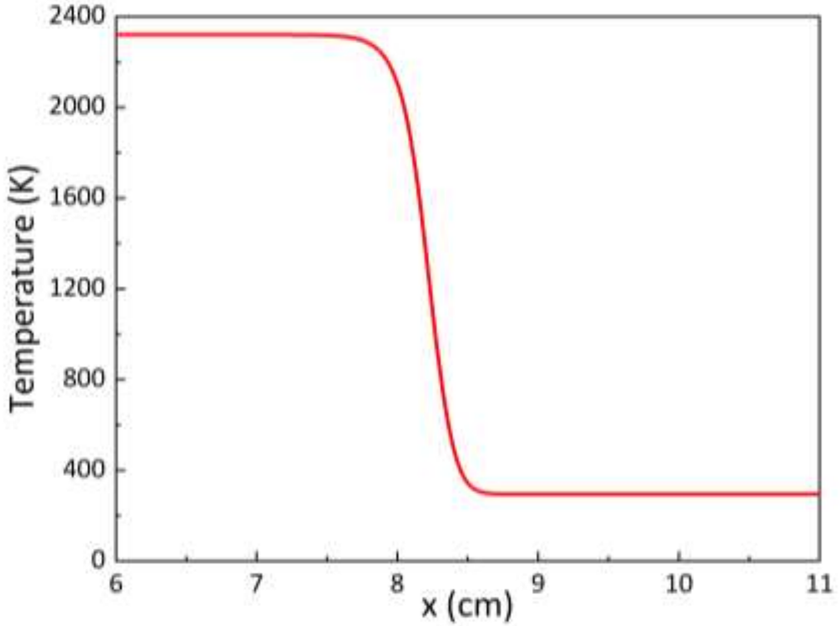
[1] BURKE M P, CHAOS M, JU Y, et al. Comprehensive H2/O2 kinetic model for high-pressure combustion [J]. Int J Chem Kinet, 2012, 44(7): 444-74.

[2] KAPLAN C R, ÖZGEN A, ORAN E S. Chemical-diffusive models for flame acceleration and transition-to-detonation: genetic algorithm and optimisation procedure [J]. Combustion Theory and Modelling, 2019, 23(1): 67-86.

Methodology

- **Mixture: φ = 1 H_2-Air, 17.24 kPa, 293K** **[Burke, Int J Chem Kinet, 2012]**
- **Input parameters**

γ	1.1648	Specific heat ratio
M	24.2	Molecular weight
A	1.332×10^8 m^3/kg-s	Pre-exponential factor
E_a	33.24 RT_0	Activation energy
q	48.70 RT_0/M	Heat release
κ_0	3.648×10^{-6} kg/s-m-K$^{0.7}$	Transport constants



One-dimensional steady flame

- **Output properties**

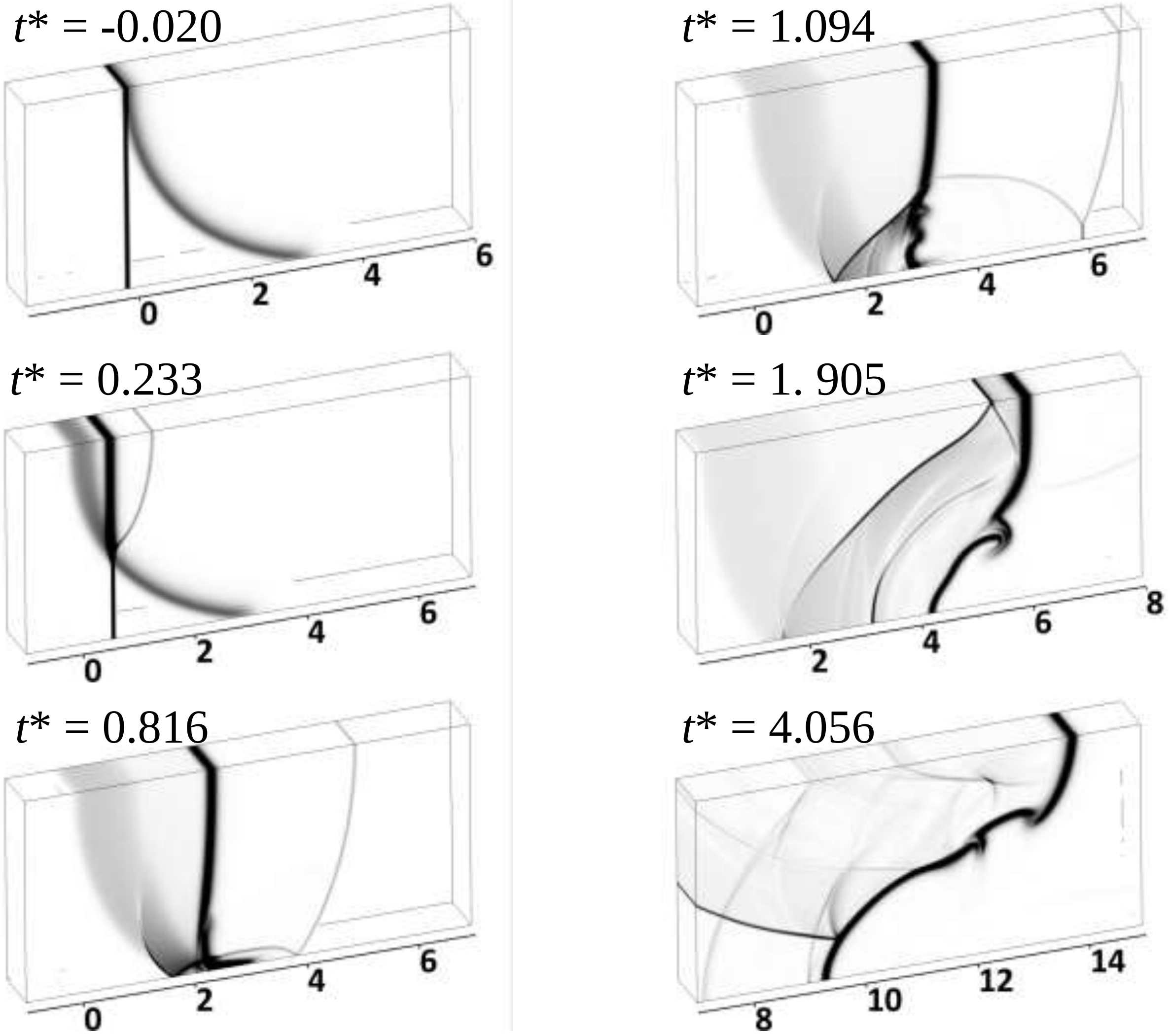
Laminar burning velocity	**1.98 m/s**
Adiabatic flame temperature	**2320 K**
Laminar flame thickness	**0.375 cm**

- ***Pr* = 0.1, *Le* = 1**

Shock-Flame Interaction and Flame Evolution

Free-slip case

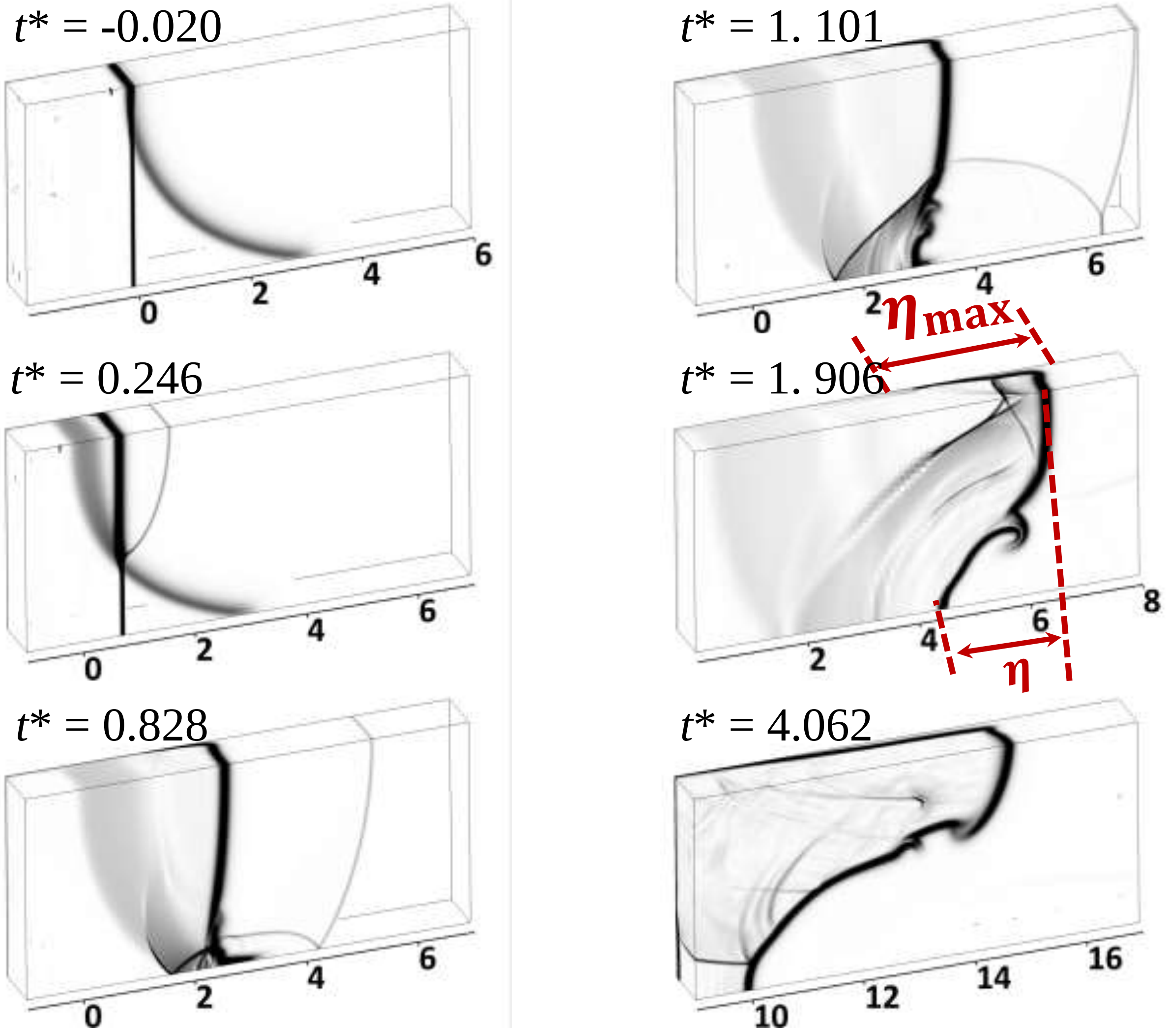
- 2D
- Long Neck



Shock-Flame Interaction and Flame Evolution

No-slip case

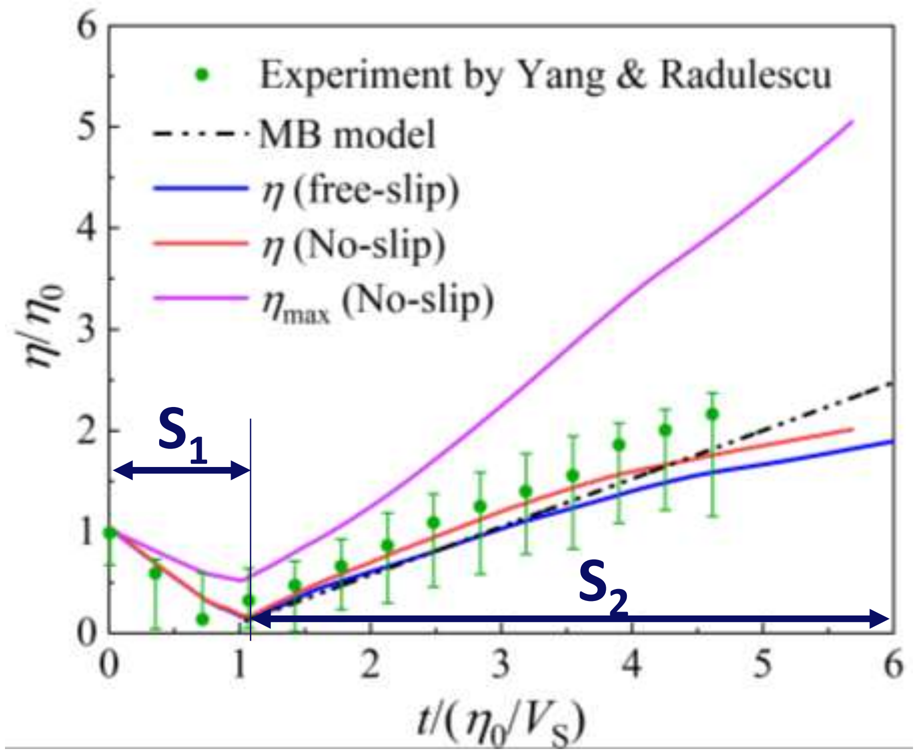
- **3D**
- **Wall friction breaks the 2D**
- **Flame stretch**



Flame Instability

Inert RMI model
Meyer & Blewett (MB) Model

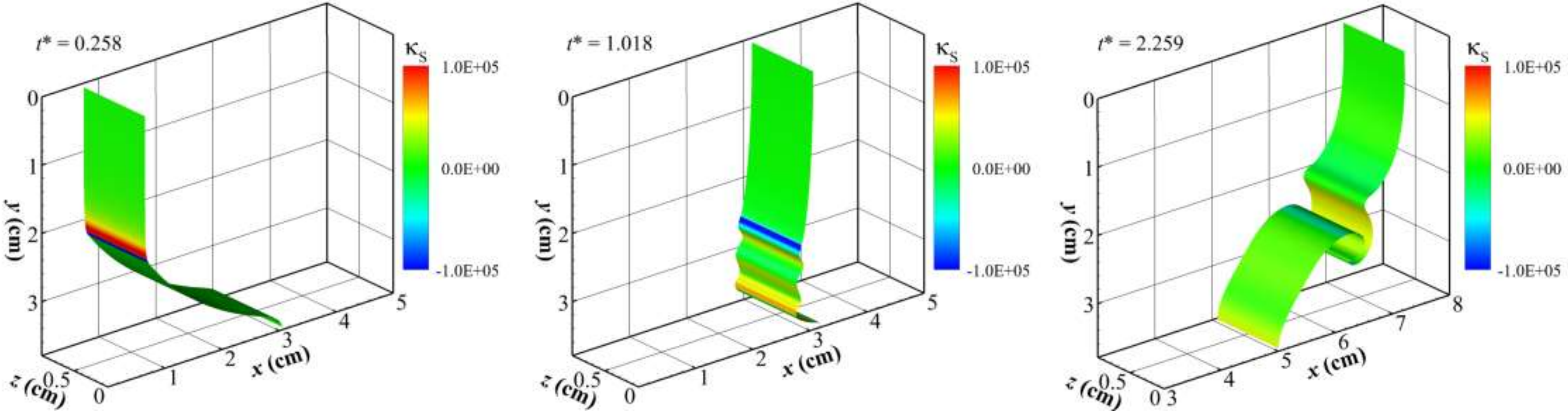
- **Good agreement with experiment [Yang & Radulescu, 2021,JFM]**
- **Two stages**
  S_1, Shock compression
  S_2, Perturbation growth stages
- **Wall friction promotes flame instability**



Flame instabilities as a function time

Flame stretch during SFI

Free-slip case

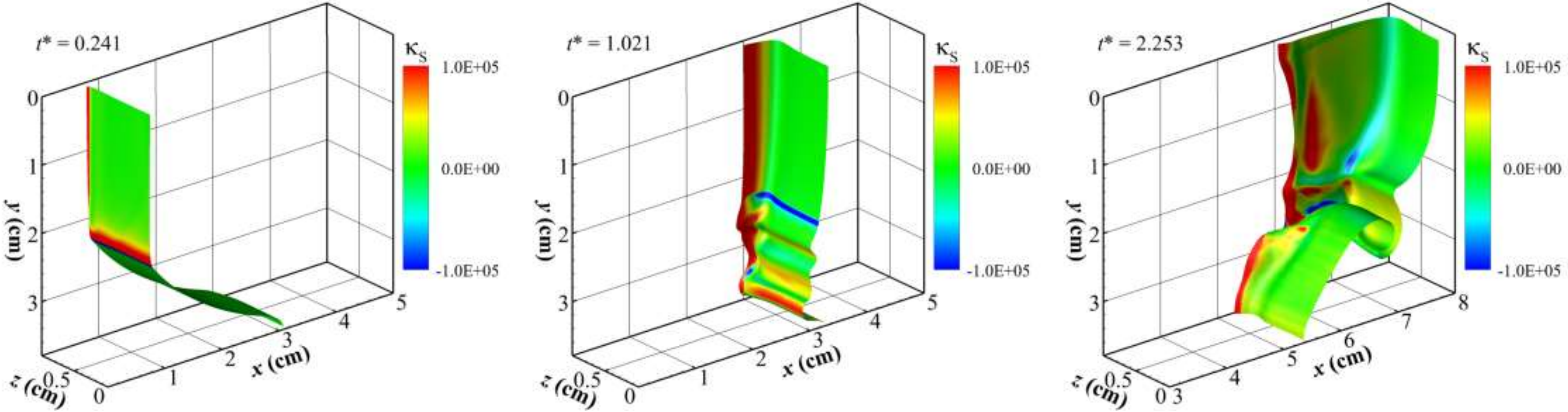


Flame stretch rate

Peak stretch rate appears at the intersection of shock and flame
No obvious stretch after shock passage

Flame Stretch during SFI

No-slip case



Flame stretch rate

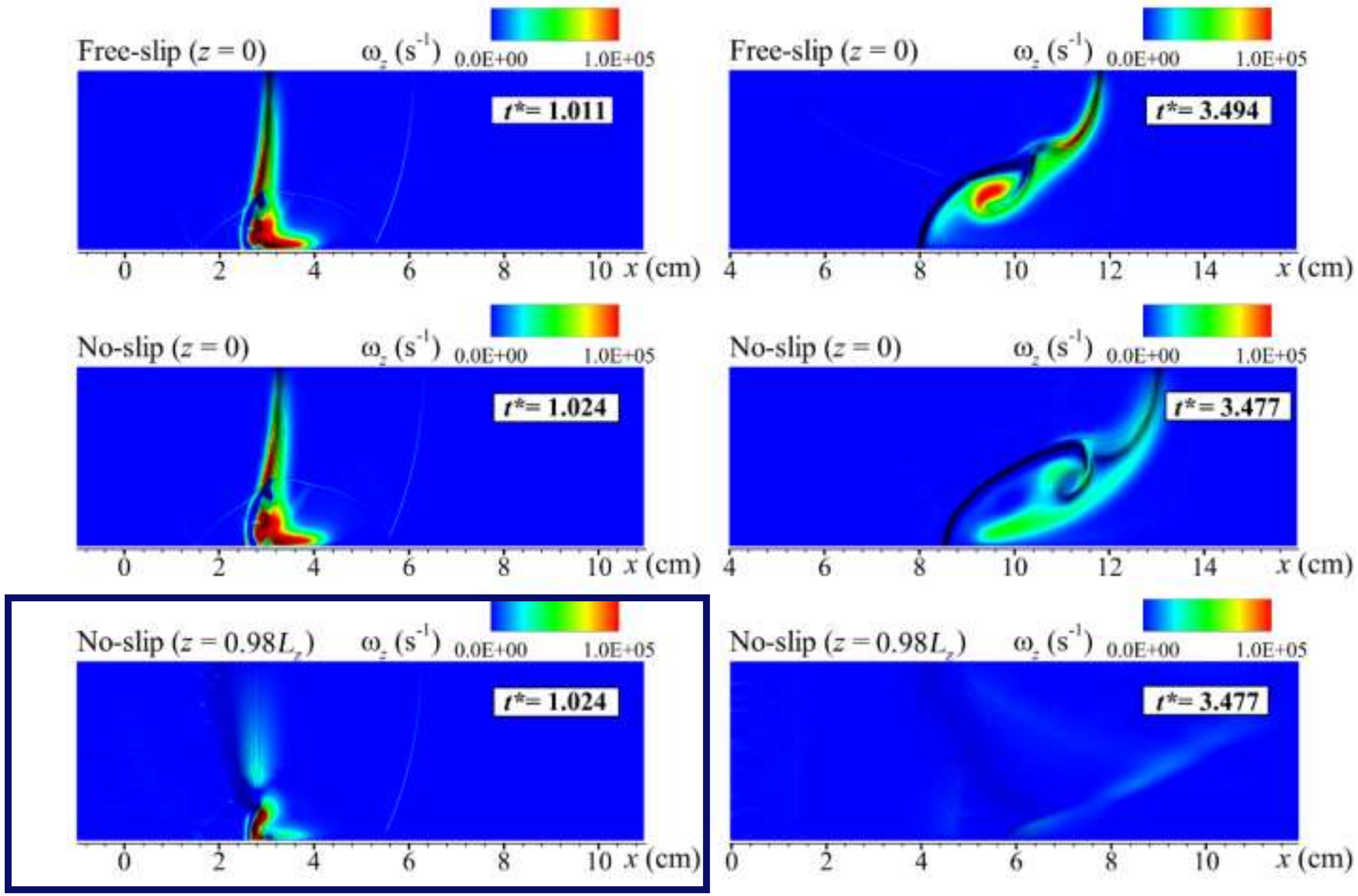
Heavy, and continuous stretch near the wall (10^5)

Thin boundary layer

Larger flame surface area

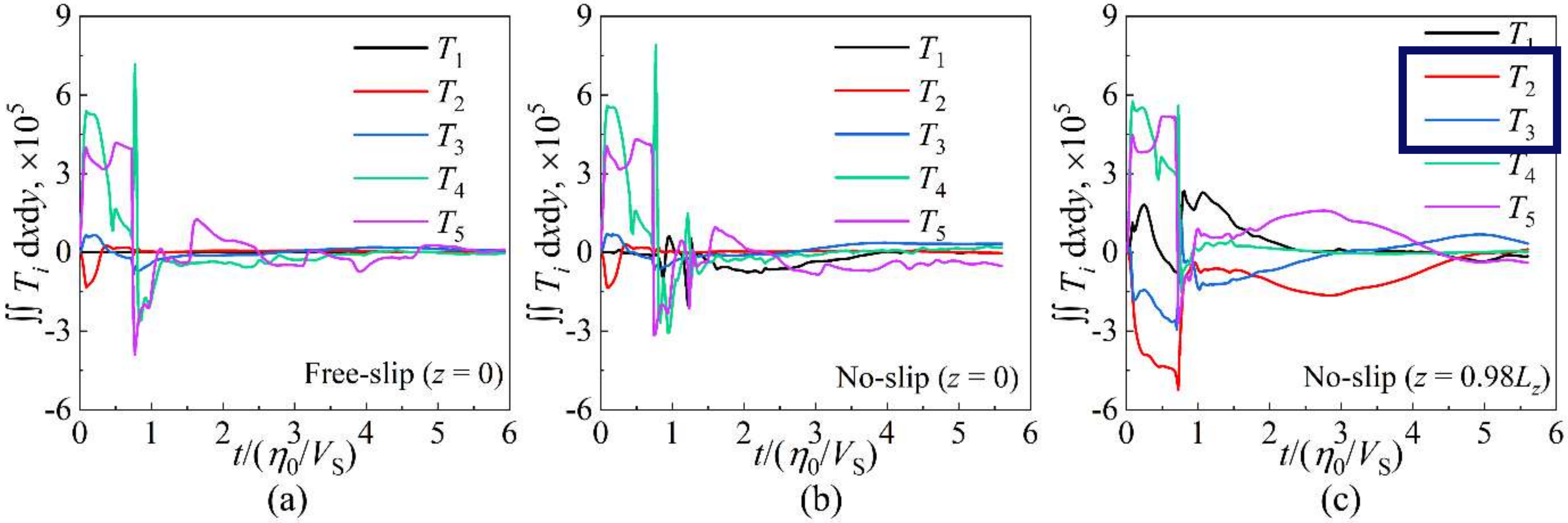
Vortex Dynamics

- **Less vorticity near the wall**
- **Damping of local flame perturbation near the wall**
- **Non-uniform perturbation evolution**



Vortex Dynamics

T_1 Vortex stretching
T_2 Viscous torque
T_3 Viscous dissipation
T_4 Dilation
T_5 Baroclinic torque



$$\frac{\partial \omega_i}{\partial t} + u_k \frac{\partial \omega_i}{\partial x_k} = \underbrace{\omega_k \frac{\partial u_i}{\partial x_k}}_{T_1} \underbrace{-\varepsilon_{ijk}\frac{1}{\rho}\frac{\partial\rho}{\partial x_j}\left(\frac{\partial\tau_{kl}}{\partial x_l}\right)}_{T_2} + \underbrace{\frac{\varepsilon_{ijk}}{\rho}\left(\frac{\partial^2\tau_{kl}}{\partial x_j\partial x_l}\right)}_{T_3} \underbrace{-\omega_i\frac{\partial u_k}{\partial x_k}}_{T_4} + \underbrace{\frac{1}{\rho^2}\varepsilon_{ijk}\frac{\partial\rho}{\partial x_j}\frac{\partial p}{\partial x_k}}_{T_5}$$

Conclusions

- Flame perturbation during shock-flame interaction can be divided into two stages, **shock compression** and **perturbation growth stages**.
- Wall friction has a significant influence on the shock-flame interaction and flame perturbation growth. Two effects of wall friction on flame-shock interaction:

  flame stretching

  damping of local flame perturbation near the no-slip wall
- **The wall friction promotes entire flame instability after SFI rather than weakening.**

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Thank you for listening!

Q&A

Québec

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