Supersonic multiphase reactive flow and shock-induced combustion

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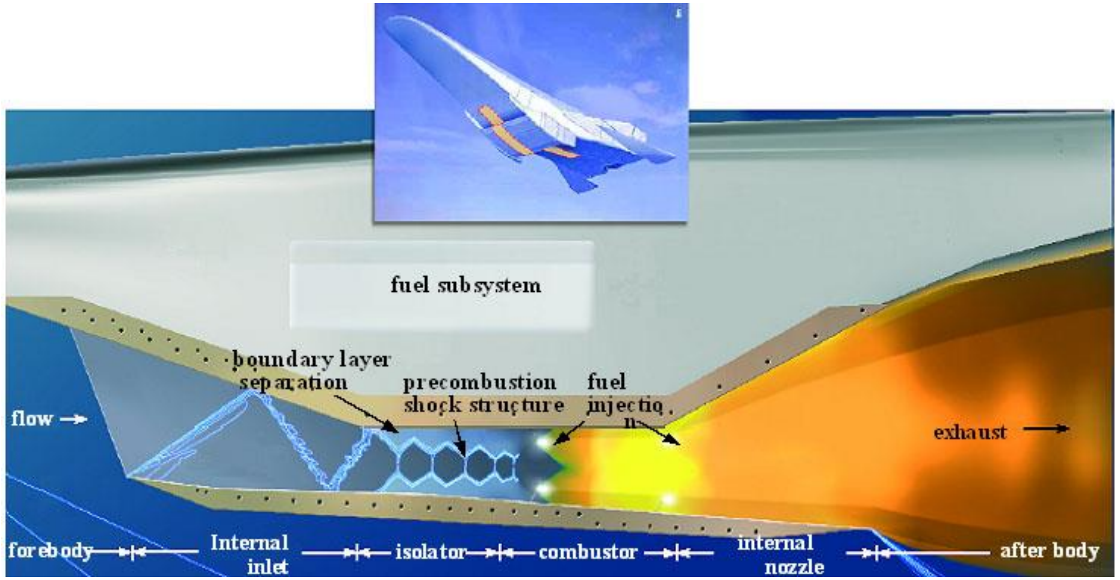
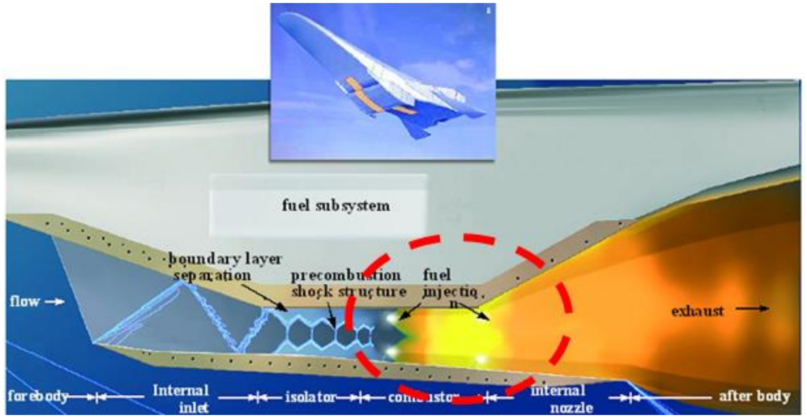
Supersonic multiphase reactive flow in SCRAMJET engine

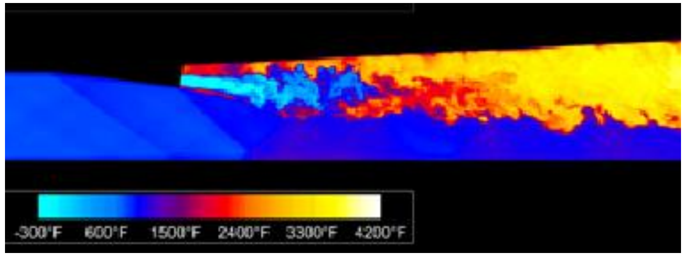


- The development of air-breathing hypersonic technology relies on understanding **supersonic multiphase reactive flow** in the scramjet engine combustor.
- The use of liquid hydrocarbon fuel is not only a need for engine cooling, but also a key measure to improve engine performance (density specific impulse).
- Studying the combustion characteristics of liquid spray in supersonic flow is of great significance to develop efficient scramjet engine technology and high-performance aircraft.

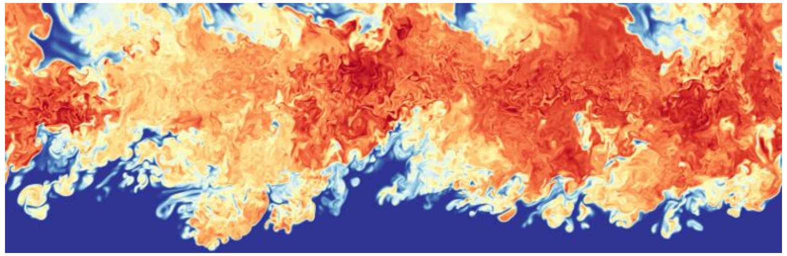
Research on Supersonic multiphase reactive flow



- Flows in scramjet combustor
  - High-speed
  - Compressibility



- Multi-scales of flame: stable combustion



- Multi-scales of turbulent eddies

- Multi-scales of spray

Couplings in multi-scales

Multi-scales of turbulent vortices, Multi-scales of spray droplets, Multi-scales of flames

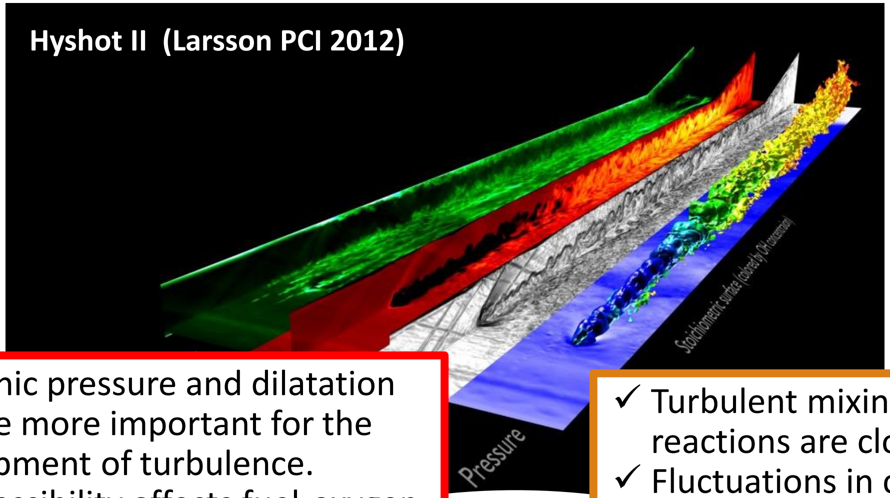
→ Multi-scale couplings between different phases

Couplings of multiple physical processes

Couplings of turbulent flow, heat and mass transfers, and chemical reactions

→ Coupling effects and mechanisms of multiple physical processes within/between multi-phases

A brief review of Supersonic multiphase reactive flow (SMRF)



Hyshot II (Larsson PCI 2012)

- ✓ Baroclinic pressure and dilatation become more important for the development of turbulence.
- ✓ Compressibility affects fuel-oxygen mixing.

- ✓ Turbulent mixing and chemical reactions are closely coupled.
- ✓ Fluctuations in chemical components are affected by strong velocity and pressure fluctuations.

Compressible turbulence

Mixing

- ✓ Chemical reaction rates are affected by flow compressibility.

Chemical reaction

Shock wave

- ✓ Turbulence-shock-combustion interaction.

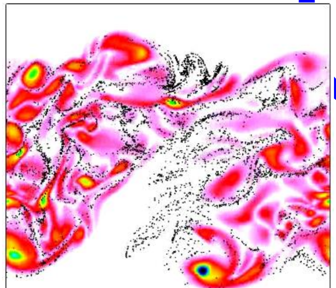
- ☐ **Turbulence development and mixing characteristics in supersonic flows.**
- ☐ **Ignition and combustion characteristics of gas and liquid fuels in supersonic flows.**
- ☐ **Interaction mechanisms of shock-turbulence-reaction.**

☐ **Characteristics of SMRF**

- ➢ **Flow compressibility**
- ➢ **Strong couplings**
- ➢ **Combustion instability**
- ➢ **Turbulence-shock-combustion interaction**

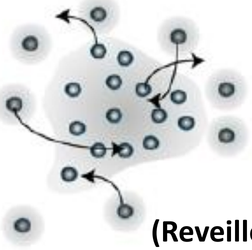
Role of vortex in Supersonic multiphase reactive flow

Dispersion of fuel droplets



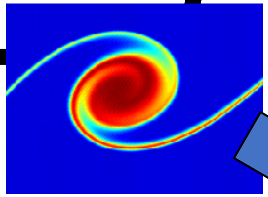
(Pitch 2009)

Evaporation and mixing

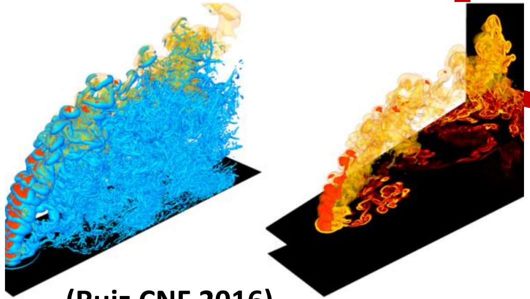


(Reveillon JFM 2007)

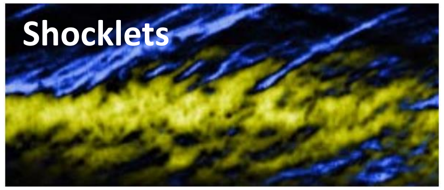
Vortex



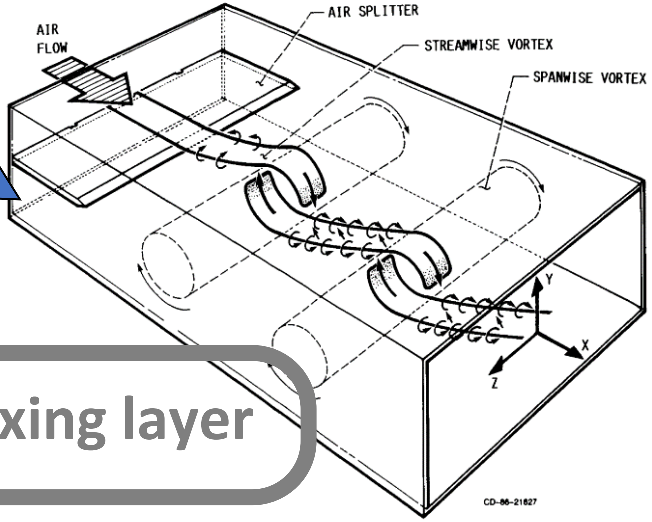
Ignition and combustion



(Ruiz CNF 2016)



(Rossmann JT 2002)



Mixing layer

Approach: high-fidelity CFD

- In-house compressible/multiphase/reactive flow solver.
- Numerical schemes and models:

✓ Sixth-order hybrid scheme (WENO-CU6, WENO-IS, TENO) for the convective fluxes.

✓ Sixth-order compact scheme for the viscous fluxes.

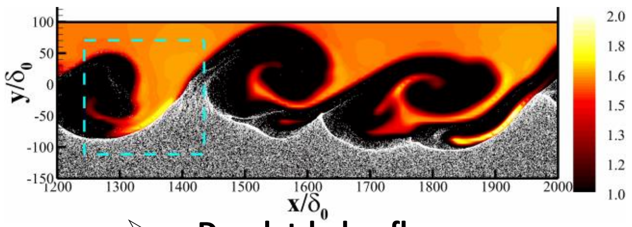
✓ Third-order Runge-Kutta scheme for the time integrations.

✓ Transportation properties based on kinetic gas theory.

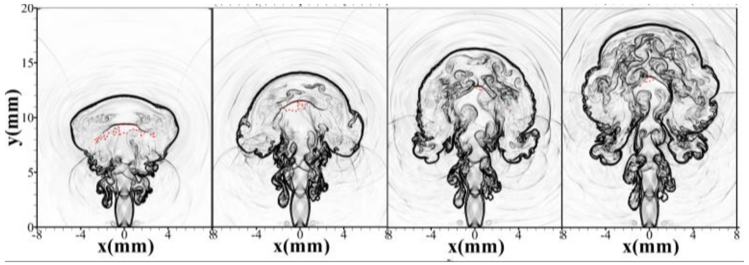
✓ Droplet/particle dynamics: Unsteady force model.

✓ Inter-phase interaction: mass-weighted coupling method.

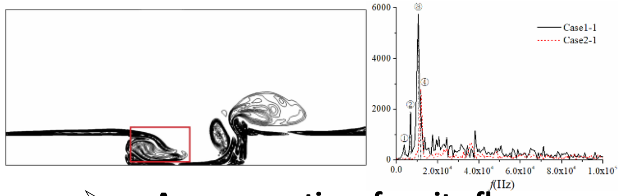
✓ Chemical reaction: detailed/simplified mechanisms.



➢ Droplet-laden flow



➢ H2 jet flow.

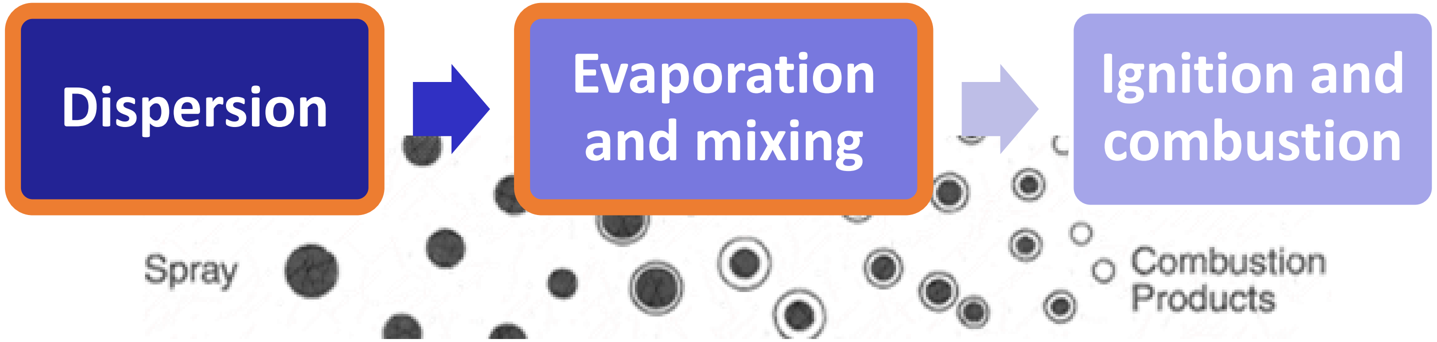


➢ Aero-acoustics of cavity flow

Results

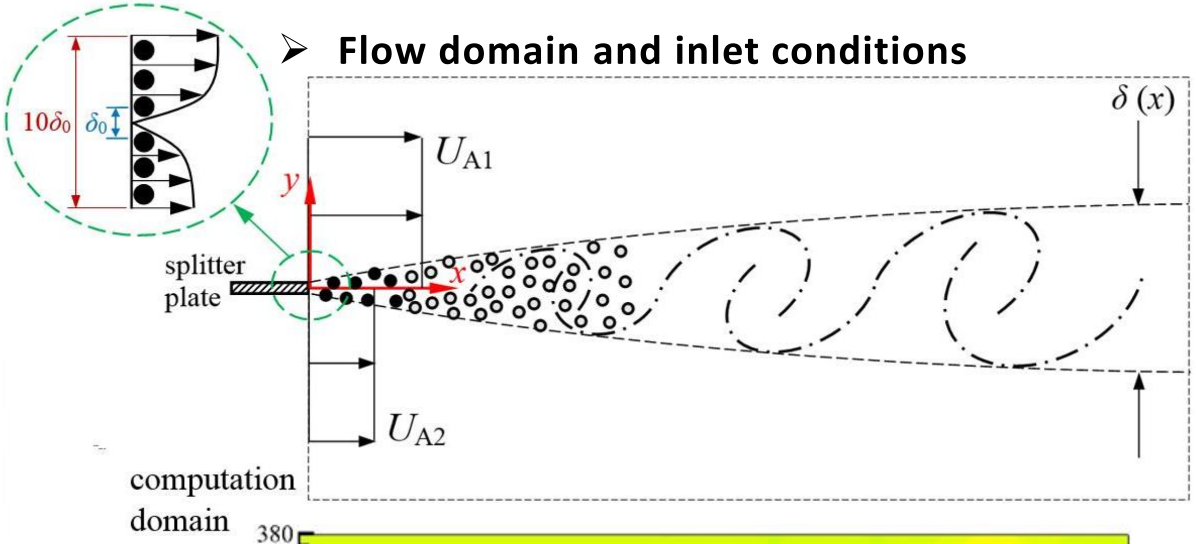
Dispersion → Evaporation and mixing → Ignition and combustion

Results


Dispersion
Evaporation and mixing
Ignition and combustion
Spray
Combustion Products

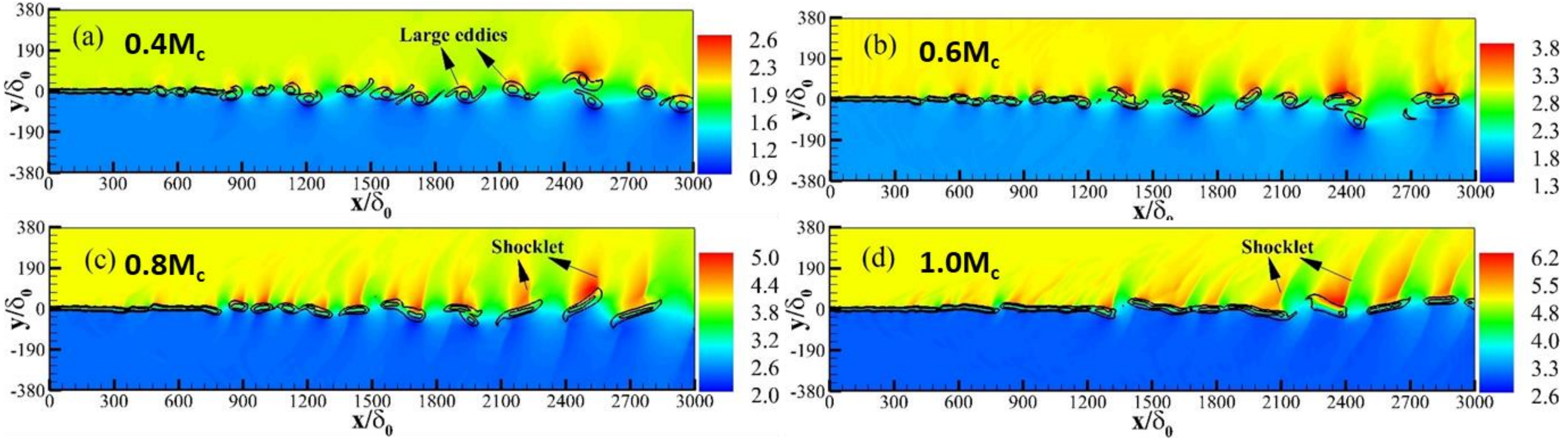
Effects of flow compressibility on fuel dispersion, evaporation and mixing

- **Flow domain and inlet conditions**



Inlet airflow static temperature T_0=700K, static pressure P_0=0.1MPa

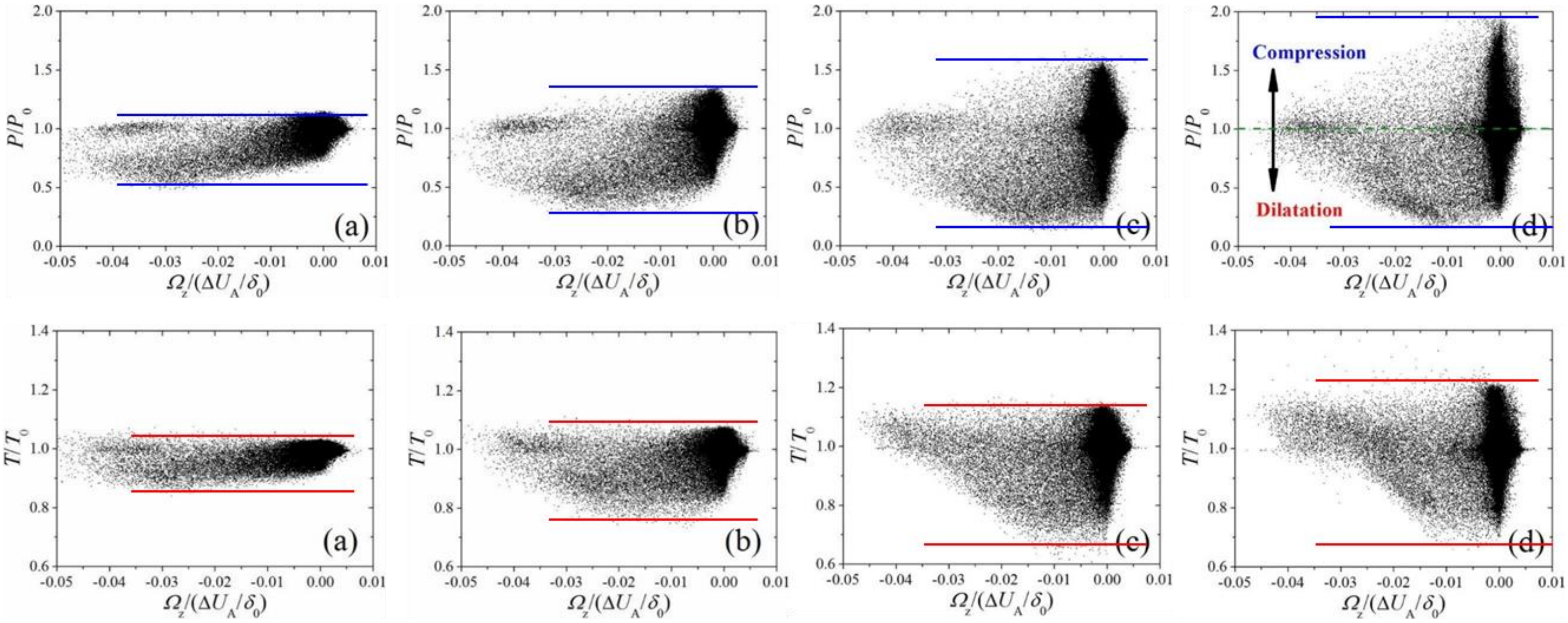
Case	Mach number M_{A1}, M_{A2}	Convective Mach number M_c
0.4M$_c$	2.0, 1.2	**0.4**
0.6M$_c$	3.0, 1.8	**0.6**
0.8M$_c$	4.0, 2,4	**0.8**
1.0M$_c$	5.0, 3.0	**1.0**



- **Without droplet laden,** spanwise vortices (($\Omega_z/(\Delta U_A/\delta_0)$=[-0.02, -0.005], black solid lines) and Mach number M_A(contours).

Ren Z, Wang B, Zhang F. International Journal of Aerospace Engineering, 2020.
Ren Z, Wang B, Zhang F, Zheng L. AIP Advances, 2019, 9(12): 125101.

Effects of flow compressibility on fuel dispersion, evaporation and mixing



- Case $0.4M_c$
- Case $0.6M_c$
- Case $0.8M_c$
- Case $1.0M_c$

- **Without droplet laden, scatters of pressure P/P_0 (upper row), and temperature T/T_0 (lower row) in spanwise vortices $((\Omega_z/(\Delta U_A/\delta_0))$ coordinates.**

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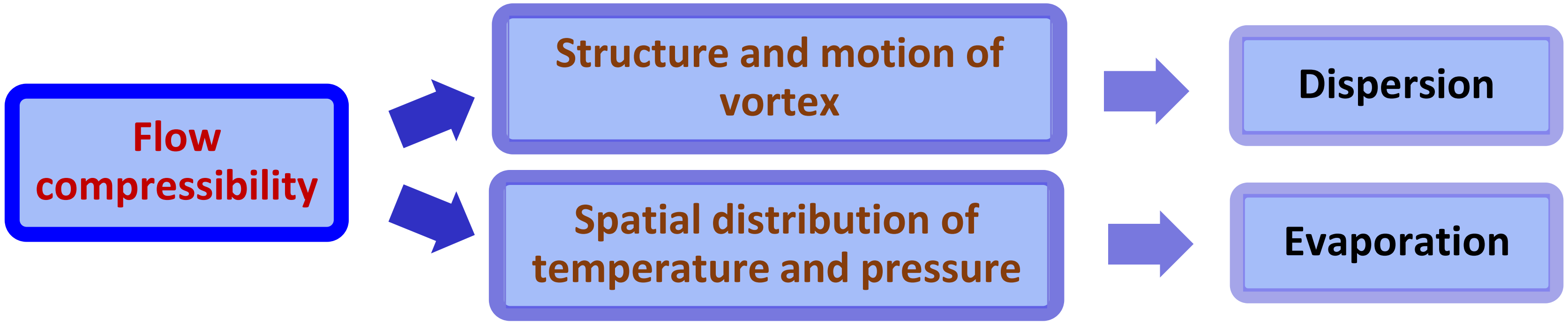

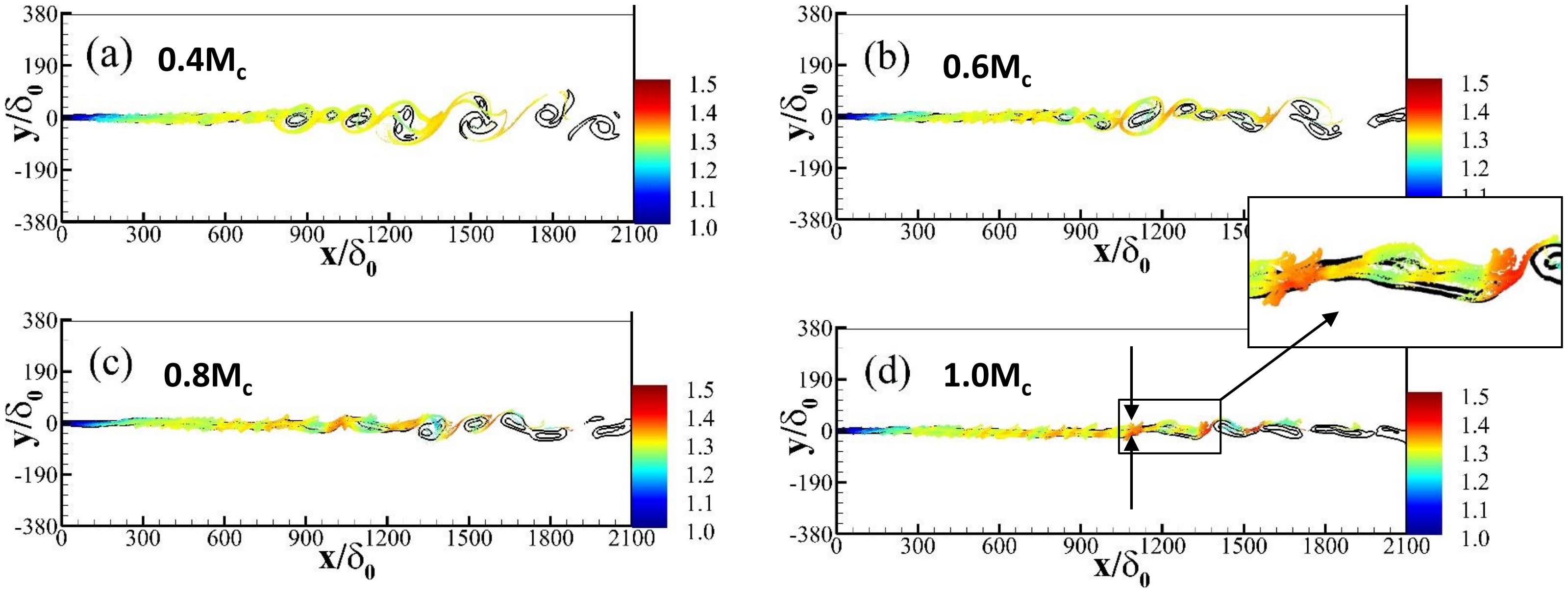

■ **Distribution of dispersing droplets (colours refer to droplet temperature $T_d/T_{d,0}$) in mixing layers.**

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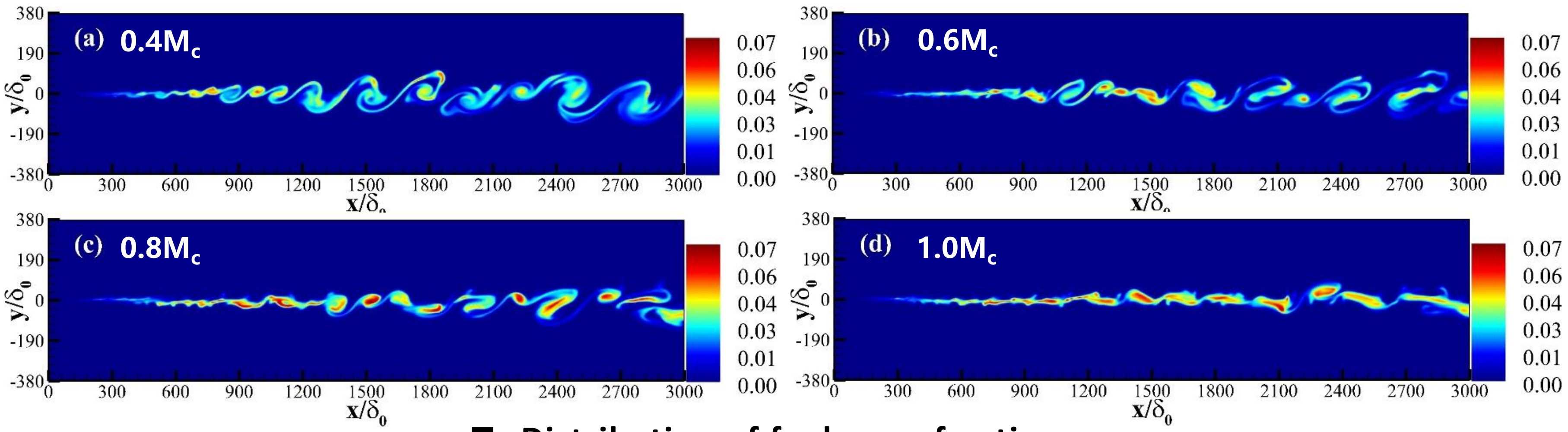
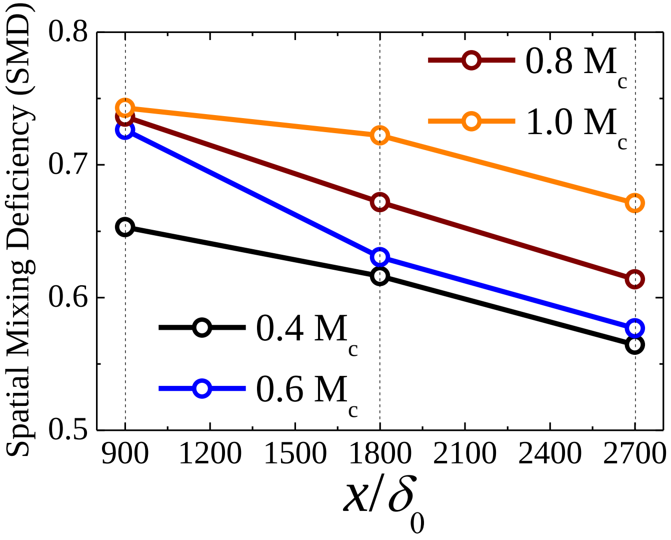


■ Distribution of fuel mass fraction.

- **Index to value the mixing level**
  (Spatial Mixing Deficiency, SMD)

$$SMD = \frac{RMS_{plane}\left(\overline{Y}_i\right)}{Avg_{plane}\left(\overline{Y}_i\right)}$$

(Poinsot FTC 2004)



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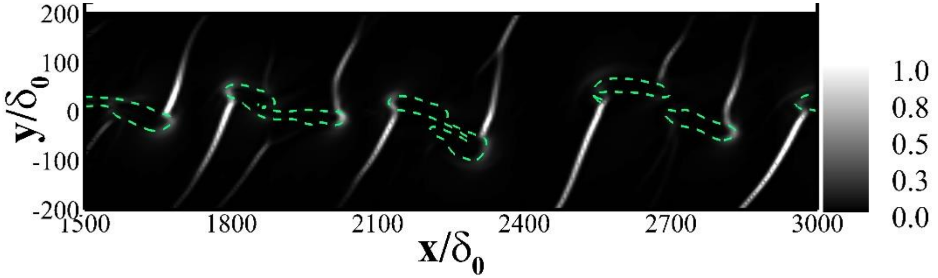
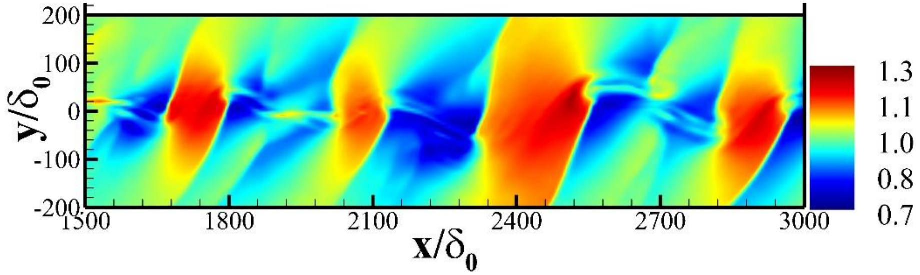
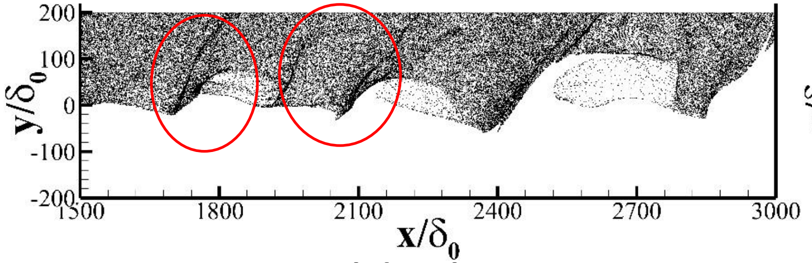
Fuel spray in highly compressible flow (M_c=1.0)



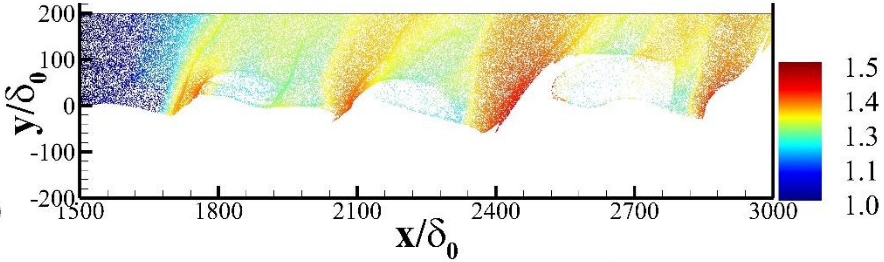
■ Numerical schlieren (green lines scale the vortex).



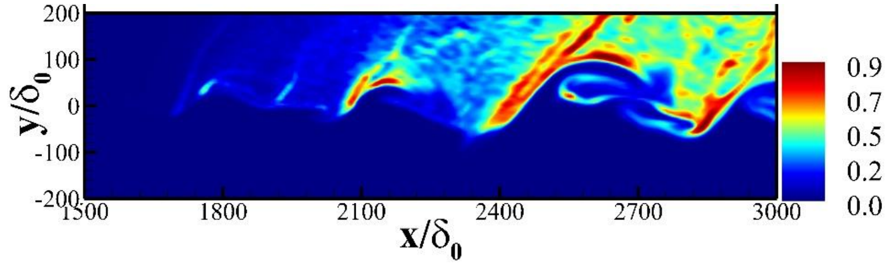
■ Temperature, T/T_0.



■ Fuel droplet.



■ Droplets' temperature, T_d/T_{d0}.



■ Fuel mass fraction, $Y_F/Y_{F,max}$.

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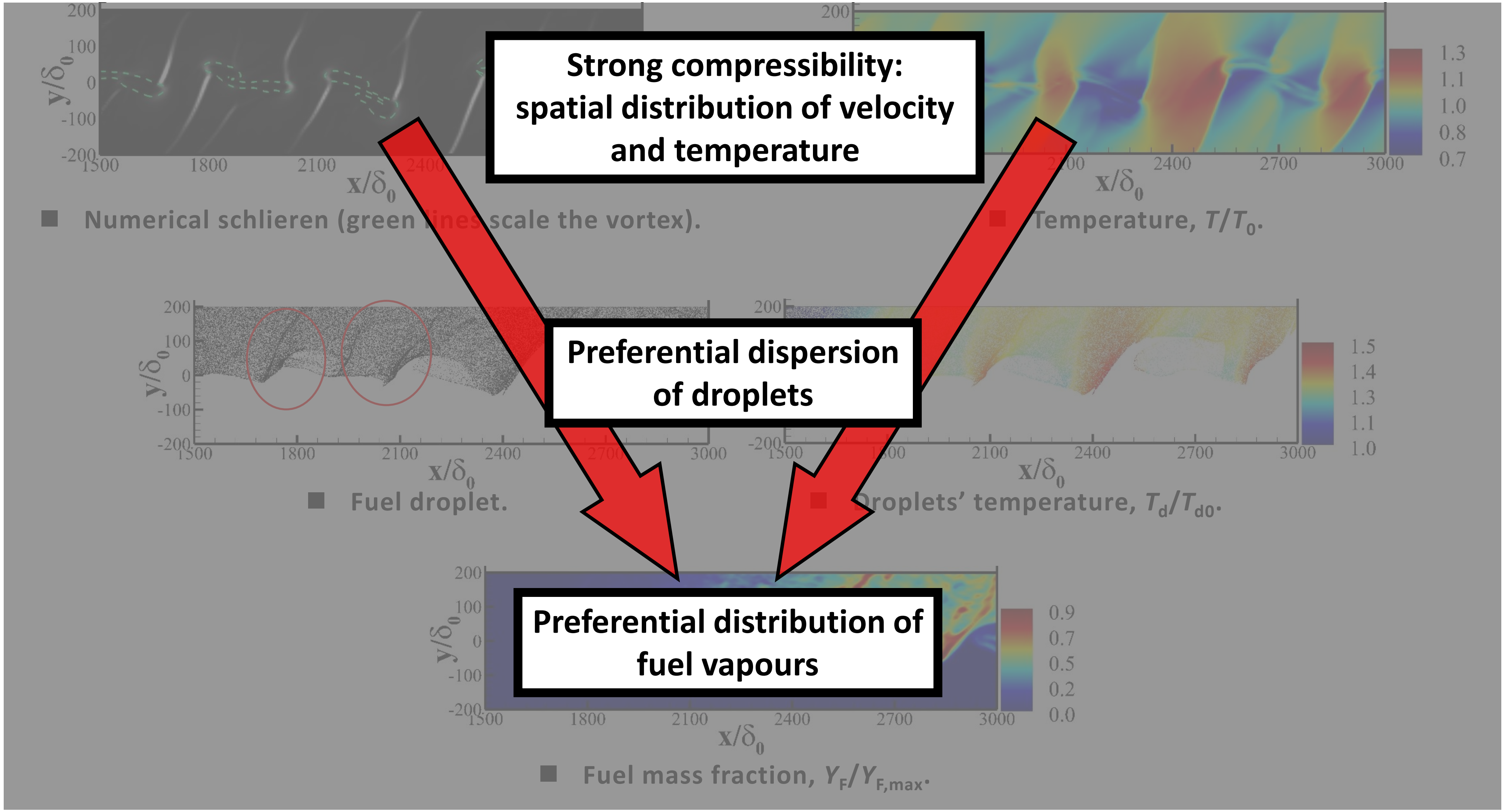
Fuel spray in highly compressible flow (M_c=1.0)



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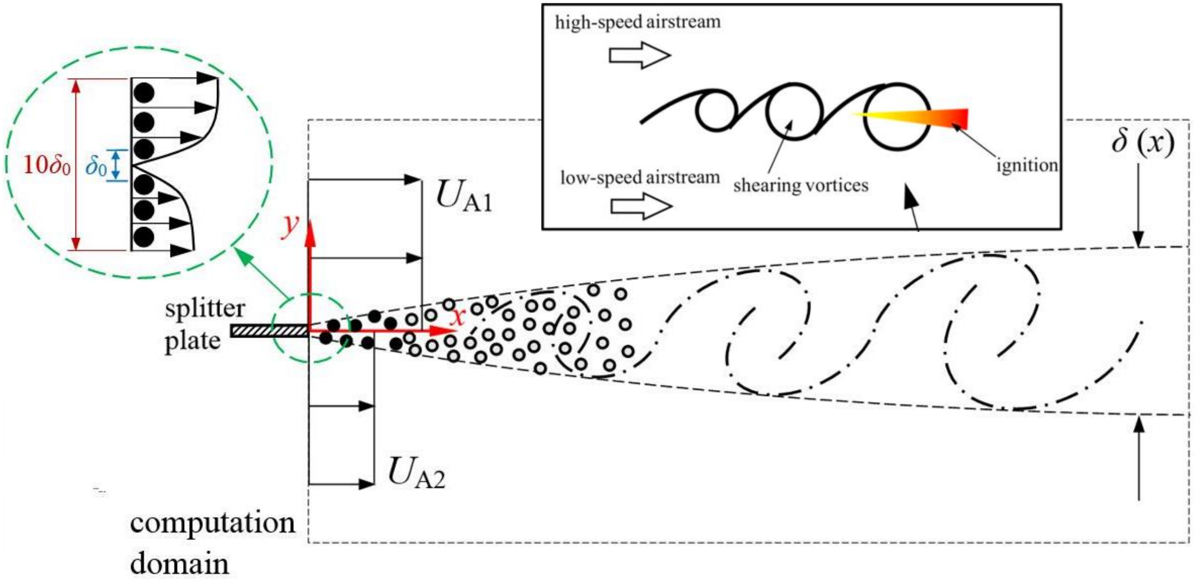
Results

Dispersion → Evaporation and mixing → Ignition and combustion

Premixed spray flame



➢ **Inlet parameter**

Temperature, T_A = 1500 K T_d = 298 K

Mach number, M_{A1} = 3.2 M_{A1} = 1.6

Convective Mach number $M_c = \frac{U_{A1} - U_{A2}}{a_{A1} + a_{A2}} = 0.8$

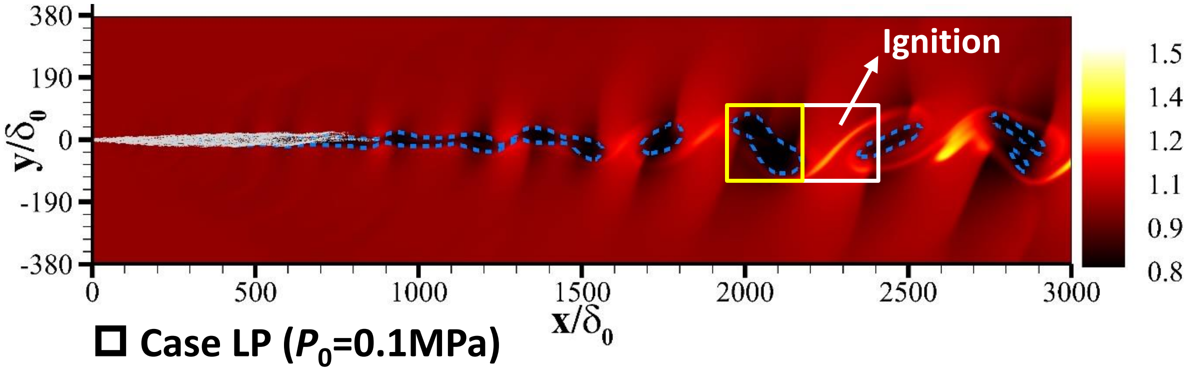
Case	LP	MP	HP	MP-HD	MP-LOW	MP-HIGH
Ambient pressure P_0 (MPa)	0.1	0.3	0.5	0.3	0.3	0.3
Reynolds number, Re	1020	3060	5100	3060	3060	3060
Stokes number, St_0	40	40	40	120	40	40
Equivalence ratio, Φ_0	1.2	1.2	1.2	1.2	0.6	2.4

➢ Effects of ambient pressure (P_0)

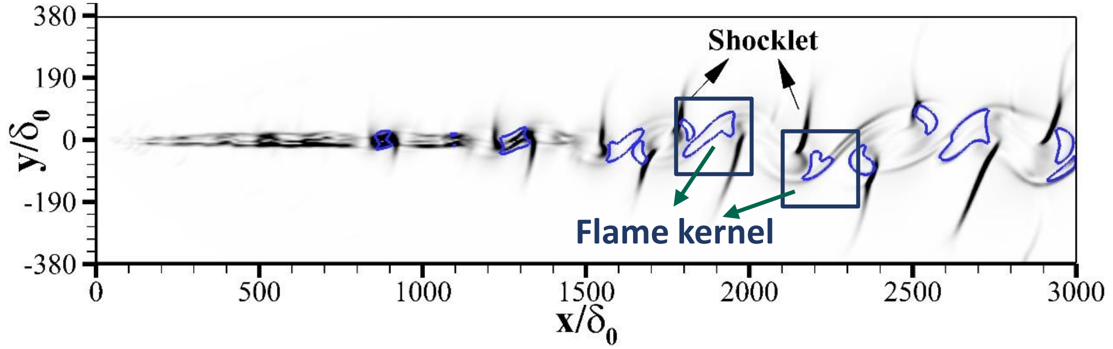
➢ Effects of droplet size (St_0)

➢ Effects of equivalence ratio (Φ_0)

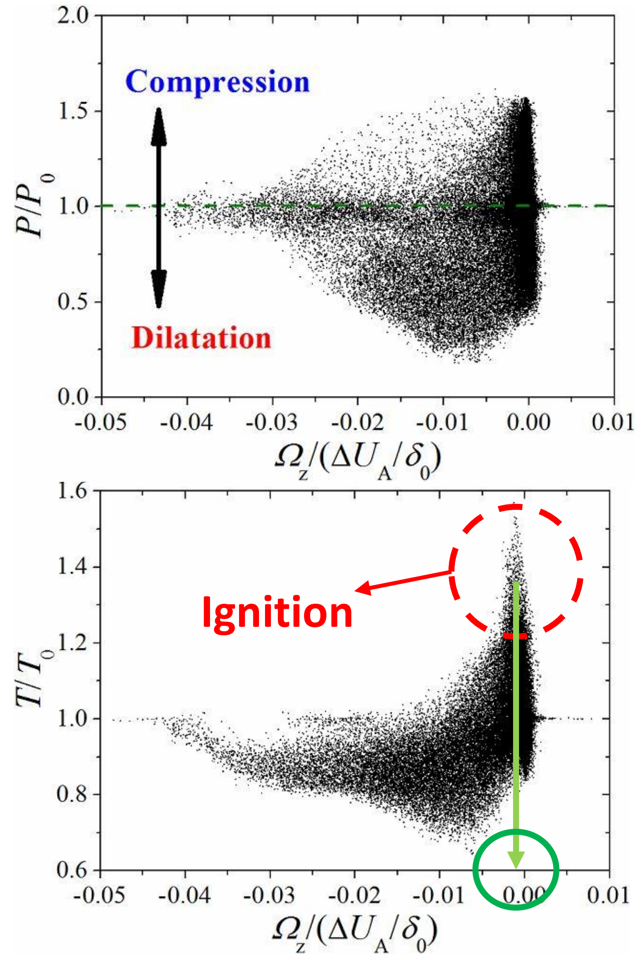
Premixed spray flame: compressibility and ignition



- ☐ Case LP (P_0=0.1MPa)
  - ■ Temperature T/T_0 contours and fuel mass fraction Y_F (blue dashed lineY_F=0.05)



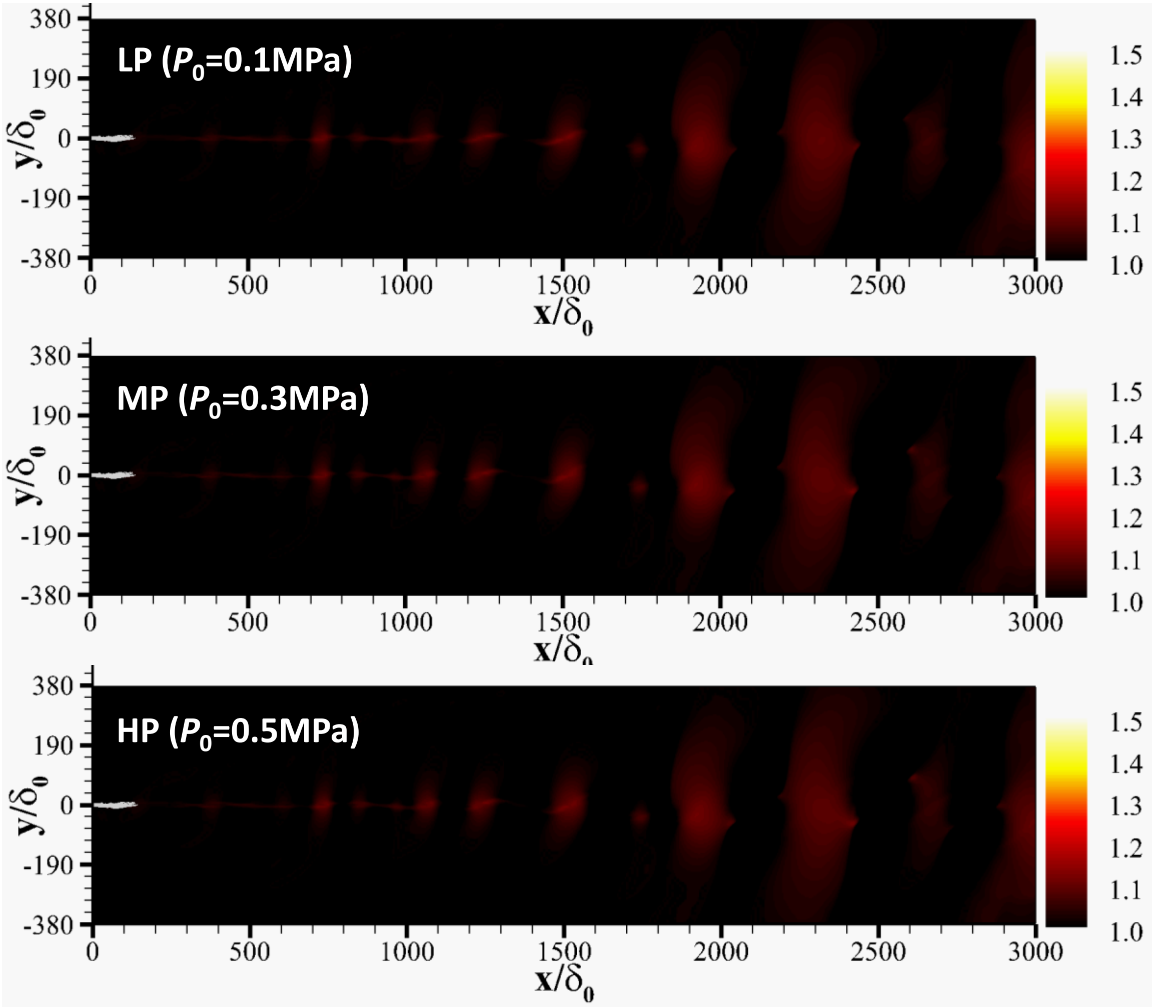
- ☐ Case LP (P_0=0.1MPa)
  - ■ Numerical schlieren and reaction rates (blue reaction rate R_F=100 (kgm^{-3}s^{-1})

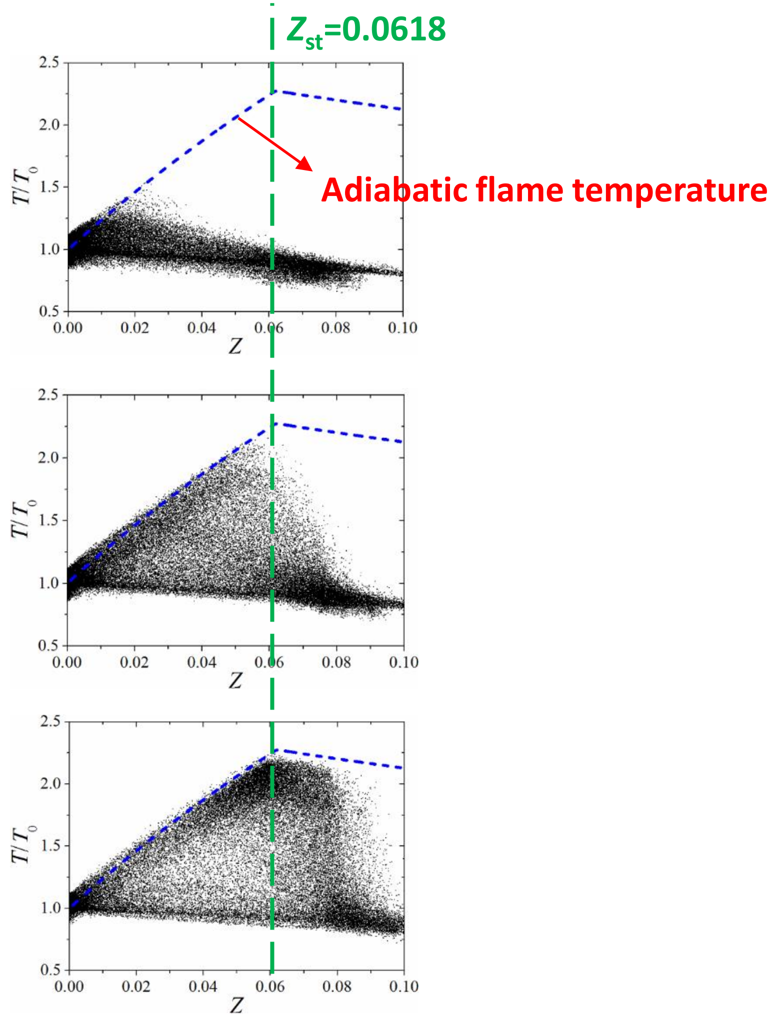


☐ Scatter plots of pressure (up) and temperature (down) in spanwise vorticities coordinates.

Ren Z, Wang B, Zhao D, Zheng L. Physics of Fluids, 2018, 30(10): 106107.
Ren Z, Wang B, Zheng L, Zhao D. Chinese Journal of Aeronautics, 2018, 31(9): 1870-1879.

Premixed spray flame: effects of ambient pressure





- Temperature T/T_0 contours and fuel mass fraction (blue dashed line for Y_F=0.05)
- Grey dots are fuel droplets.
- Scatters plots of T/T_0 in mixture fraction Z.

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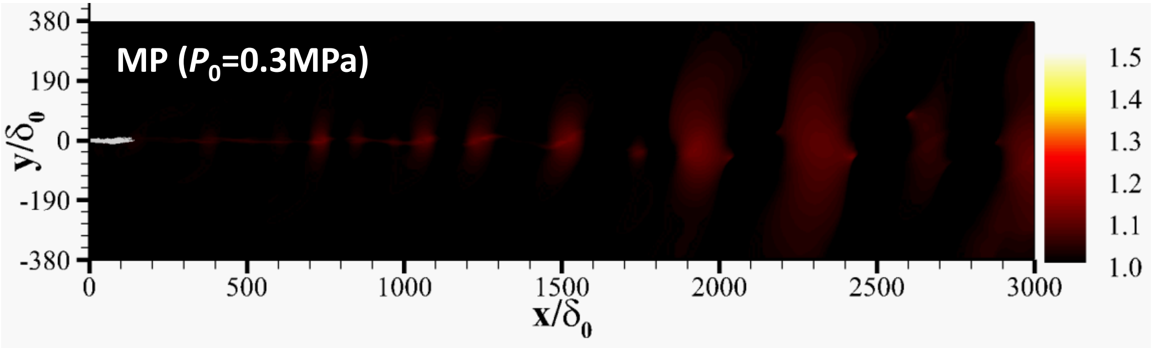
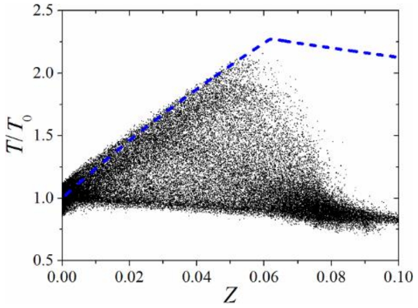


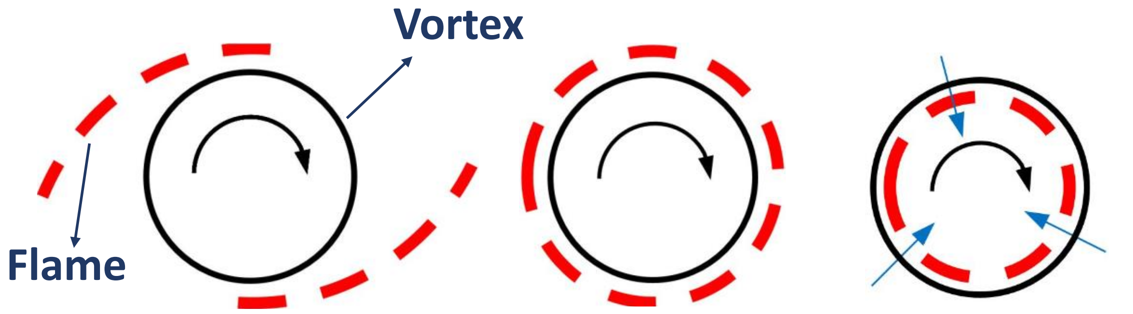


■Schematic diagram of the evolution process of the flame kernel：

(a) Ignition occurs in vortex braid

(b) As the vortex rotates, the flame spreads and wraps around the vortex

(c) The fuel is consumed from the outer edge of the vortex to the core, forming a vortex core flame



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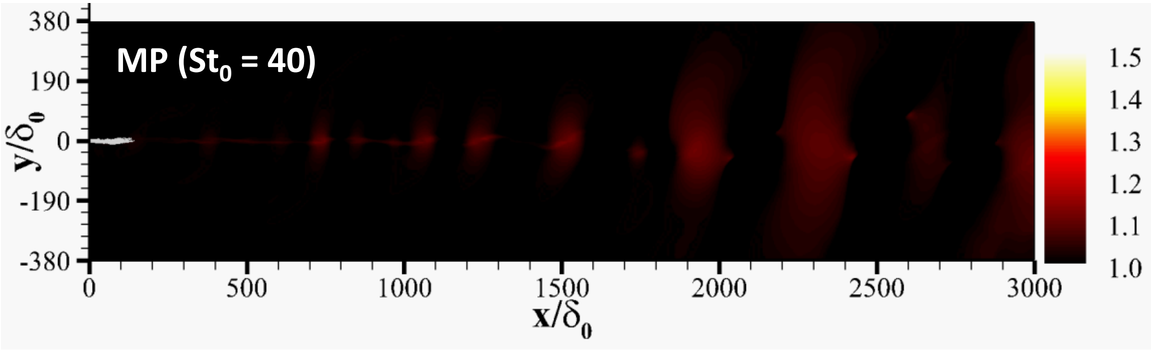
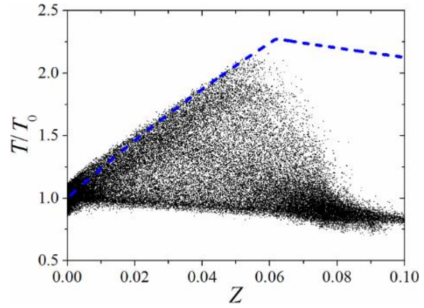
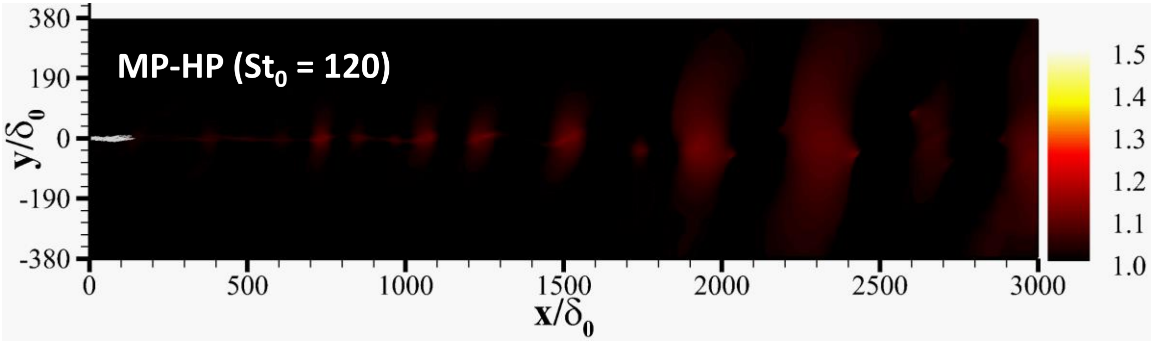
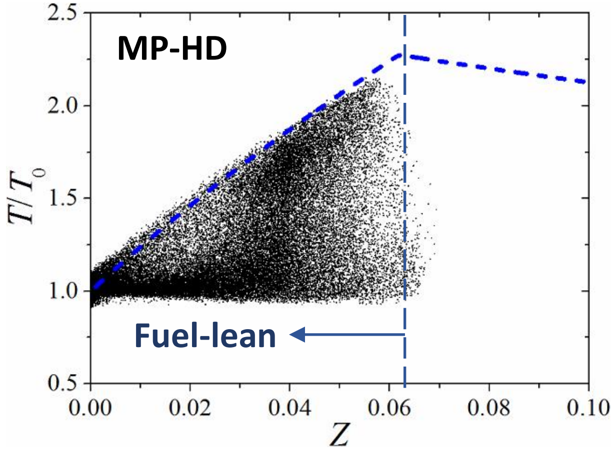
Premixed spray flame: effects of droplet size









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- Grey dots are fuel droplets.

- Scatters plots of T/T_0 in mixture fraction Z.

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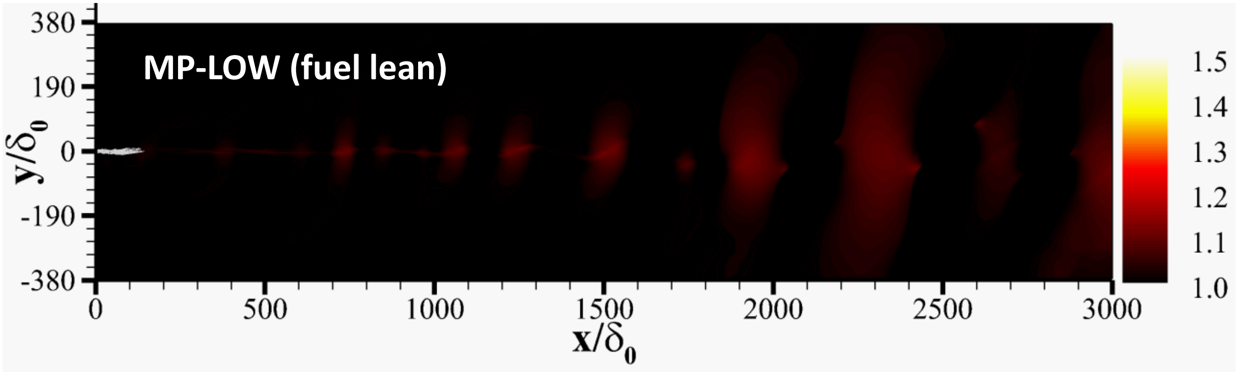
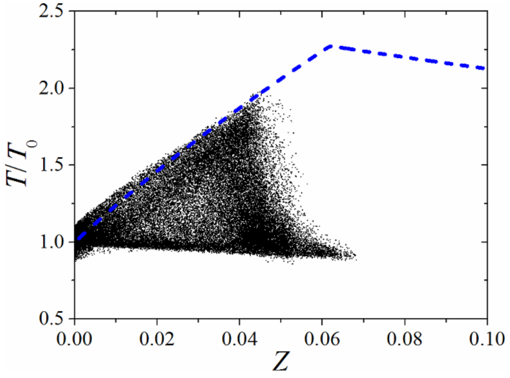
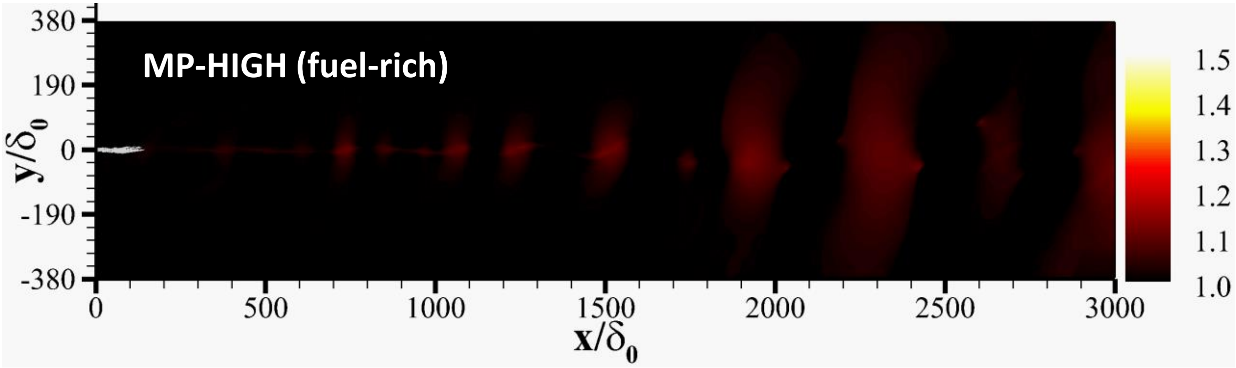
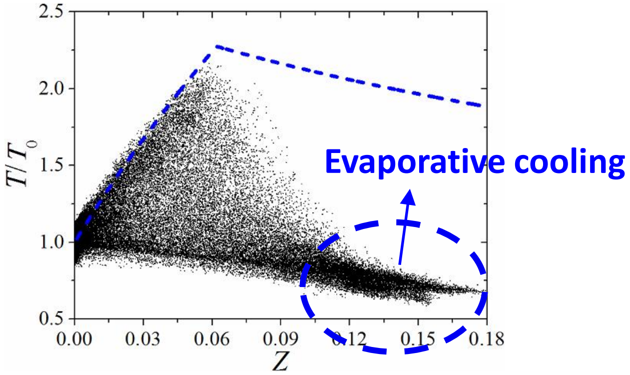
Premixed spray flame: equivalence ratio









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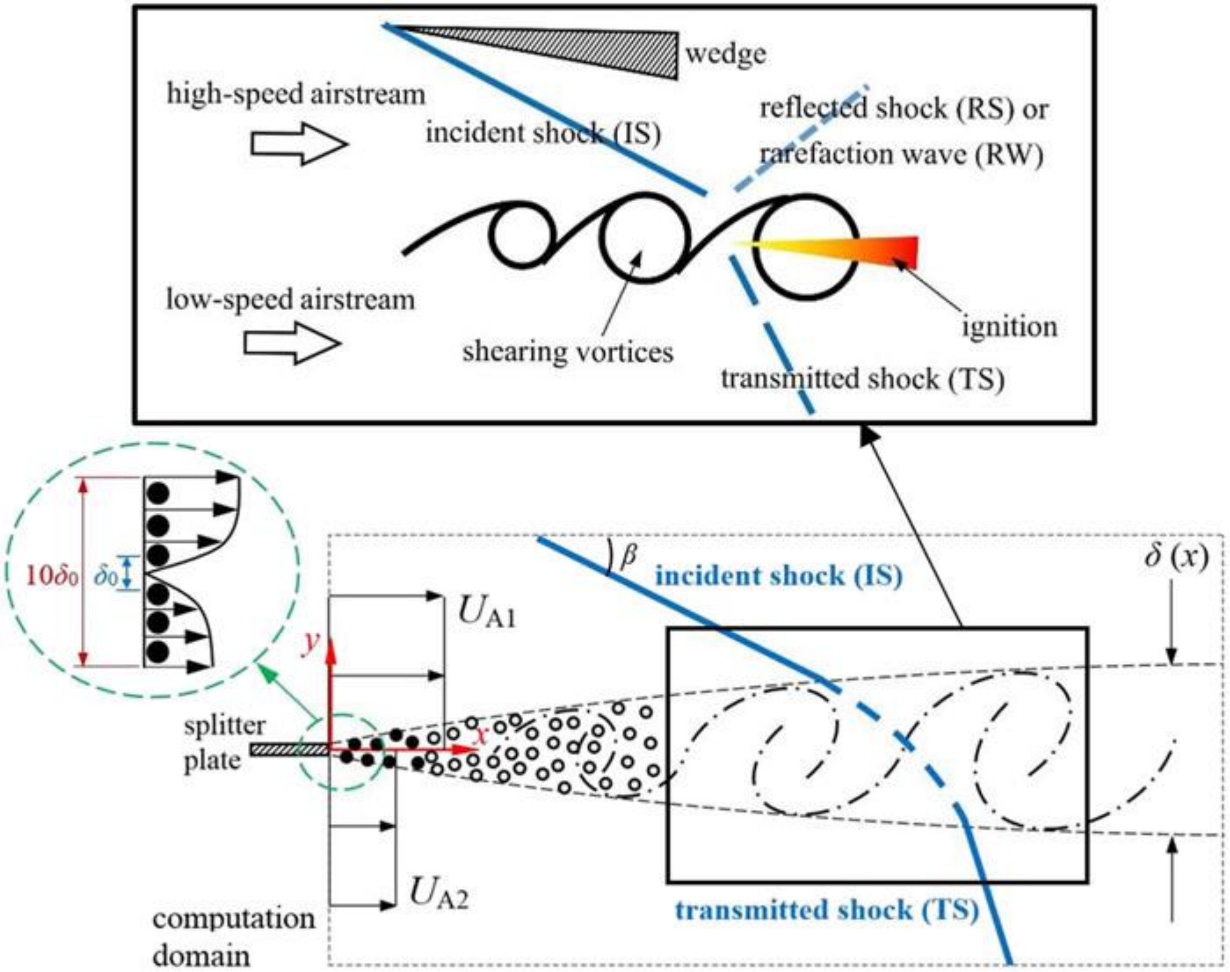
Premixed spray flame: Shock-induced flame

Effects of shock wave

- **Accelerate mixing** **(Yang AIAA J 1993)**
- **Promote combustion (increasing temperature/pressure)** **(Rubins JPP 1994)**



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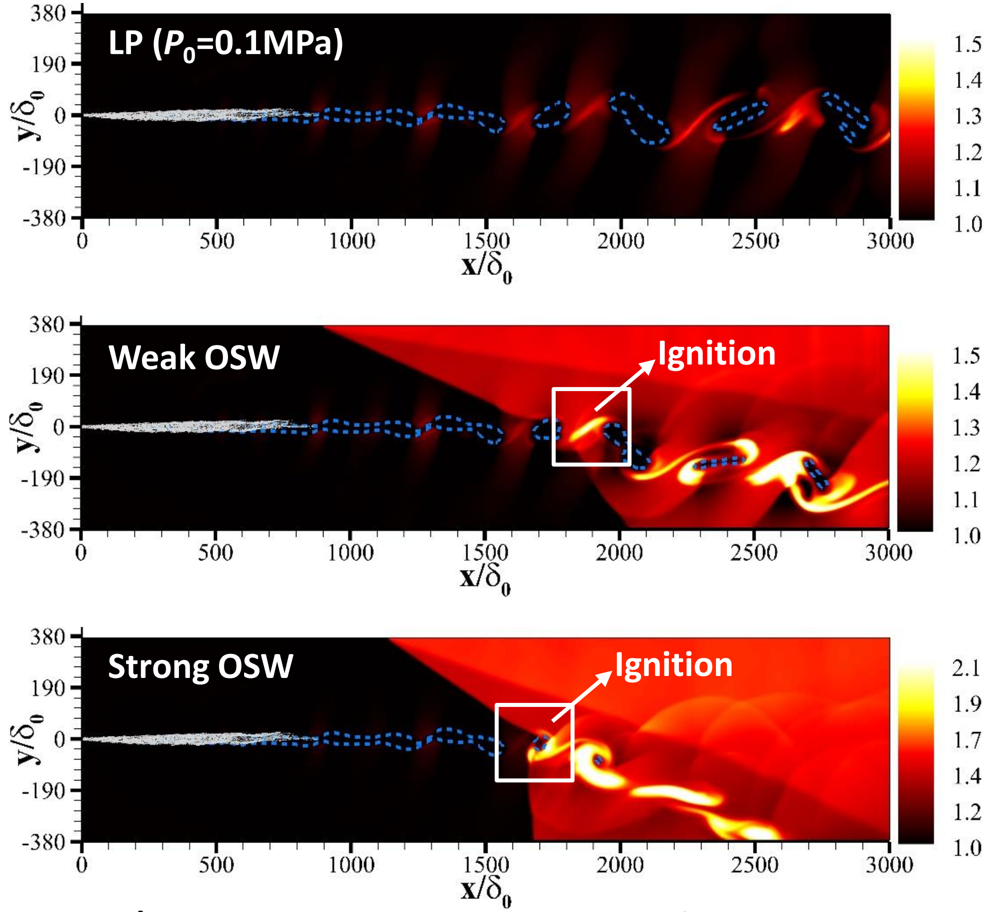
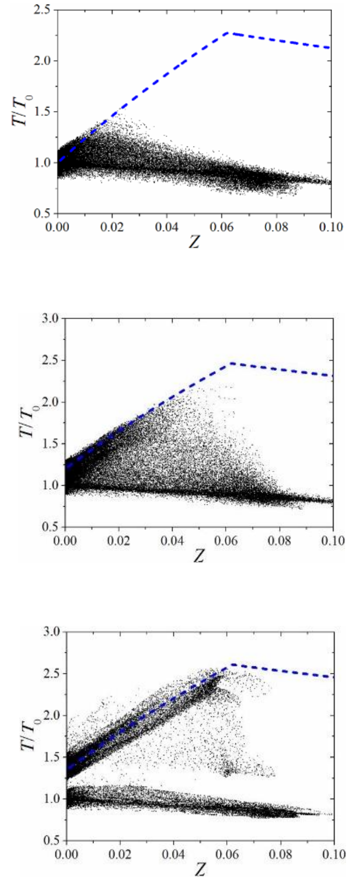
Premixed spray flame: flame induced by oblique shock wave (OSW)





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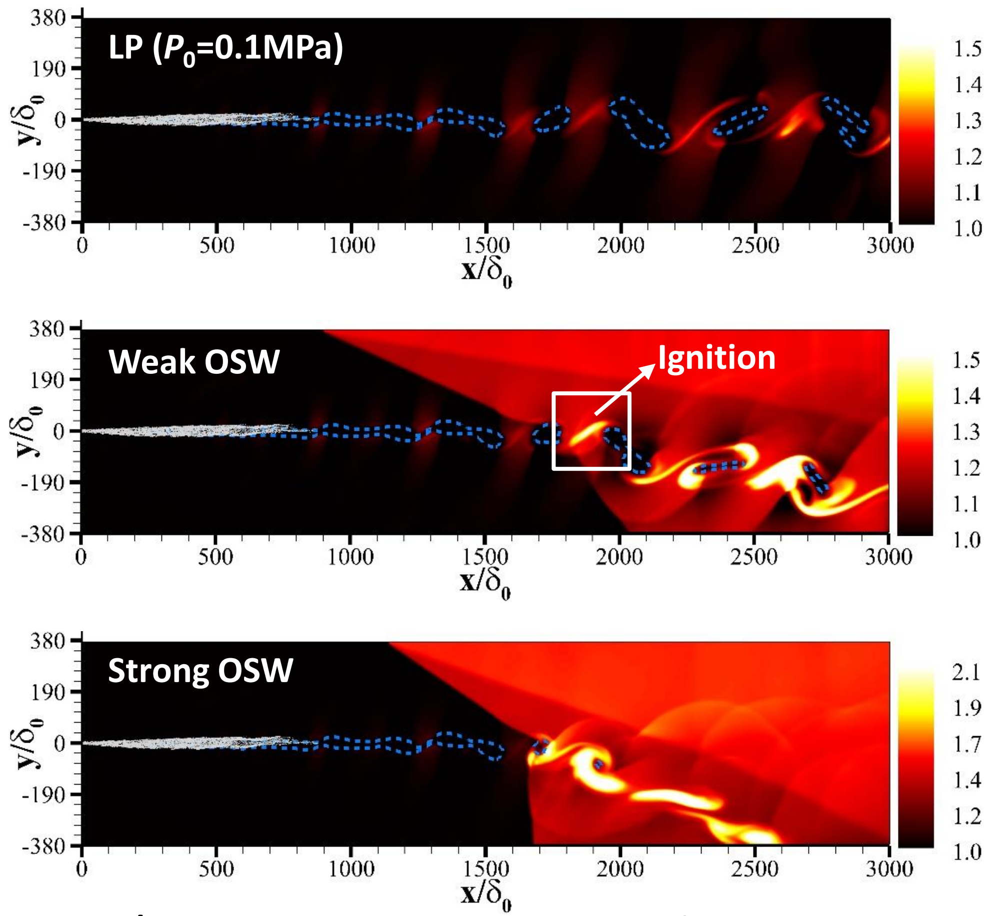
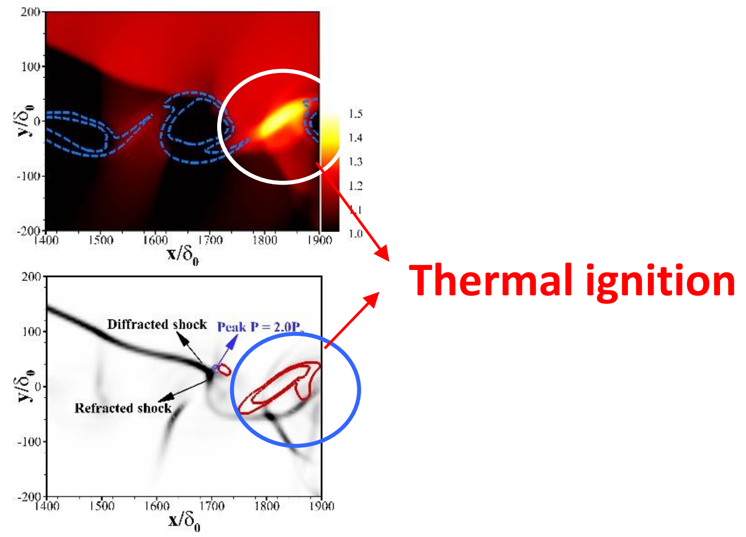
Premixed spray flame: flame induced by oblique shock wave (OSW)

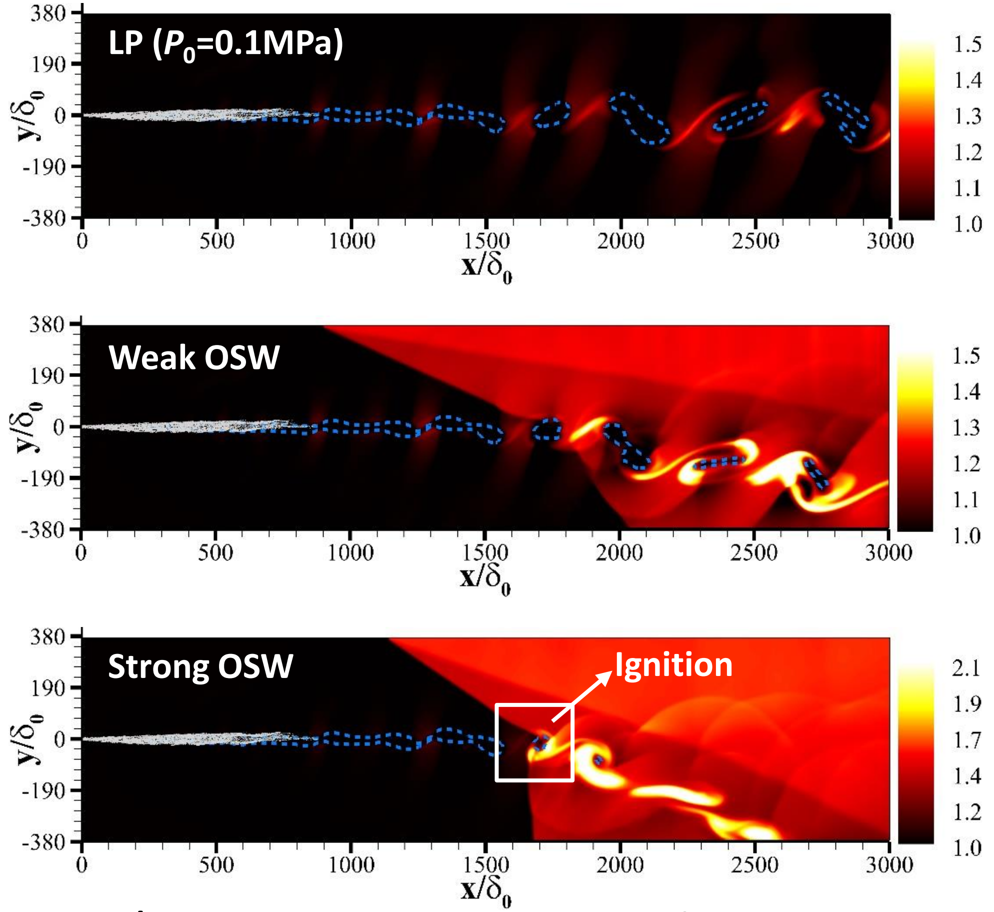


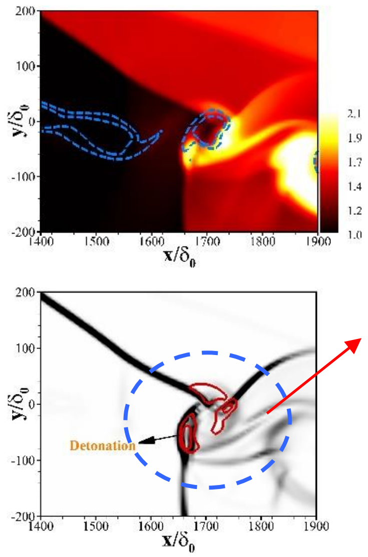


- Temperature T/T_0 contours and fuel mass fraction (blue dashed line for Y_F=0.05)
- Grey dots are fuel droplets.

Ren Z, Wang B, Zheng L. Physics of Fluids, 2018, 30(3): 036101.

Premixed spray flame: flame induced by oblique shock wave (OSW)

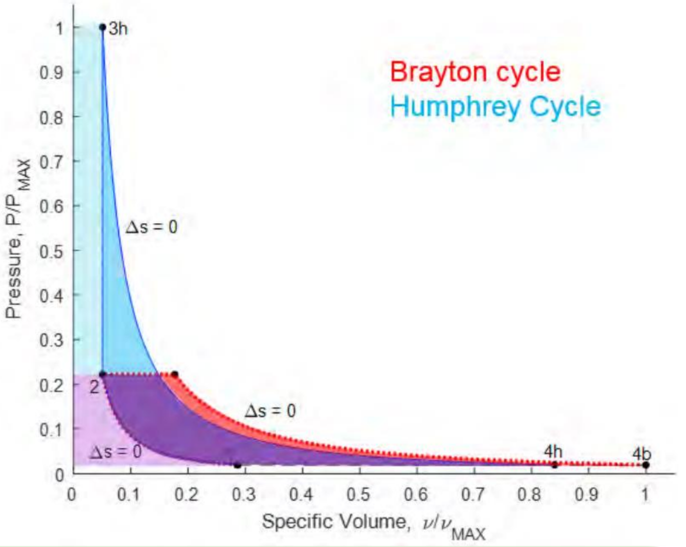




Detonation

- Temperature T/T_0 contours and fuel mass fraction (blue dashed line for Y_F=0.05)
- Grey dots are fuel droplets.

Detonation for propulsion



- **Detonation - Pressure Gain Combustion**

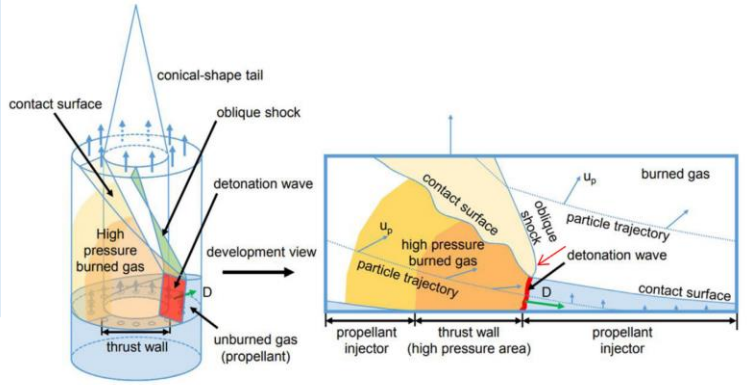
✓ Detonative combustion may provide pressure increase, resulting in higher efficiency.

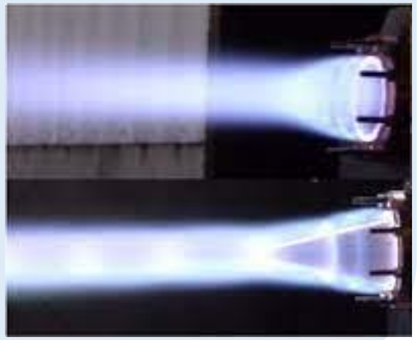
✓ 10-15% increase in theoretical efficiency or up to 5x reduction in initial combustion pressure.

- **Utilization of detonation wave (DW) to create thrust**

✓ **Propagating DW: Rotating detonation engine (RDE)**

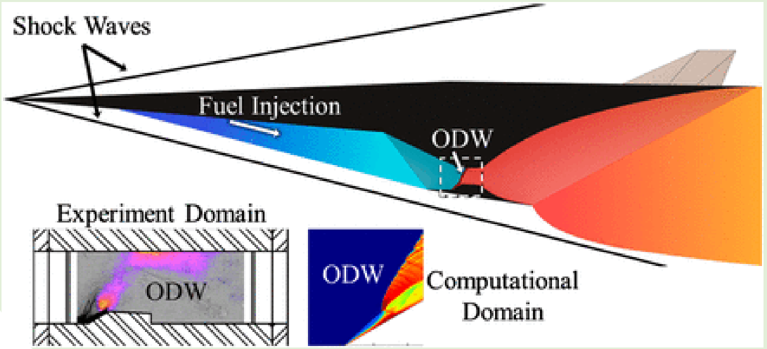
- Combustible gas mixture is injected along axial direction, and DWs propagates in azimuthal direction.
- DWs can continuously propagate.
- Mechanically simple and compact.

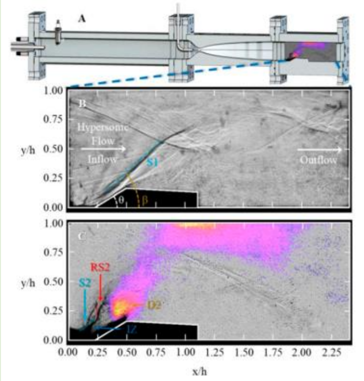




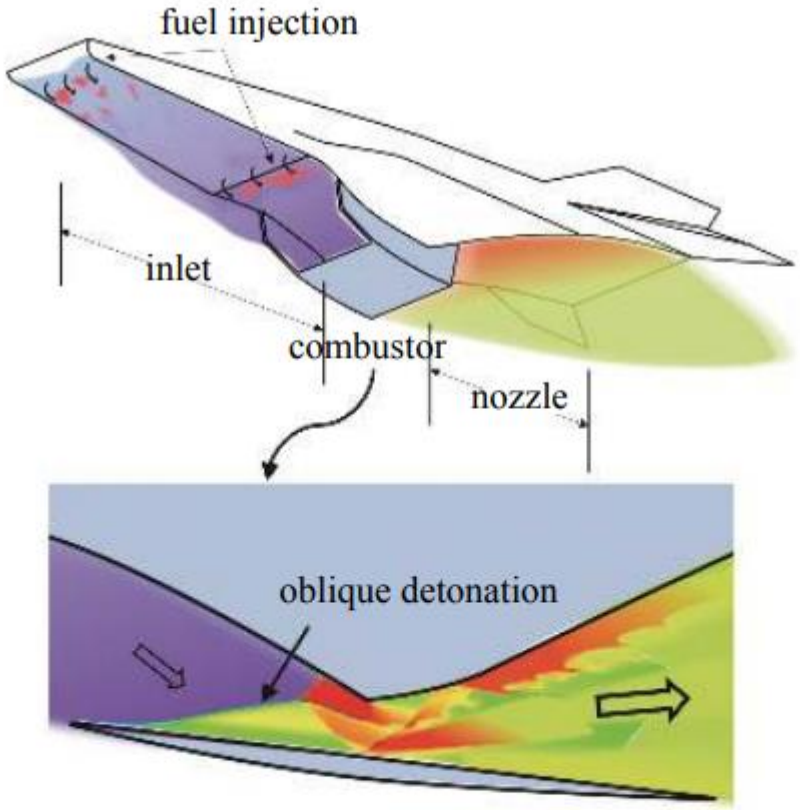
✓ **Standing DW: Oblique detonation engine (ODE)**

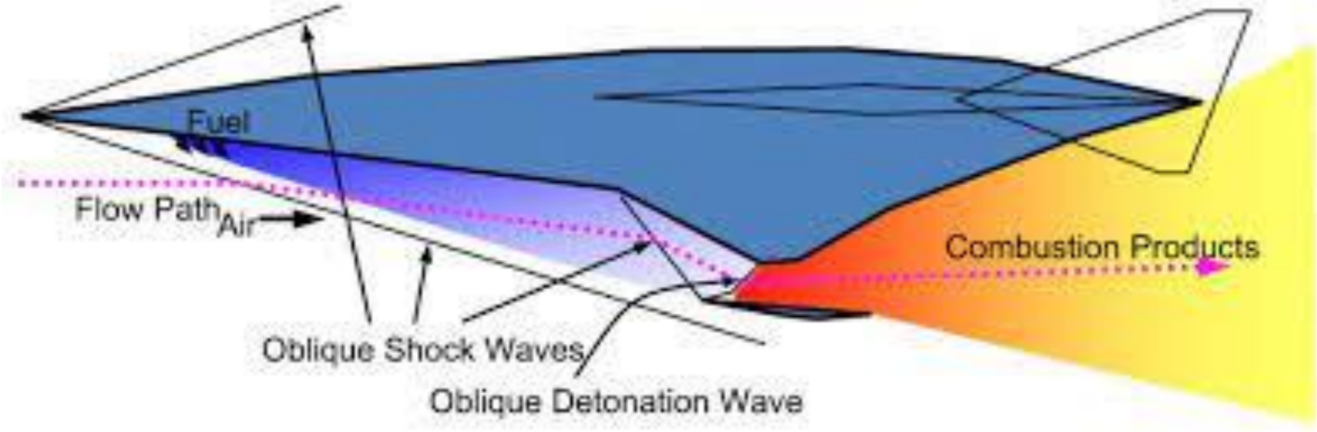
- Combustible gas mixture velocity equals or exceeds Chapman-Jouguet (CJ) velocity.
- Combustion stabilization in supersonic flows. (Shcramjet)
- Simple geometry and good performance for high Ma flight.





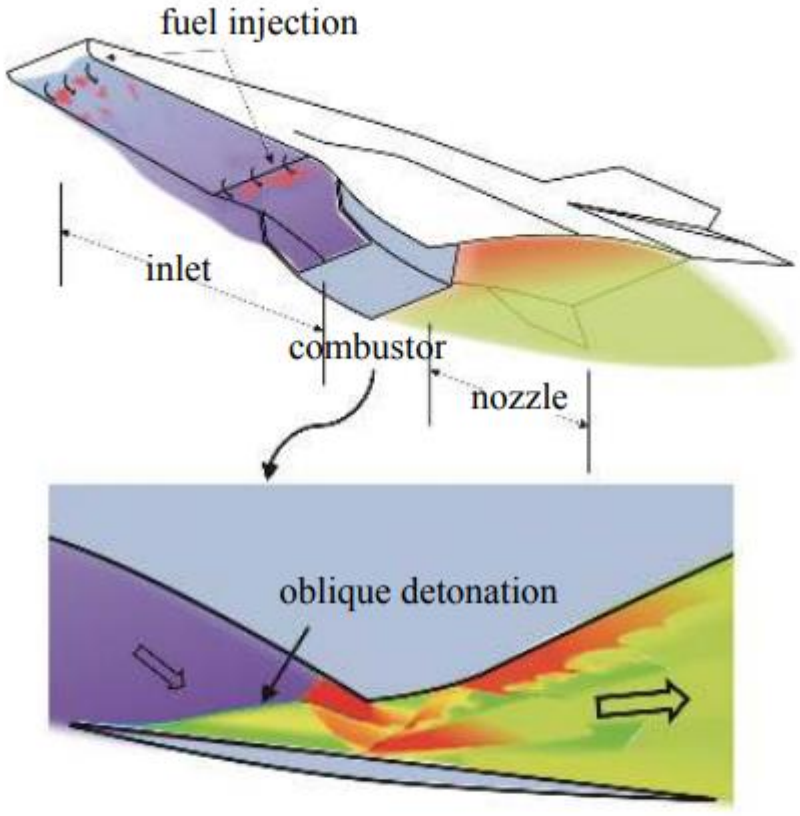
Standing DW: Oblique detonation engine (ODE) - CFD



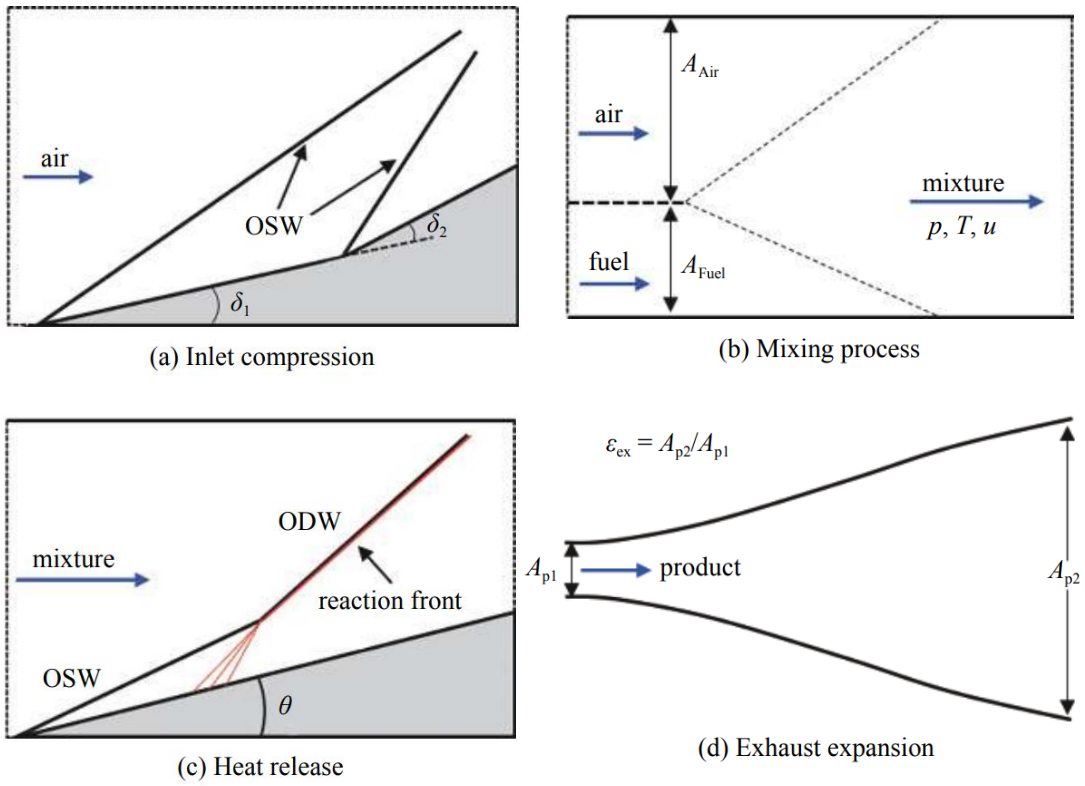


- **Schematic diagram of the ODE.**

Standing DW: Oblique detonation engine (ODE) - CFD



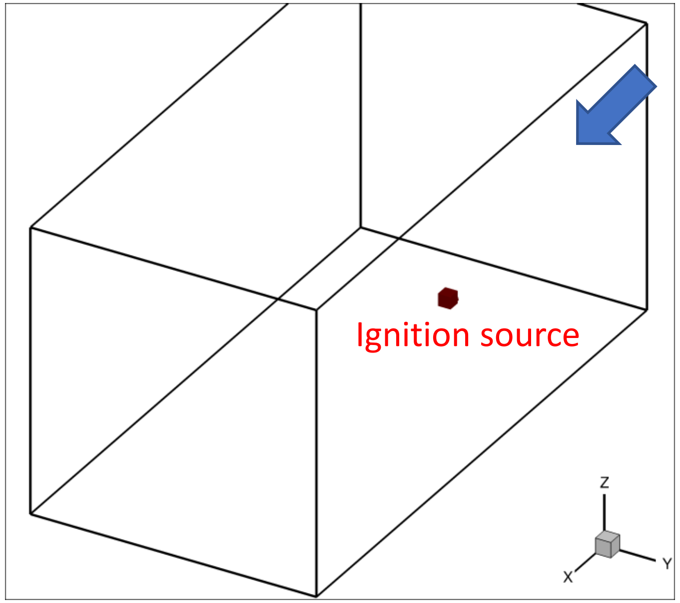
- Schematic diagram of the ODE.



- Schematics of four typical processes.

Standing DW: Oblique detonation engine (ODE) - CFD

- Compared with supersonic deflagration in the combustor of scramjet engine.



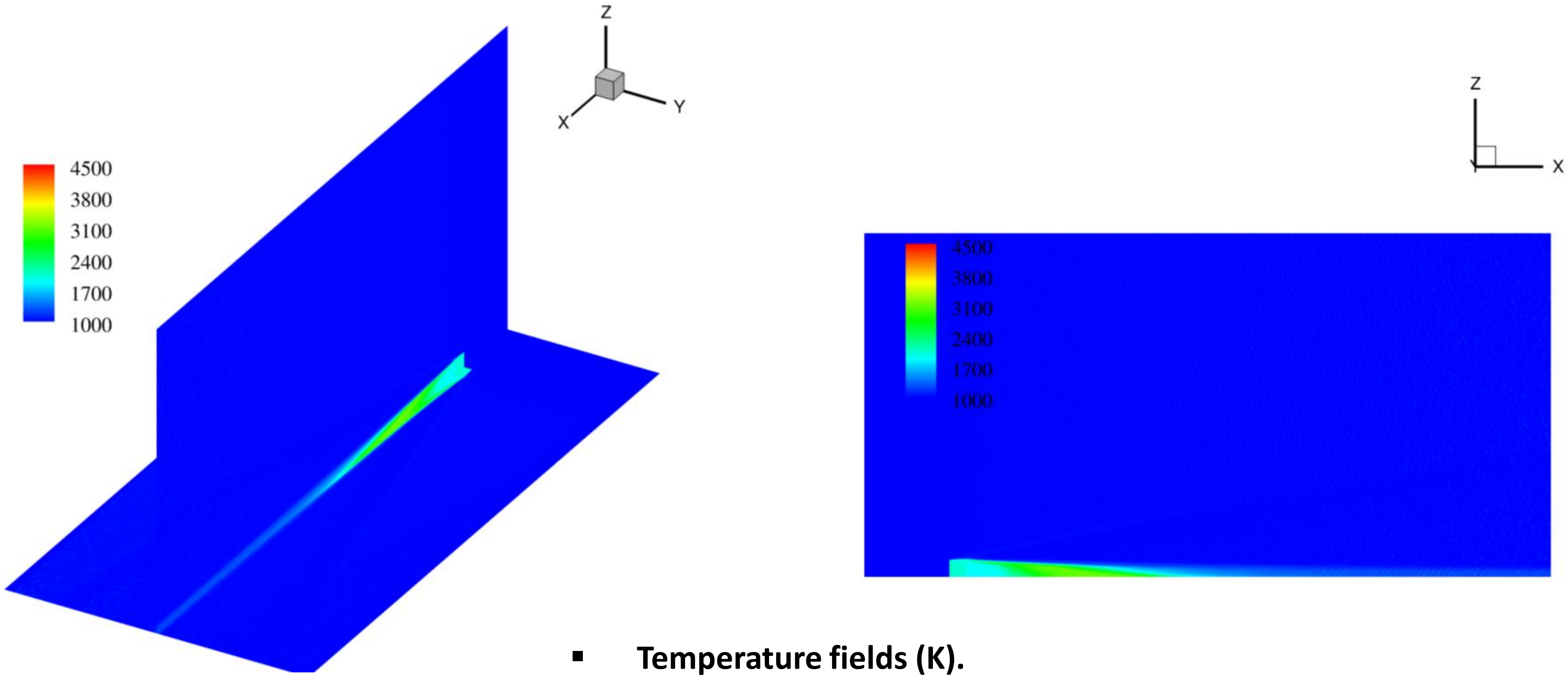
Premixed fuel-air
mixture, Ma = 5.0

Grid size: 50µm
Total 128 million grids

Standing DW: Oblique detonation engine (ODE) - CFD

- Ignition in supersonic premixed flow.

✓ **Typical spark ignition (T_{ig} = 2000 K, P_{ig} = P_0)**

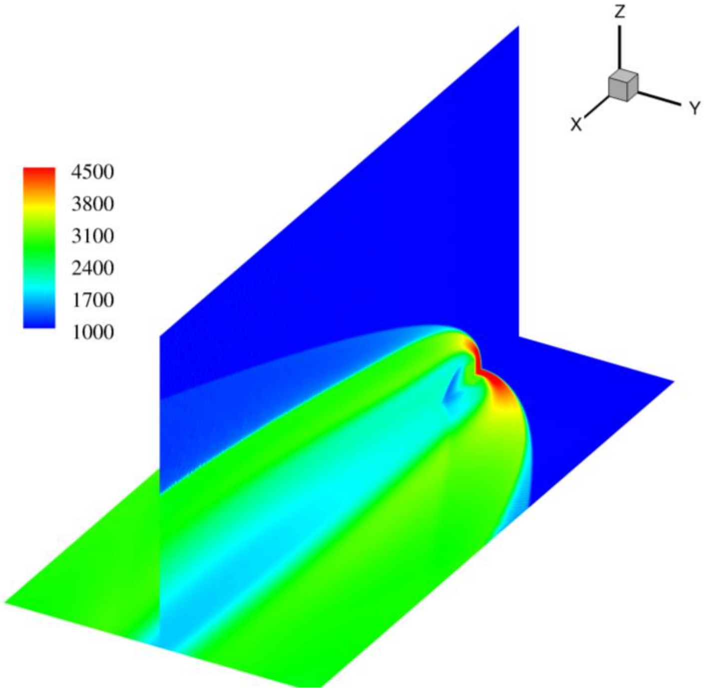


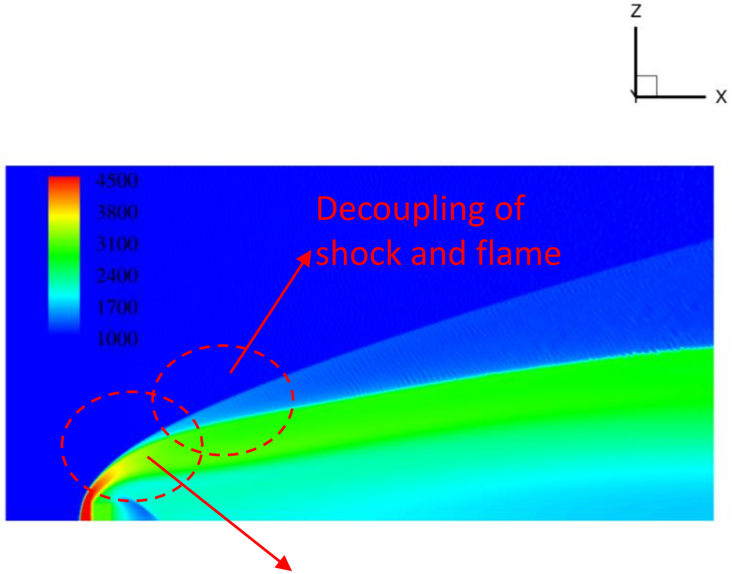
- **Temperature fields (K).**

Standing DW: Oblique detonation engine (ODE) - CFD

- Ignition in supersonic premixed flow.

✓ **High-energy ignition (T_{ig} = 3000 K, P_{ig} = 30 P_0)**



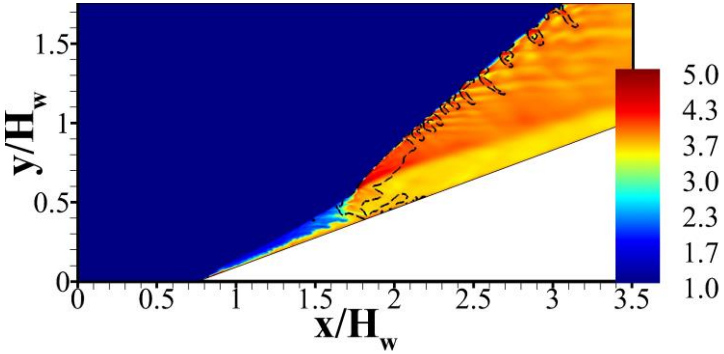


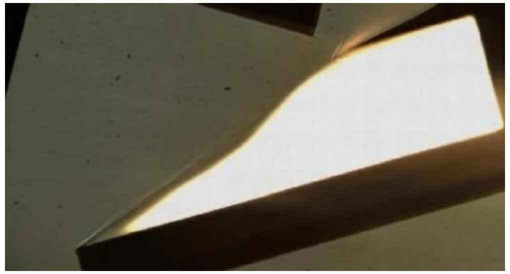
- **Temperature fields (K).**

- **Pressure fields (P/P_0).**

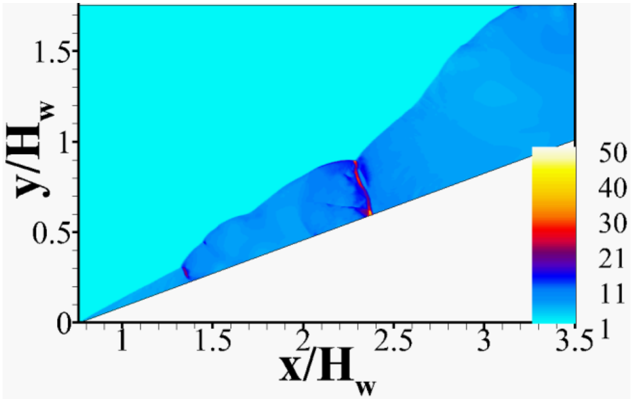
Standing DW: Oblique detonation engine (ODE) - CFD

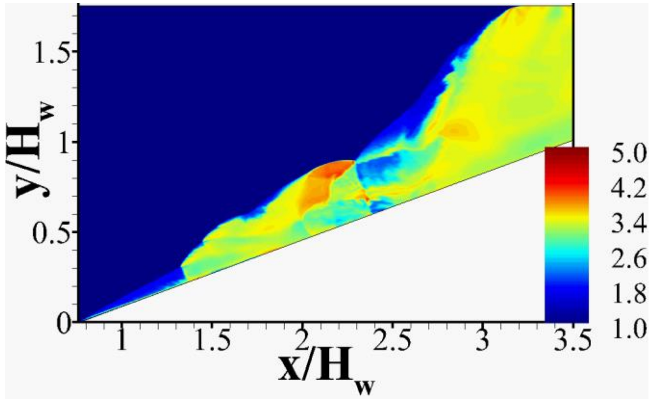
- Wedge-induced DW.





- **Temperature fields (T/T_0) from simulations.**
- **Experiments.**





- **Wedge-induced DW in disturbed inflow.** (Left: Pressure; Right: Temperature)

Ren Z, Wang B, Xiang G, Zheng L. Proceedings of the Combustion Institute, 2019, 37(3): 3627-3635.
Ren Z, Wang B, Xiang G, Zheng L., Journal of Fluid Mechanics, 2018, 846: 411-427.
Wang B, Ren Z*. Flow, Turbulence and Combustion, 2023.
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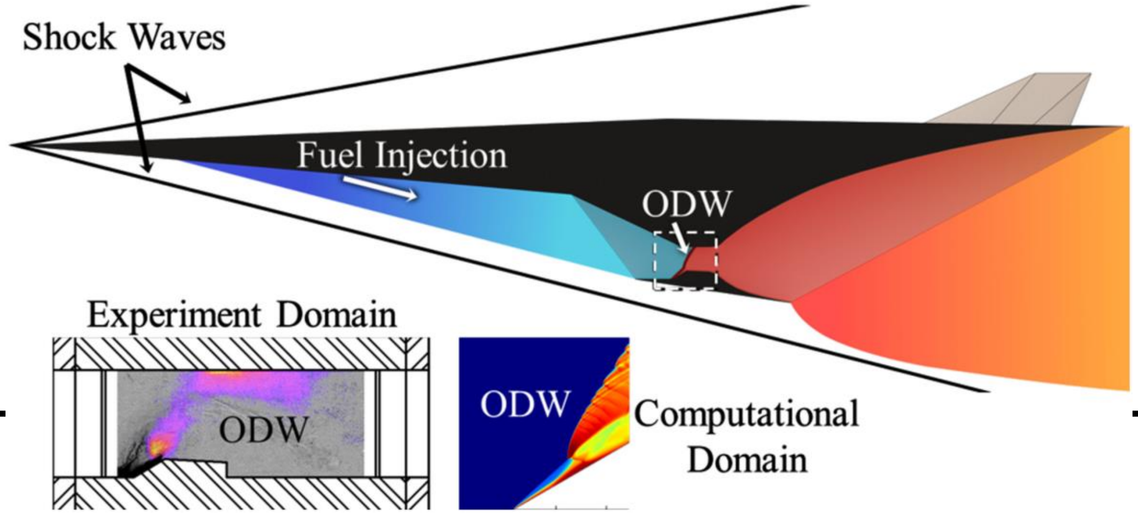
Ren Z. Aerospace Science and Technology, 2021: 106472.
Ren Z, Wang B. Aerospace Science and Technology, 2020, 107: 106245

Review and Further research

- Ignition and flame features in supersonic reactive flows is very different from low-speed combustion in the gas turbine.
    1. ignition in high-strain regions
    2. strong fluctuation of pressure/temperature,
    3. effects of shocklets…
    4. shock-flame coupling
- Pressure gain combustion (PGC) or detonation provides a choice for the stable combustion technology for scramjet engine.

- High-fidelity CFD for the inlet/combustor/nozzle integration.
- Confirm the pressure gain in ODWE.



Supersonic multiphase reactive flow and shock-induced combustion

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