超音速燃焼に関する数値シミュレーション

松尾亜紀子
慶應義塾大学理工学部機械工学科

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「工学における計算科学の展開」

慶應義塾

超音速燃焼:Detonation

- ***Detonation（デトネーション:爆轟波）*** は燃焼波である。
- 今回の発表では、気相における燃焼波である「デトネーション」について話をする。
  - Detonation in Gas-phase
  - Detonation in Condensed-Phase
    - 液体、固体における爆轟波は、爆薬中の燃焼波。

燃焼形態には何がある？

- 一般に、二種類の燃焼形態がある:

  Premixed Flame ←→ Diffusion Flame

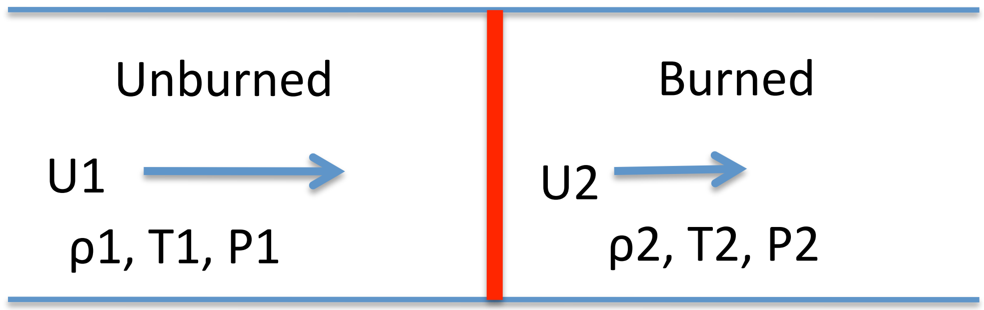
  （予混合火炎） （拡散火炎）

  - 予混合火炎（detonation, deflagration）
    - 燃料と酸化剤は完全に混合された状態であり、その中を燃焼波が伝播する。
  - 拡散火炎(Non-premixed flame)
    - 燃料と酸化剤は拡散により混合しながら燃焼を維持する。よって伝播性は無い。

- **デトネーションは予混合気体中を超音速で伝播する燃焼波である。よって、燃焼波には衝撃波と発熱帯がある。**

Detonation vs. Deflagration

デトネーション と 普通の予混合火炎



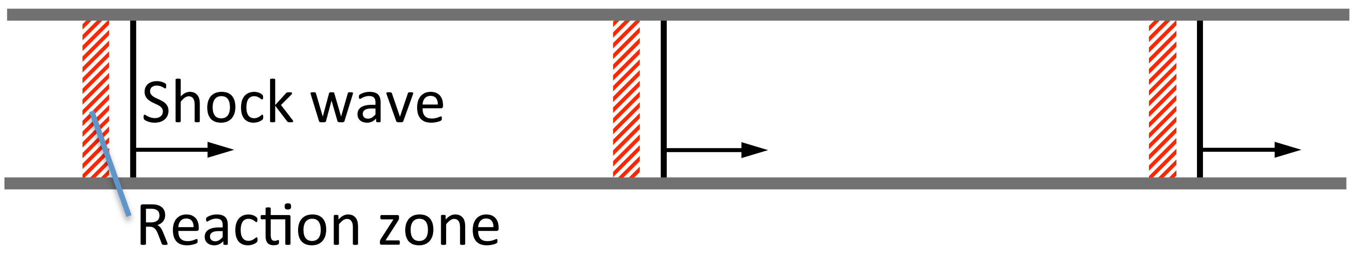
Stationary 1-Dimensional Premixed Combustion Wave

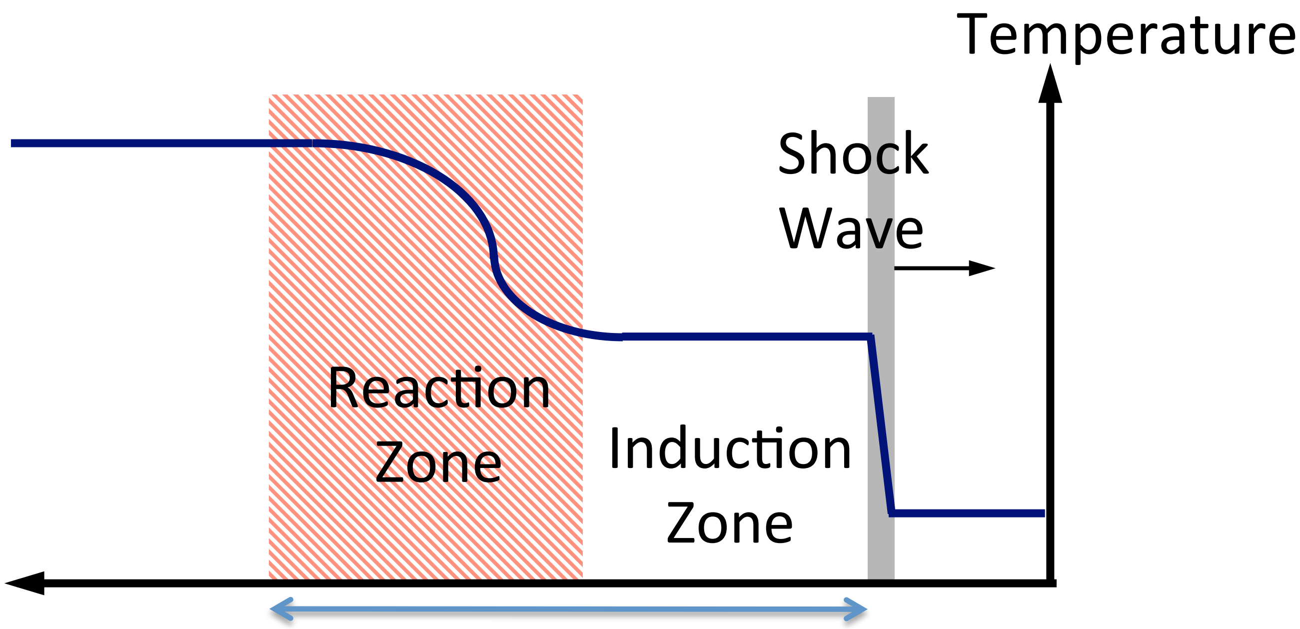
	Detonation	*Deflagration*
U1/C1	5-10 : Mach number	0.0001-0.003
U2/U1	0.4-0.7 (deceleration)	4-6 (acceleration)
P2/P1	13-55 (compression)	0.98 (slight expansion)
T2/T1	8-21 (heat addition)	4-16 (heat addition)
ρ2/ρ1	1.7-2.6	0.06-0.25

デトネーションの波面構造

ZND 1-D Wave Structure:

The classical C-J theory by Zel'dovich, Neumann, and Doring:
strictly one-dimensional and steady relative to the detonation front





Hugoniot Curve & Rayleigh Line

Chapman (1899), Jouguet (1905)

Mass conservation

①$\rho_1 u_1 = \rho u$

Momentum conservation

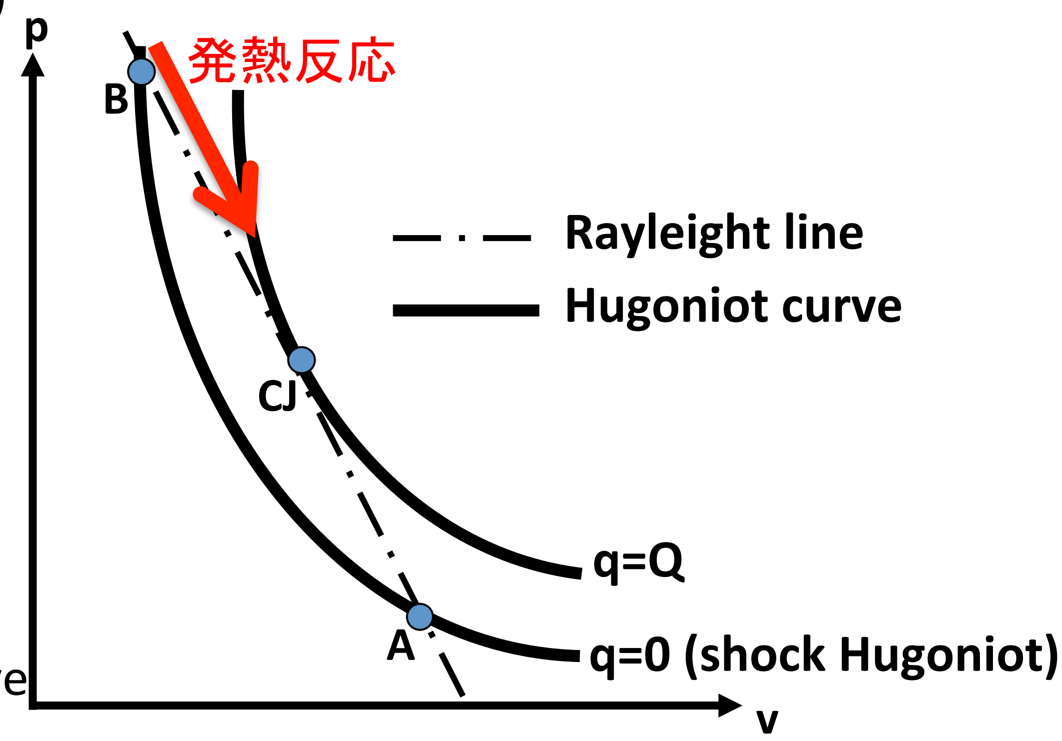
②$P_1 + \rho_1 u_1 = P + \rho u$

Energy conservation

③$c_p T_1 + u_1^2/2 + q = c_p T + u^2/2$

①, ② ➔ Rayleigh Line

①, ②, ③ ➔ Hugoniot Curve



- A：初期値（未燃状態）
- B：von Neumann Spike (衝撃波)
  衝撃波後方では流れ場は亜音速となり、発熱反応が起きる。
- CJ：Chapman-Jouguet Condition
  デトネーションはCJ状態で伝播する。

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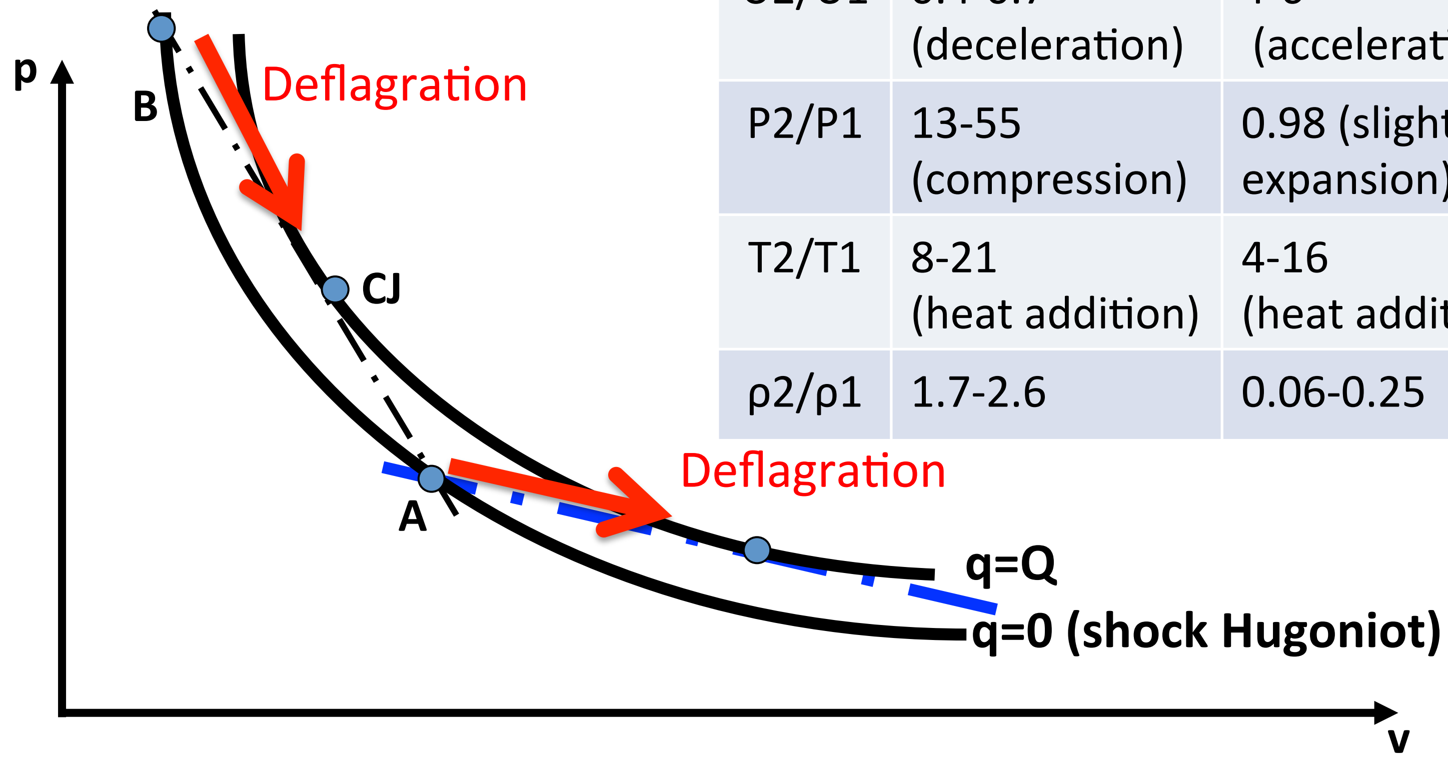

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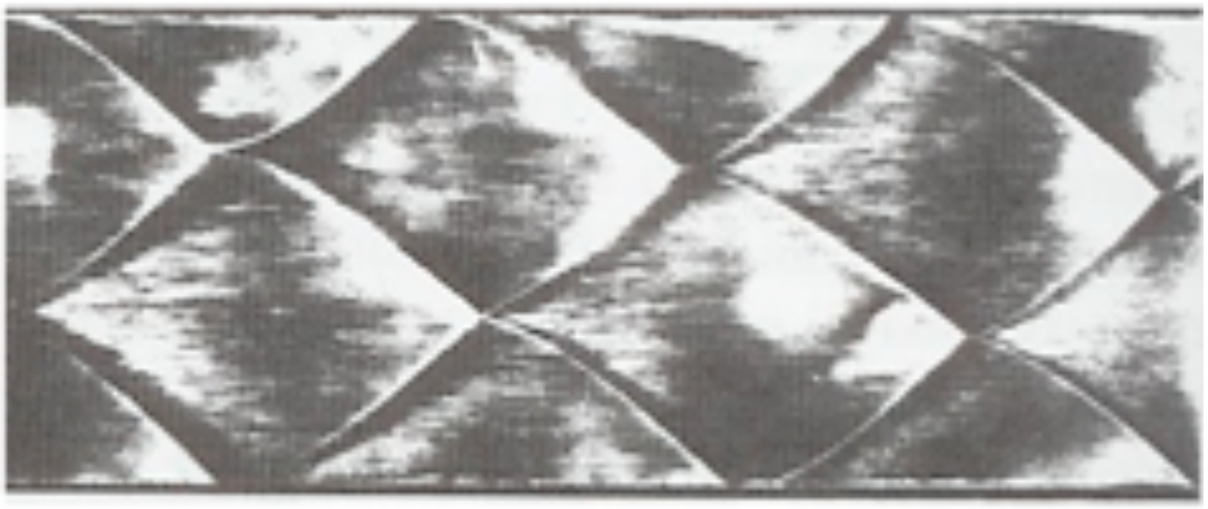
デトネーション管内部のセル模様

管内壁にすす膜を塗布し、伝播後に形成される



Smoked foil : $2H_2$+O_2+70%Ar
(R.A.Strehlow, 1968)

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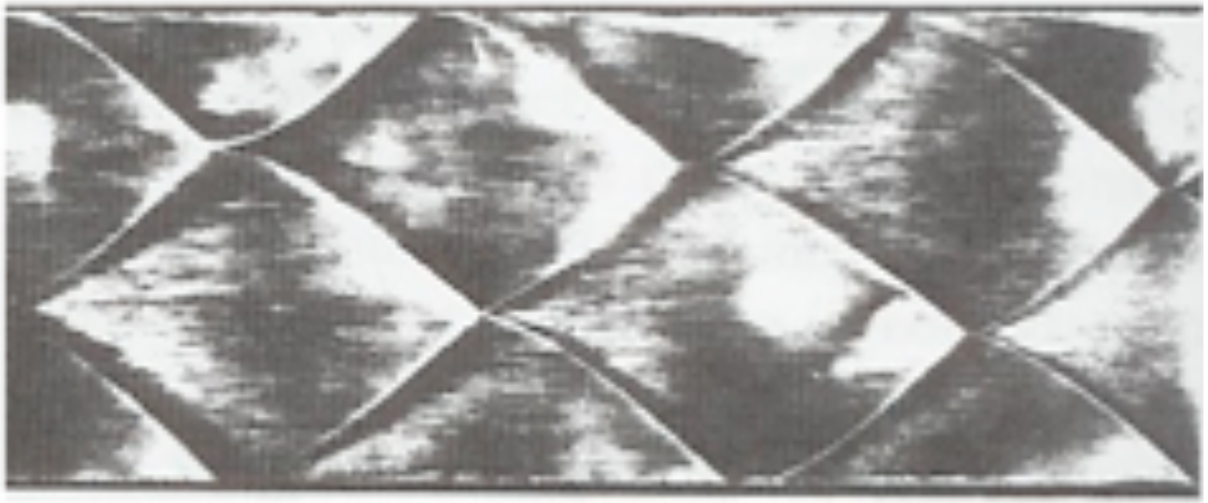

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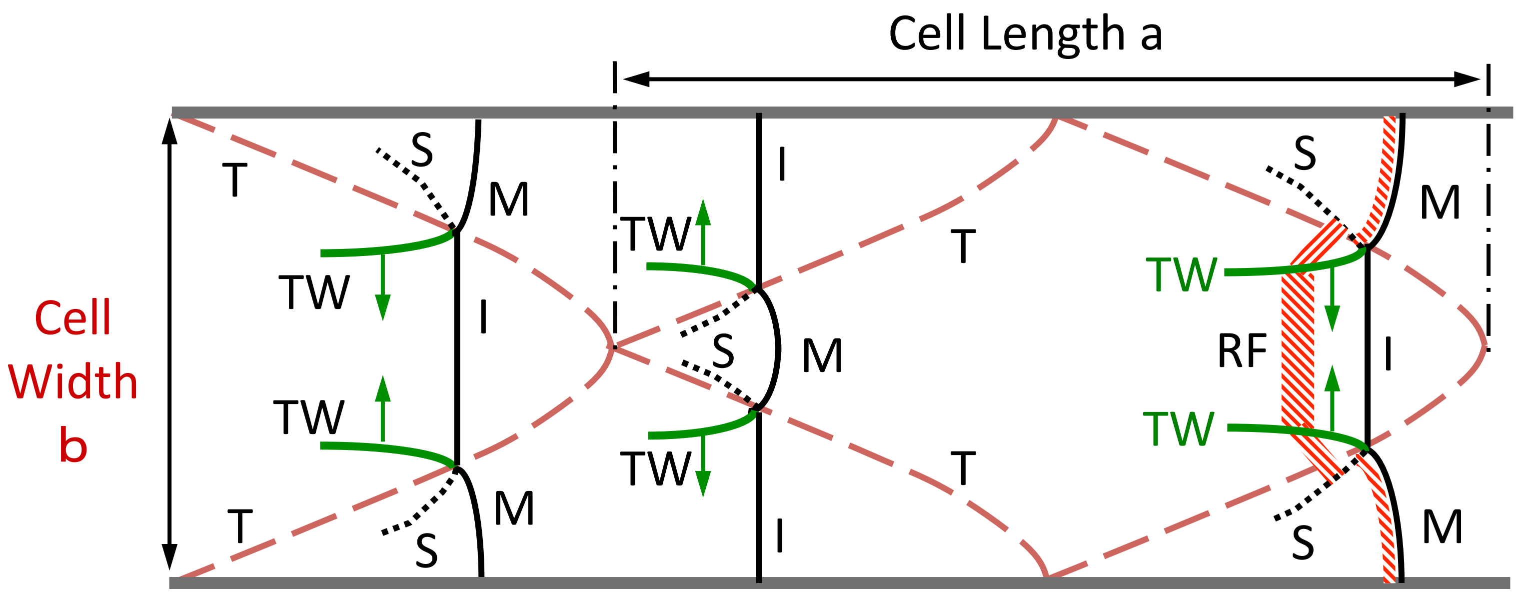
Cellular Structure of Detonation



Numerical Method for 2-D

2-Dimensional Compressible Euler equations

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} = \mathbf{S}$$

$$e = \frac{P}{\gamma - 1} + \rho Q Z + \frac{\rho}{2}\left(u^2 + v^2\right)$$

$$\mathbf{Q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \\ \rho Z \end{bmatrix}, \ \mathbf{E} = \begin{bmatrix} \rho u \\ P + \rho u^2 \\ \rho v u \\ (e+P)u \\ \rho u Z \end{bmatrix}, \ \mathbf{F} = \begin{bmatrix} \rho v \\ \rho u v \\ P + \rho v^2 \\ (e+P)v \\ \rho v Z \end{bmatrix}, \ \mathbf{S} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \omega \end{bmatrix}$$

Scheme: Yee's Non-MUSCL Type Second-Order TVD Upwind Scheme

Time-integration: Point Implicit Method

Chemical Reaction Model: Arrhenius Type one-step reaction

$$\omega = -\rho K Z \exp\left(-Ea/T\right)$$

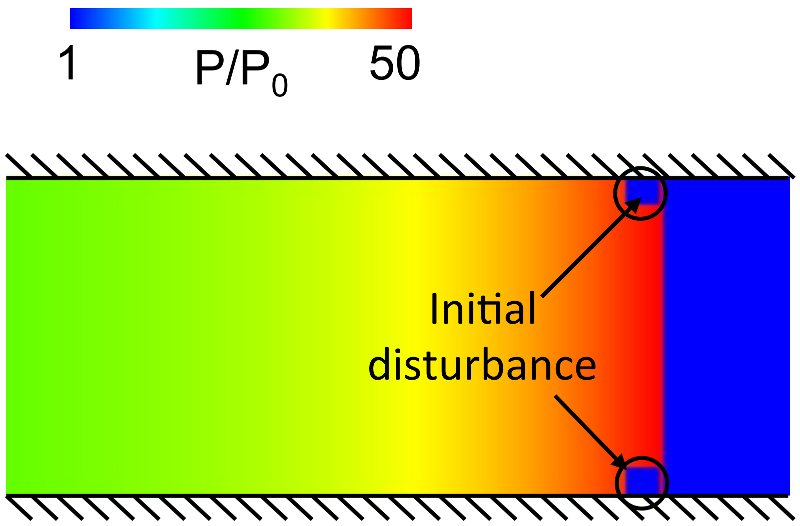
Chemical Parameter

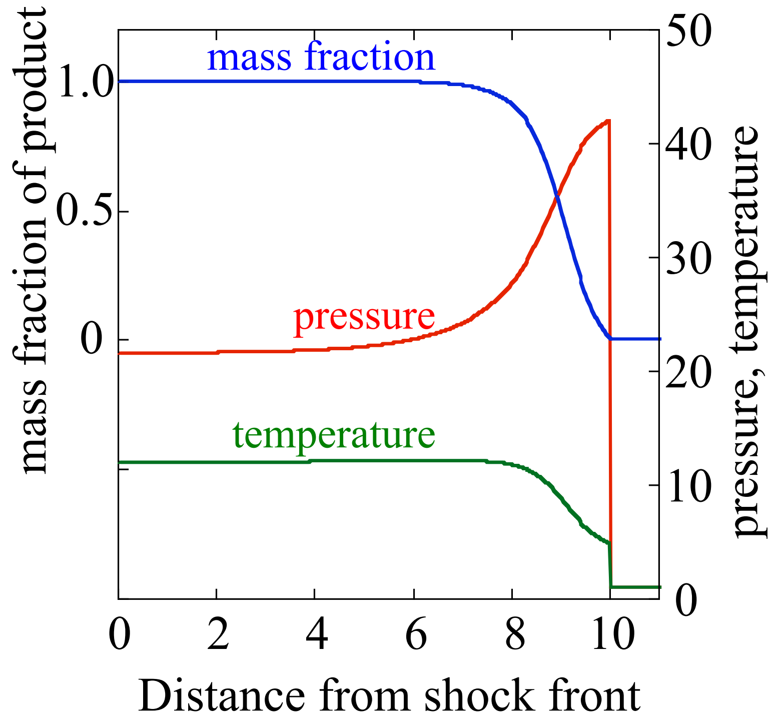
Specific heat ratio: γ = 1.2

Exothermicity: Q = 50

Activation energy: Ea = 27

Initial Condition for 2D Channel





Steady profile of 1-D detonation

(Q=50, γ=1.2, Ea=27)

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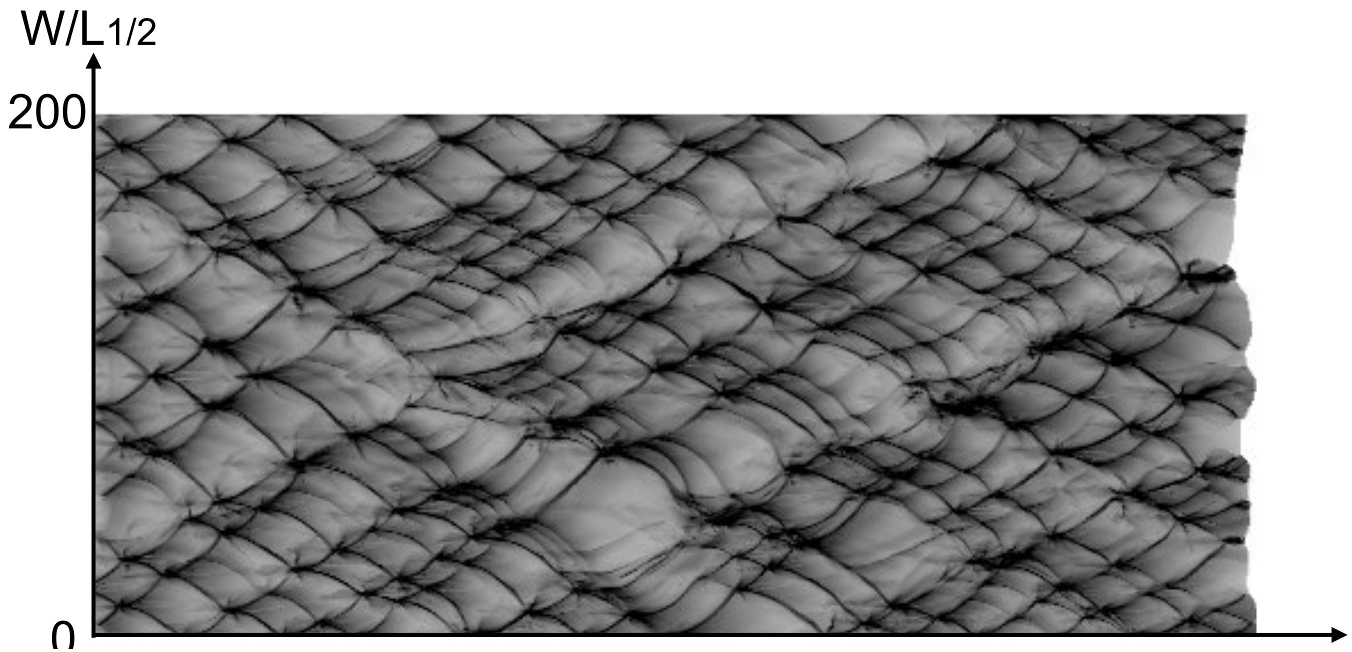
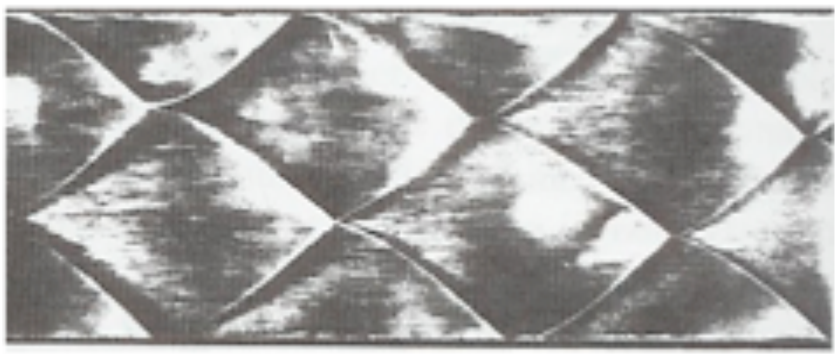
Cellular Structure of 2-D Channel



Smoked Foil Image of Simulation (Q=50, Ea=27, γ=1.2)



R. A. Strehlow (196

Can We Use Detonation for Practical Devices?

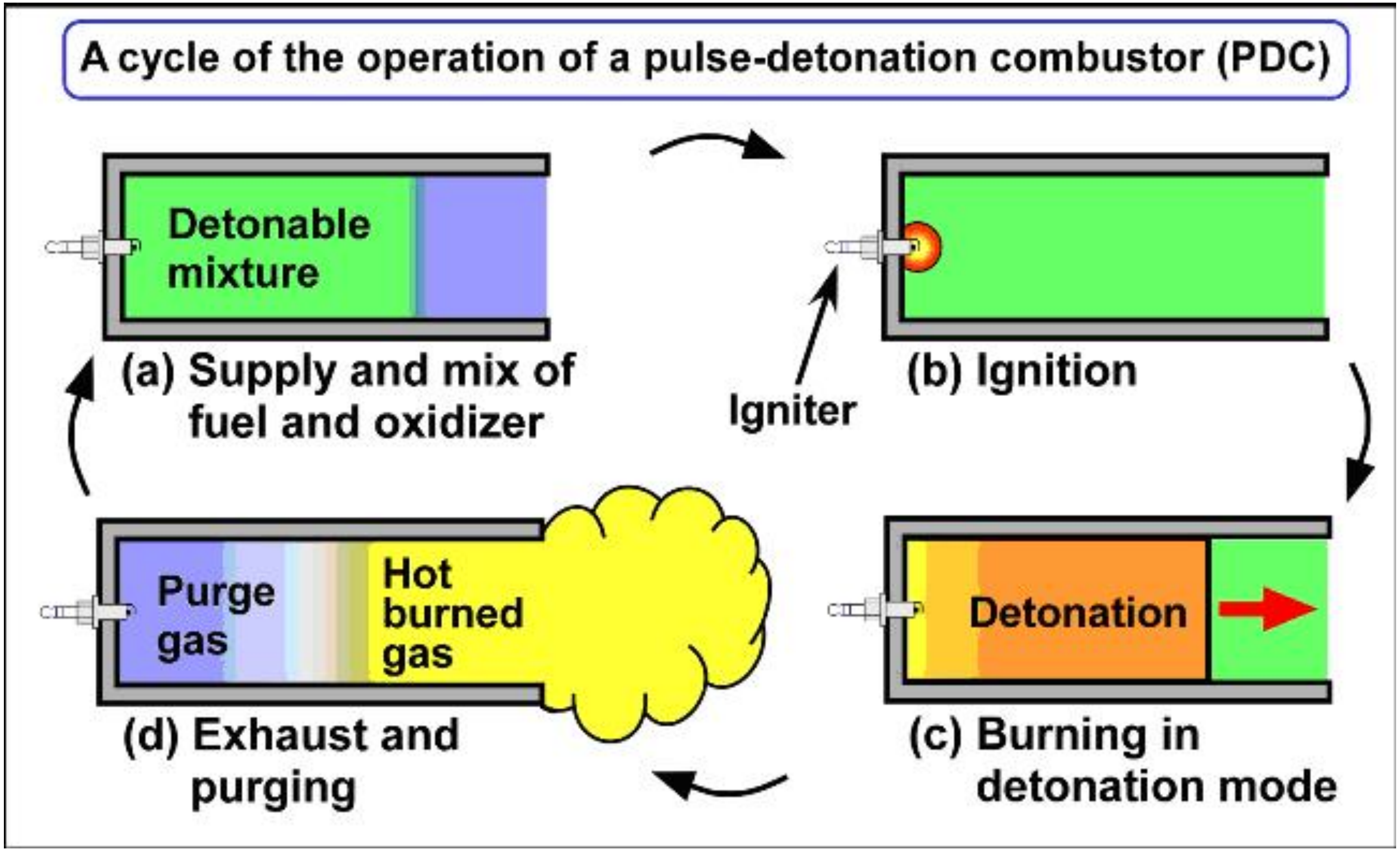
DETONATION ENGINES

Detonation Engines

- **Higher energy release rate, higher thermodynamic efficiency, and easier scaling.**

- **Pulse Detonation Engine (PDE):**
  - **Wide operating conditions (flight Mach# = 0-5).**
  - **Repetitive and intermittent thrust**
    Fast purging and refilling are required.
- **Rotating Detonation Engine (RDE)/Continuous Detonation Wave Engine (CDWE):**
  - **Simple configuration and higher thrust due to continuous injection.**
  - **Wide operating conditions without limitation of injection velocity.**

Cycle of Pulse Detonation Engine



Background : Fundamental and application studies of PDE, and evolution to very high frequency PDE operation

Pulse detonation engine (PDE) - simplified PDE

specific impulse 4200sec (air-breathing jet engine (H_2-air))

190sec (rocket engine (H_2-O_2))

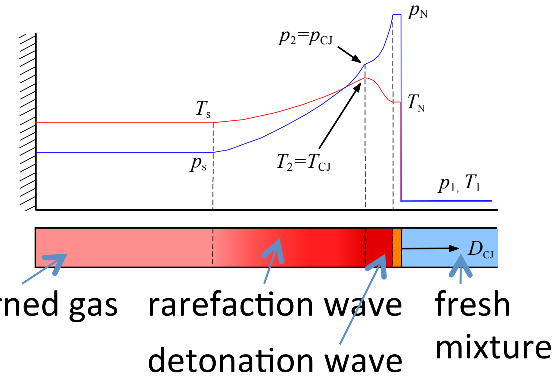
Endo et al., JPP, 2004, Cooper et al., JPP, 2002,

Wintenberger et al., JPP, 2003

Specific impulse increases if partial fill fraction increases.

Sato et al., JPP 2006, Cooper et al., JPP, 2004

Kasahara et al., AIAA Journal, 2008



Simplified PDE pressure and temperature histories

If the ambient pressure is sufficiently low, burned gas in PDE tube can be accelerated by a convergent-divergent nozzle.

Morris, JPP, 2005, Cooper and Shepherd, JPP, 2008

The first PDRE sliding test is demonstrated by pulse detonation rocket Todoroki.

Kasahara et al., JPP, 2009-1

University of Tsukuba, ISE, JAXA

The first manned PDE flight test was conducted by AFRL-ISSI.

Hoke et al., Japanese Shock wave Sym., Jan 2008.

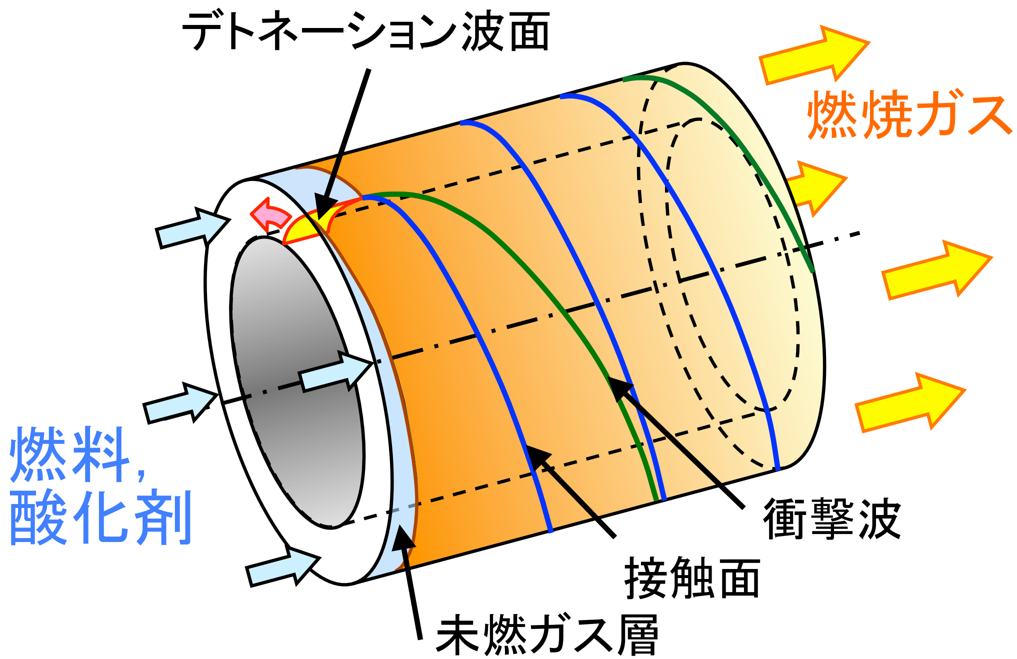
Specific impulse of 305 sec was achieved using multi-cycle partial-fill effect

Kasahara et al., JPP, 2009-2

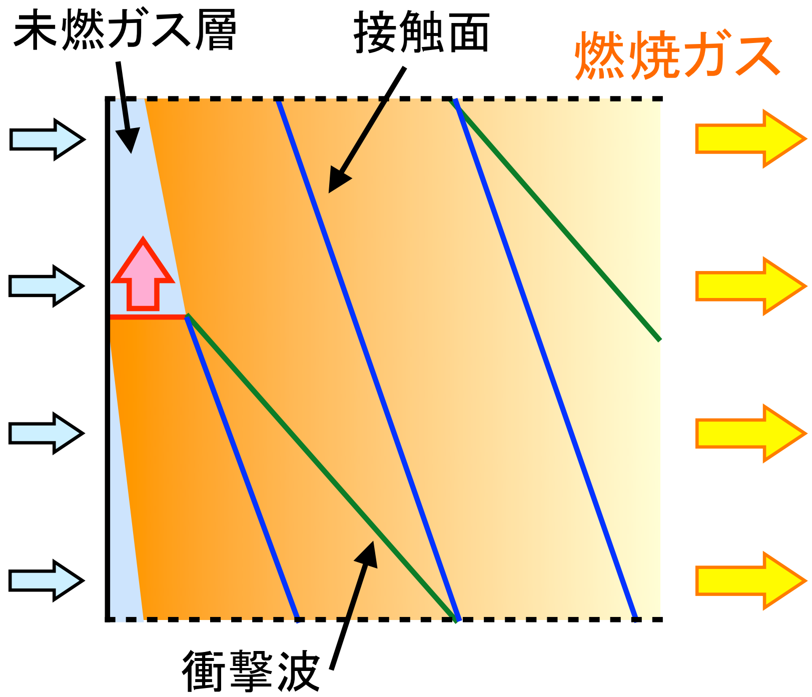
Most recent interests are flight demonstration by rocket system, very high frequency operation, real application as RCS.

ISSI-AFRL

Rotating Detonation Engine (RDE)/ Continuous Detonation Wave Engine (CDWE)



RDEの概要



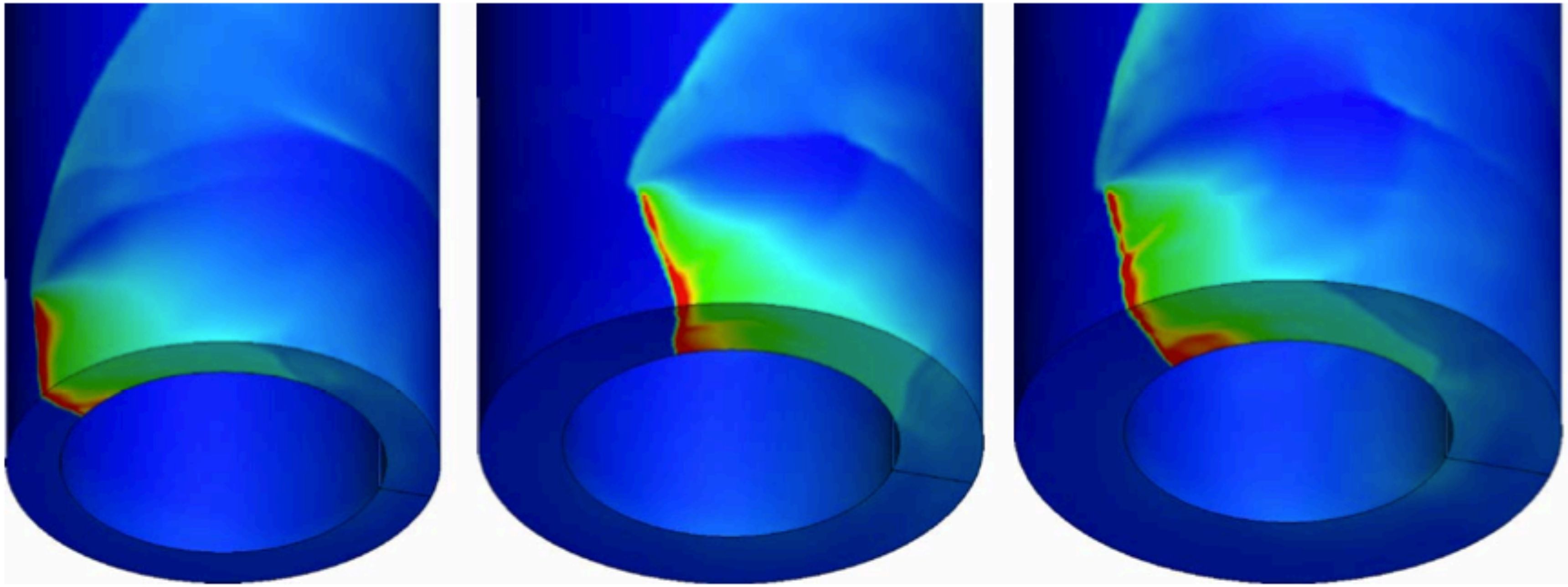
外壁上の流れ場 （z-θ面）

- 環状燃焼器内をデトネーションが連続的に伝播するため、点火・DDTが初回のみである。

RDEに関する3次元数値解析

Kailasanath et al. (2011)

- 量論混合気の水素−空気を用いたエンジンの三次元性を検証する研究（管幅の変化）



圧力分布

- デトネーションは安定に伝播している。
- 管幅が増すと、3次元性が現れる。

Japanese detonation engine researches：

PDRE

University of Tsukuba, Dr. Kasahara
PDE, PDRE, PDTE, RDE, Experiment, Fundamental Study

Keio University, Dr. Matsuo
Fundamental Detonation Study, CFD

JAXA (Japan Aerospace Exploration Agency), Dr. Funaki, Dr. Kojima
PDE, PDRE, PDTE, Feasibility Study

feasibility study

Hiroshima University, Dr. Endo
PDE, PDTE, Experiment, System, Theory

Saitama University, Dr. Ooyagi
PDE, PDTE, Experiment, System

PDTE

Kyusyu Institute of Technology, Dr. Tsuboi
PDE, RDE, CFD, System, Nozzle, Fundamental Study

Aoyama Gakuin University, Dr. Hayashi
PDE, RDE, CFD, System, Nozzle

RDE

Hokkaido university, Dr. Wakita
PDE, Experiment, Initiator

Yokohama National University, Dr. Ishii
PDE, Experiment, Initiator, Fundamental Study

Tokyo Metropolitan University, Dr. Sakurai
PDE, Experiment, Fuel-Oxidizer Mixing

element and fundamental study