Fundamentals of Rotating Detonation

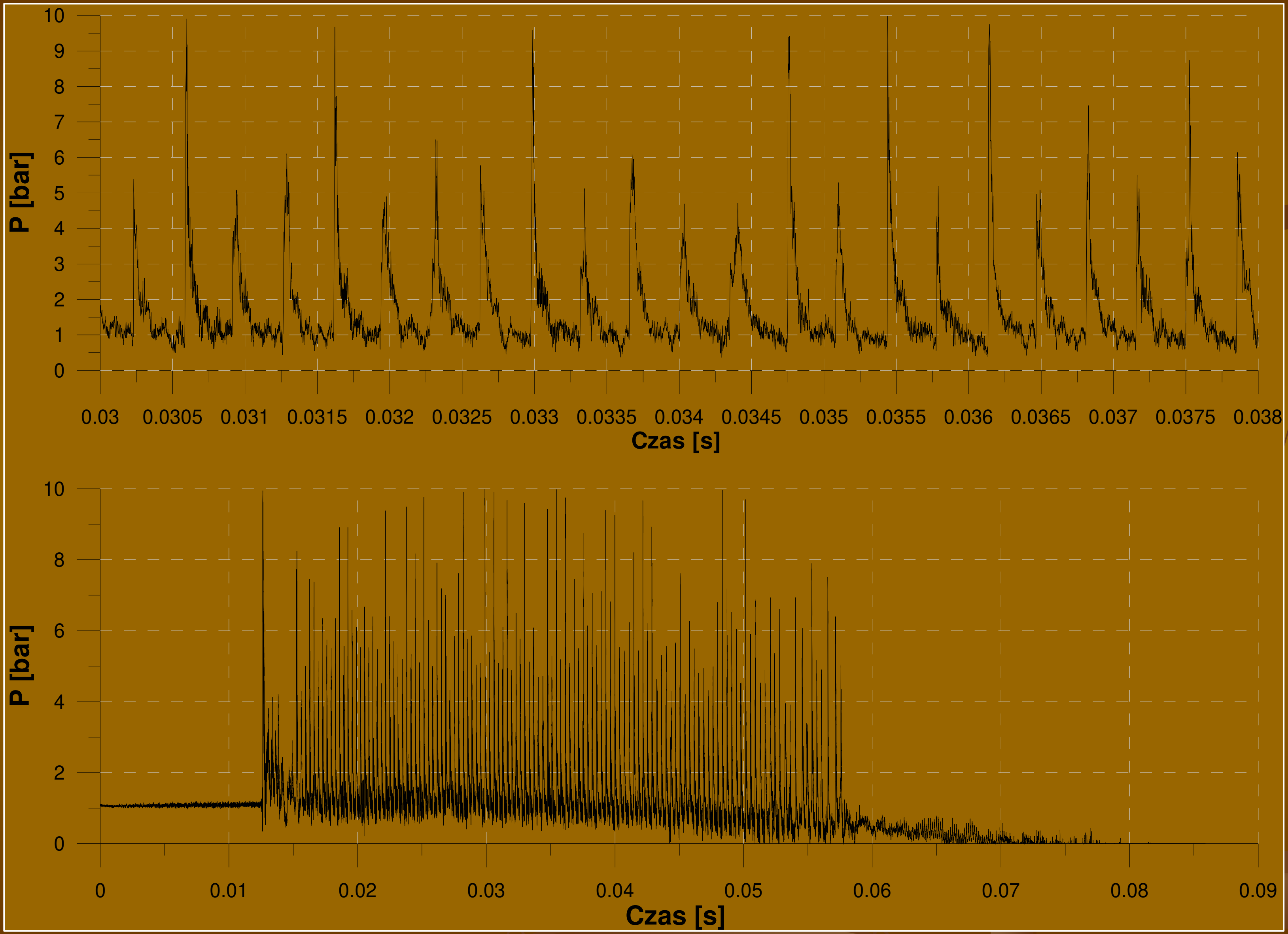
Toshi Fujiwara (Nagoya University)

New experimental results

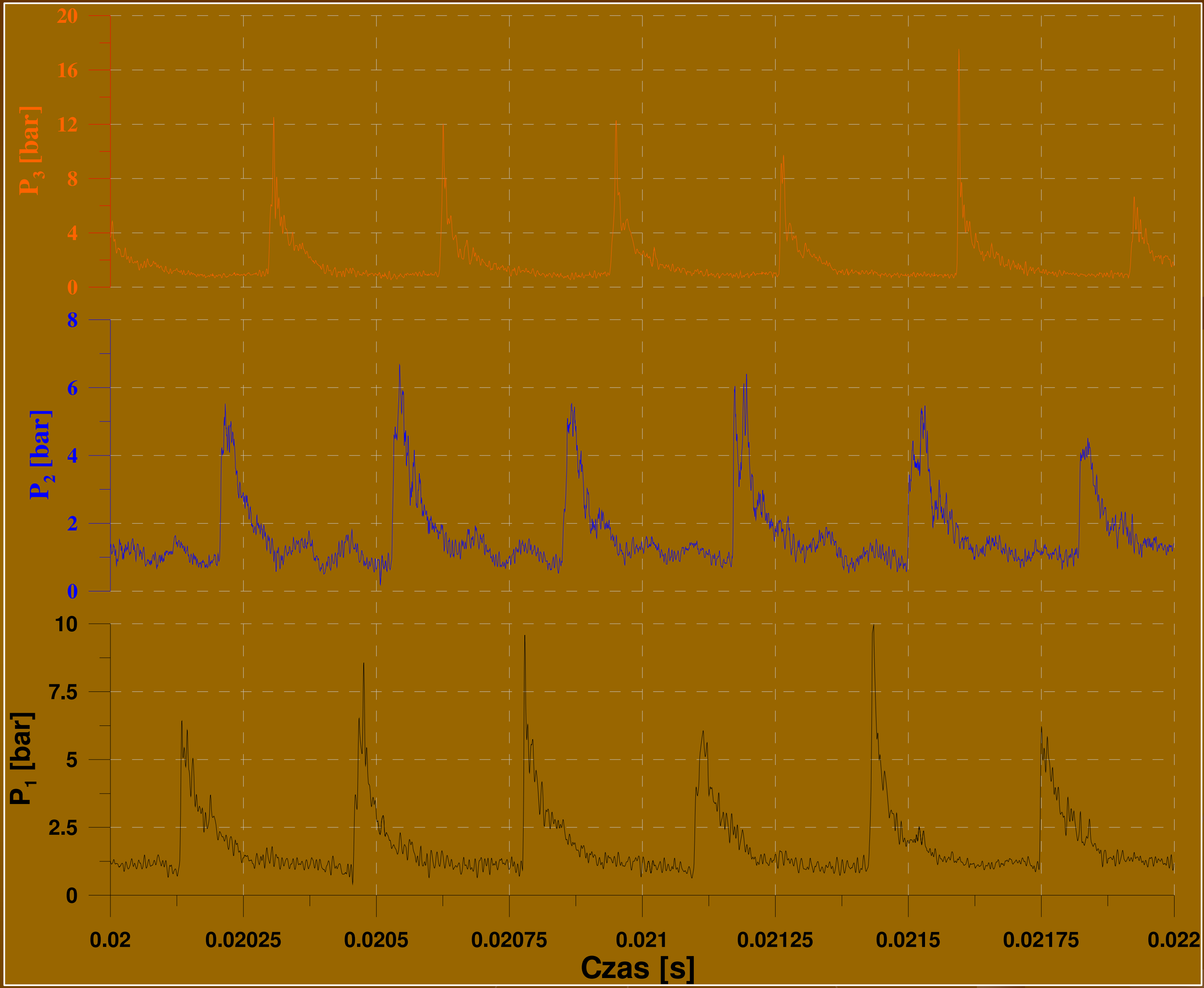
Cylindical channel D=140/150mm

Hydrogen – air; p_o=1.0bar

Professor Piotr Wolanski



- Total duration = 55-13msec = 42msec = 238 rotations



- (1) Steady propagation and (2) period of rotation 350microsec.

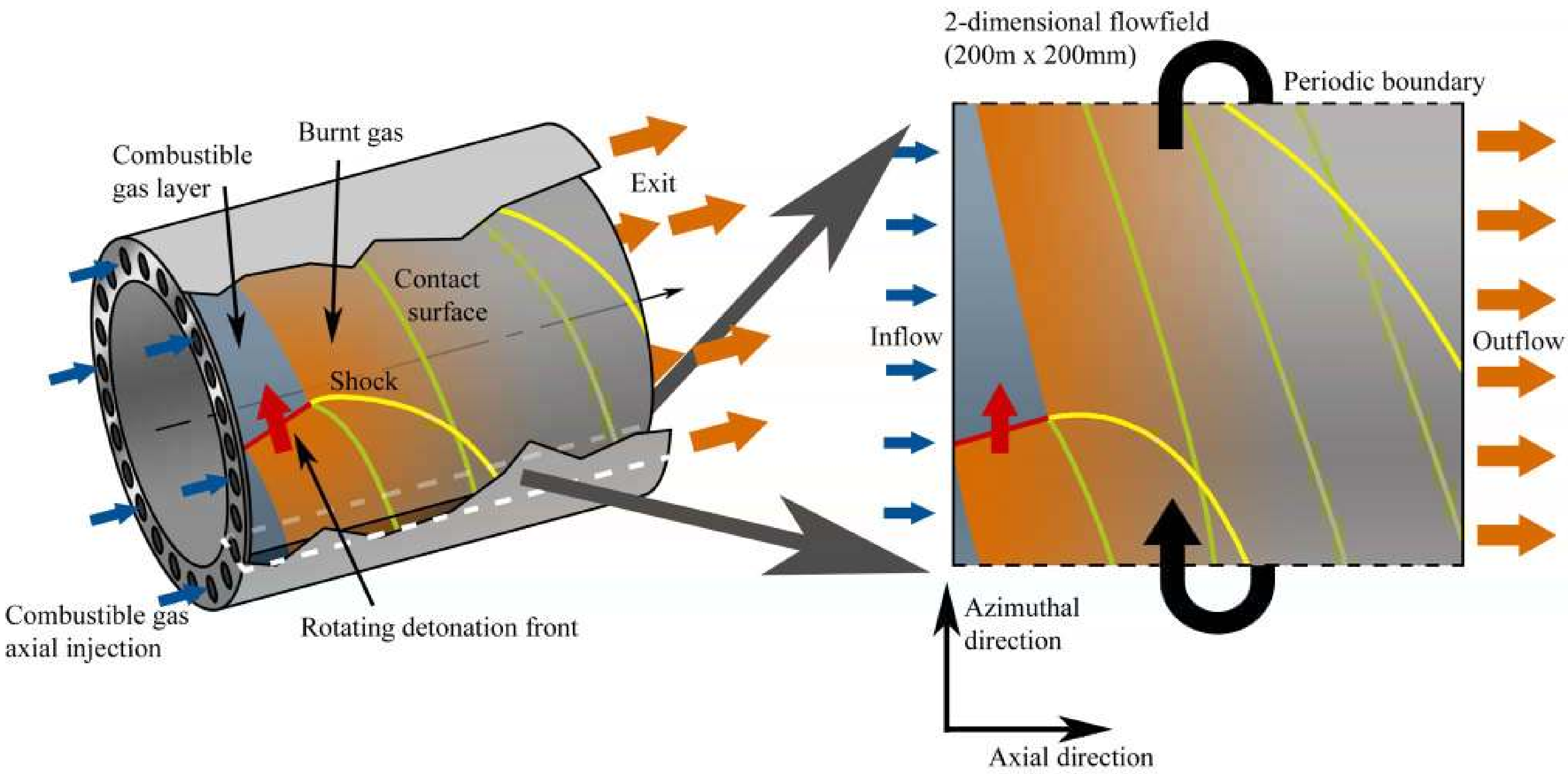
Rotating Detonation Engine (RDE)

- Detonation engines:
  - **Higher energy release rate, higher thermodynamic efficiency, and easier scaling compared with conventional engines using deflagration.**
  - **Applicable to spaceplanes or high-speed airplanes.**
  - **Standing Detonation Engine:**
    - **Continuous injection of combustible gas = simple system.**
    - **Injection velocity is strictly limited (faster than CJ value) = narrow operating conditions.**
  - **Pulse Detonation Engine (PDE):**
    - **Wide operating conditions (flight Mach number = 0~5).**
    - **Repetitive and intermittent thrust = complicated system for fast purging and refilling.**
  - **Rotating Detonation Engine (RDE):**
    - **Simple configuration and higher thrust due to continuous injection.**
    - **Wide operating conditions without limitation of injection velocity.**

⬇ RDE has advantages, but

Flowfield in RDE is unknown, could be complicated and yet is absolutely necessary for application to thrusters.

RDE configuration and modeling



Flowfield in an annular cylindrical channel of RDE can be unrolled into a 2-D one with a periodic boundary, assuming radial thickness of channel << radius of channel.

Purpose of Present Study

(1) A 2-D numerical simulation of RDE gives a nearly-steady periodical solution for Ar-diluted stoichiometric oxyhydrogen mixture $2H_2 + O_2 + 7Ar$ as combustible gas ?

(2) What are detonation and pressure wave propagations like ? Flowfield characteristics needs to be clarified.

(3) Flow exhausted from exit, which should be introduced into turbine for aircraft thrusters, is discussed.

(4) New physics discovered during study is discussed.

Governing equations

- Unsteady compressible 2-D Euler equations.
  - Modified Korobeinikov-Levin 2-step chemical reaction model.

    Constants in model are selected to agree with Oran's elementary reaction model, with regard to induction time and temperature profile.

$$\omega_\alpha \equiv \frac{d\alpha}{dt} = -\frac{1}{\tau_{\text{ind}}} = -k_1 \rho \exp\left(-\frac{E_1}{RT}\right)$$

$$\omega_\beta \equiv \frac{d\beta}{dt} = \begin{cases} 0 & (\alpha > 0) \\ -k_2 p^2 \left\{ \beta^2 \exp\left(-\frac{E_2}{RT}\right) - (1-\beta)^2 \exp\left(-\frac{E_2+Q}{RT}\right) \right\} & (\alpha \le 0) \end{cases}$$

Numerical method

- HLLE scheme with MUSCL method for advection terms: Harten-Lax-van Leer-Einfeldt.
  - Van Albada limiter is applied to satisfy TVD condition.

- 4-step Runge-Kutta time integration.

- Grid size = 100 μm, which is sufficient to provide reasonable detonation characteristics. Induction length of detonation = 240 μm.

Stabilized Detonations for Different Inflow Velocities.

There are 3 different cases of stabilized detonation:

(a) Rotating detonation,

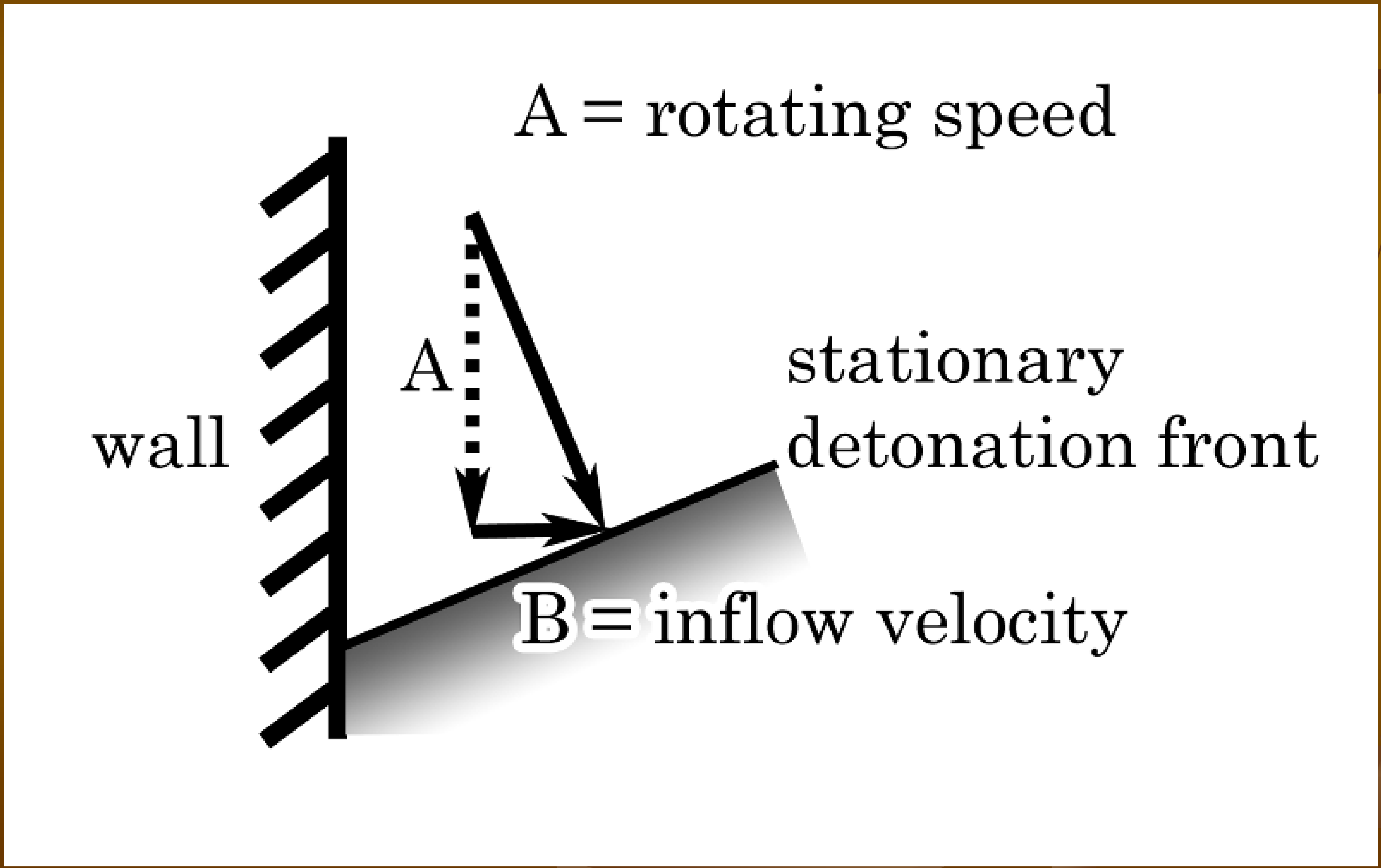
(b) C-J detonation,

(c) Oblique detonation,

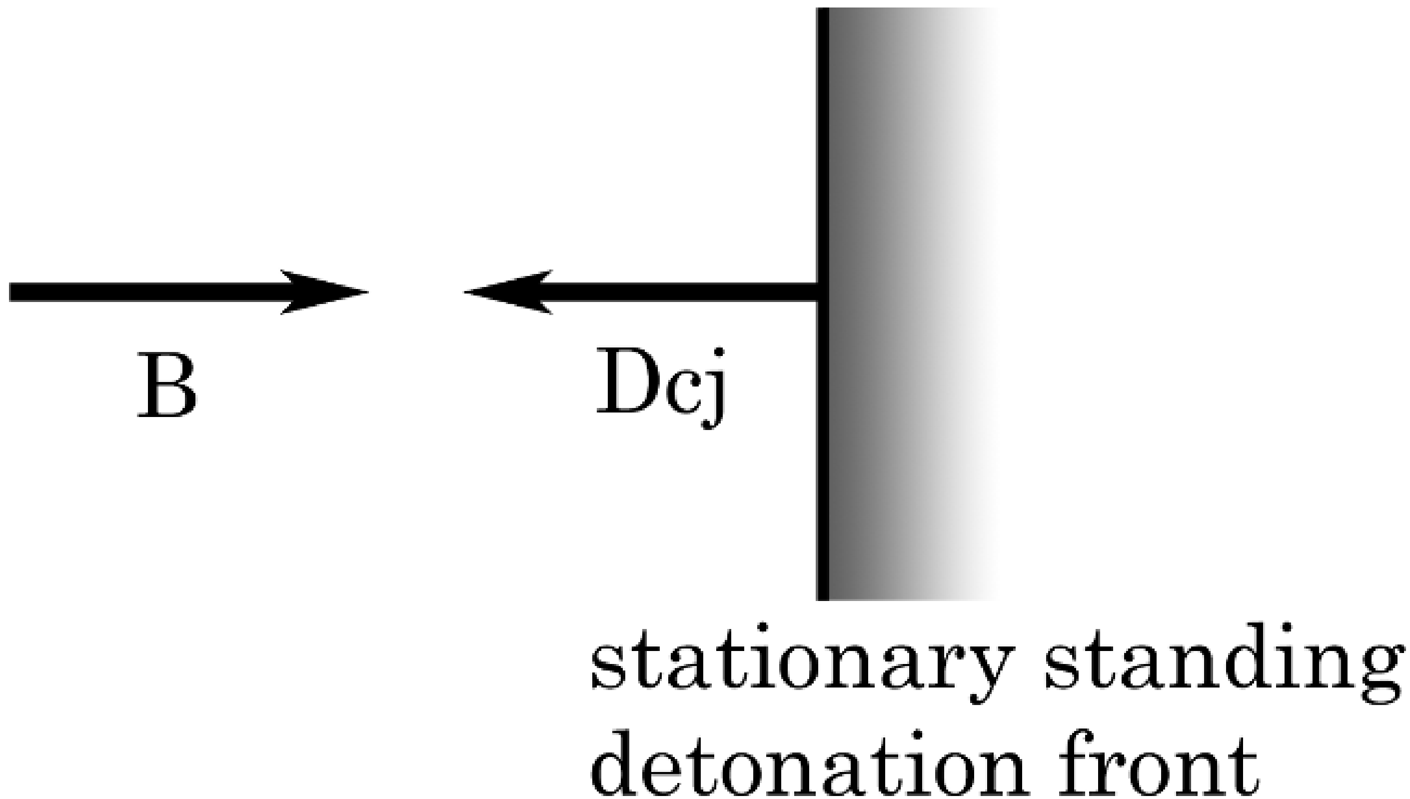
as shown in the followings.

(a) Rotating Detonation: $0 < B < D = (A^2 + B^2)^{1/2} < Dcj$

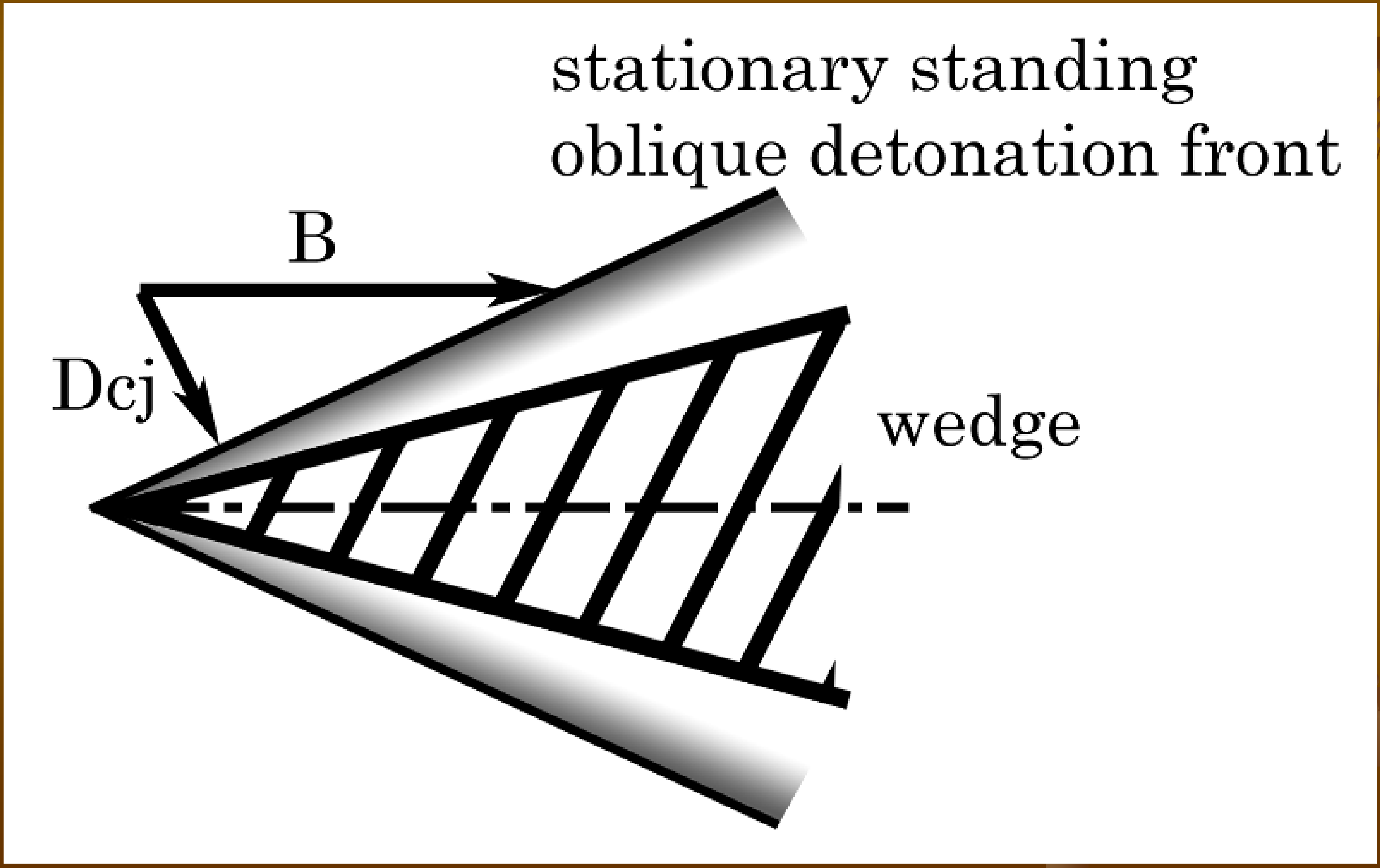
Inflow velocity of combustible mixture is subdetonative.



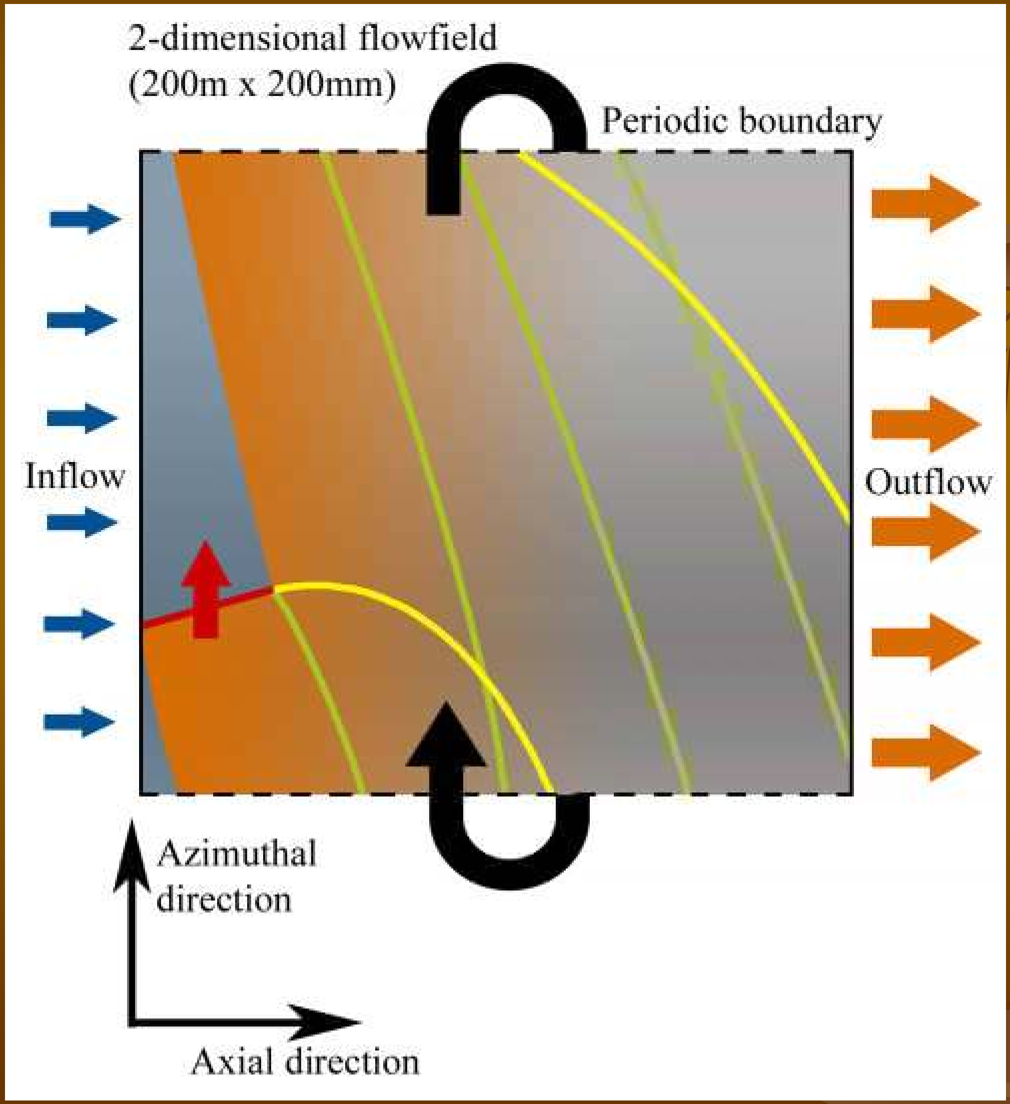
(b) Standing Normal Detonation: B = Dcj, Inflow velocity of combustible mixture is equal to Dcj.



(c) Standing Oblique Detonation: B > Dcj,
Inflow velocity of combustible mixture is superdetonative.



Numerical conditions



1. Boundary conditions:

- Inflow: (1) Choking case;
  Combustible gas ($2H_2 + O_2 + 7Ar$) at 2atm, 298K, and M=1 (331.4m/s) is injected continuously.
  (2) Non-choking case; isentropic expansion from reservoir
  (3) No-inflow case; $p_1 > p_{reservoir}$
- Outflow
  Open to quiescent air at ground conditions

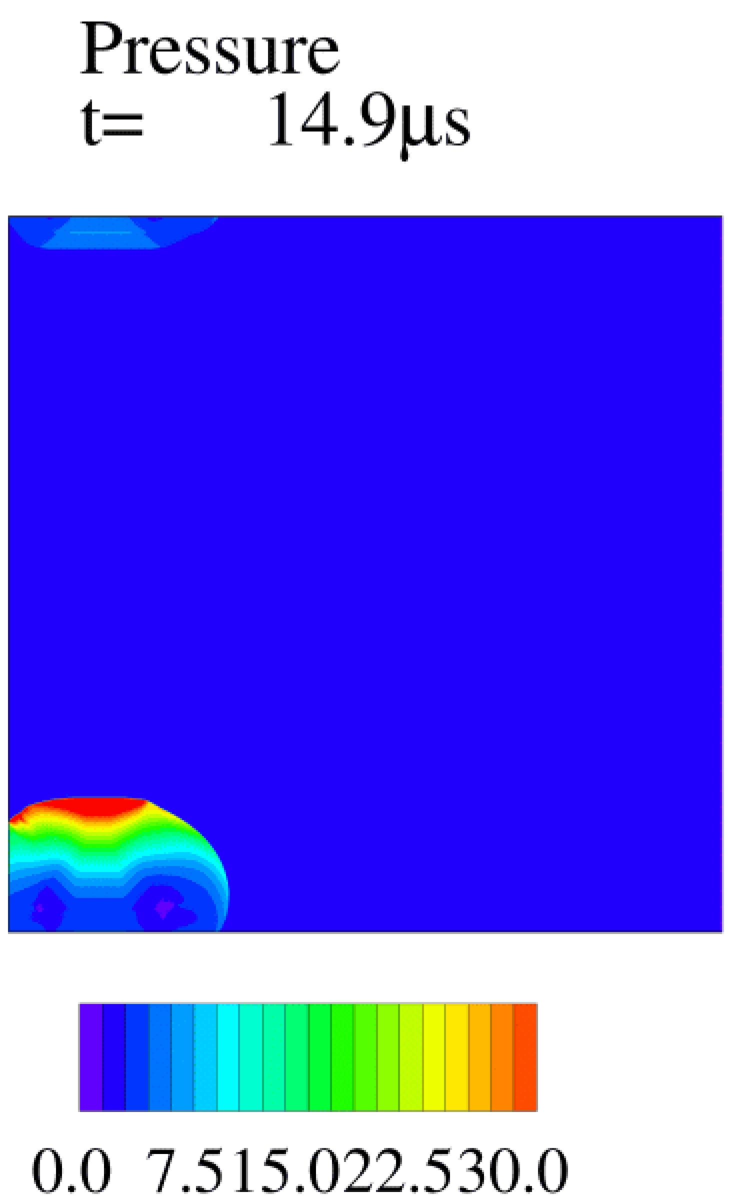
2. Initial conditions:

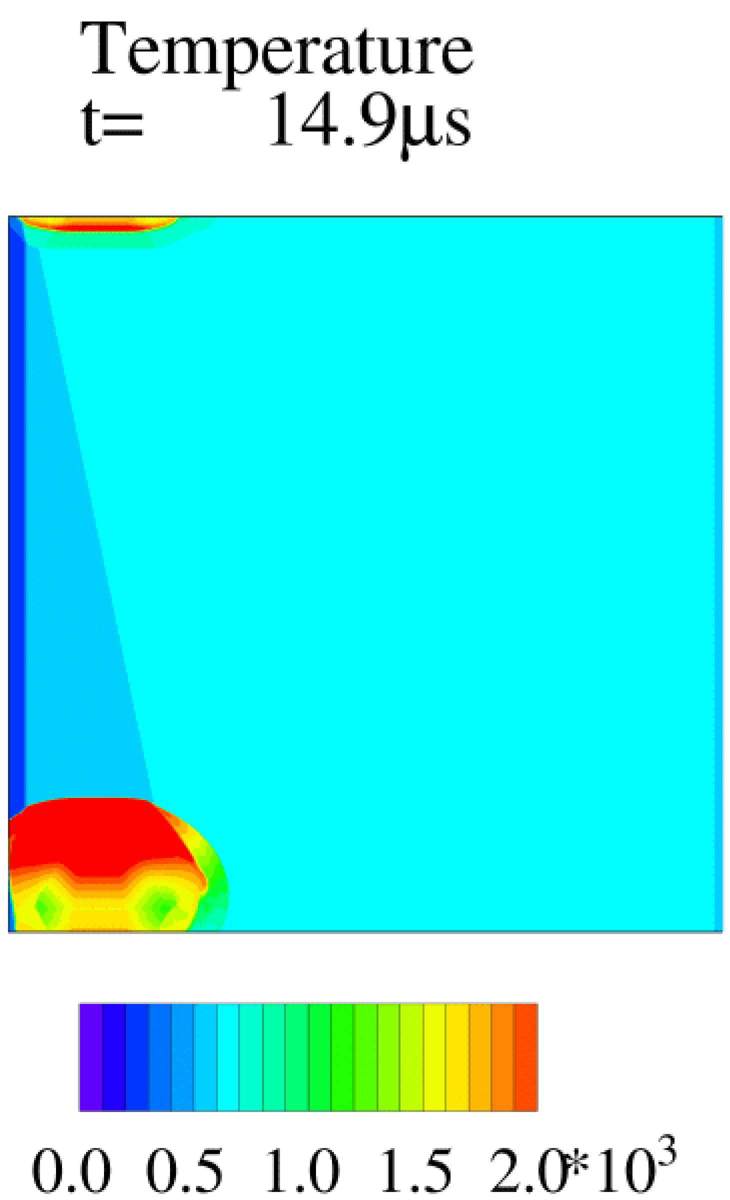
- Combustible gas at 1atm, 298K, and 331.4m/s in blue region of figure (max. width of blue region in axial direction is 4.17cm).
- Inert gas at 1atm, 298K, and 331.4m/s downstream of blue region.

3. Ignition:

- A CJ detonation segment is placed along a red line in figure.

Development of flowfield in Model RDE

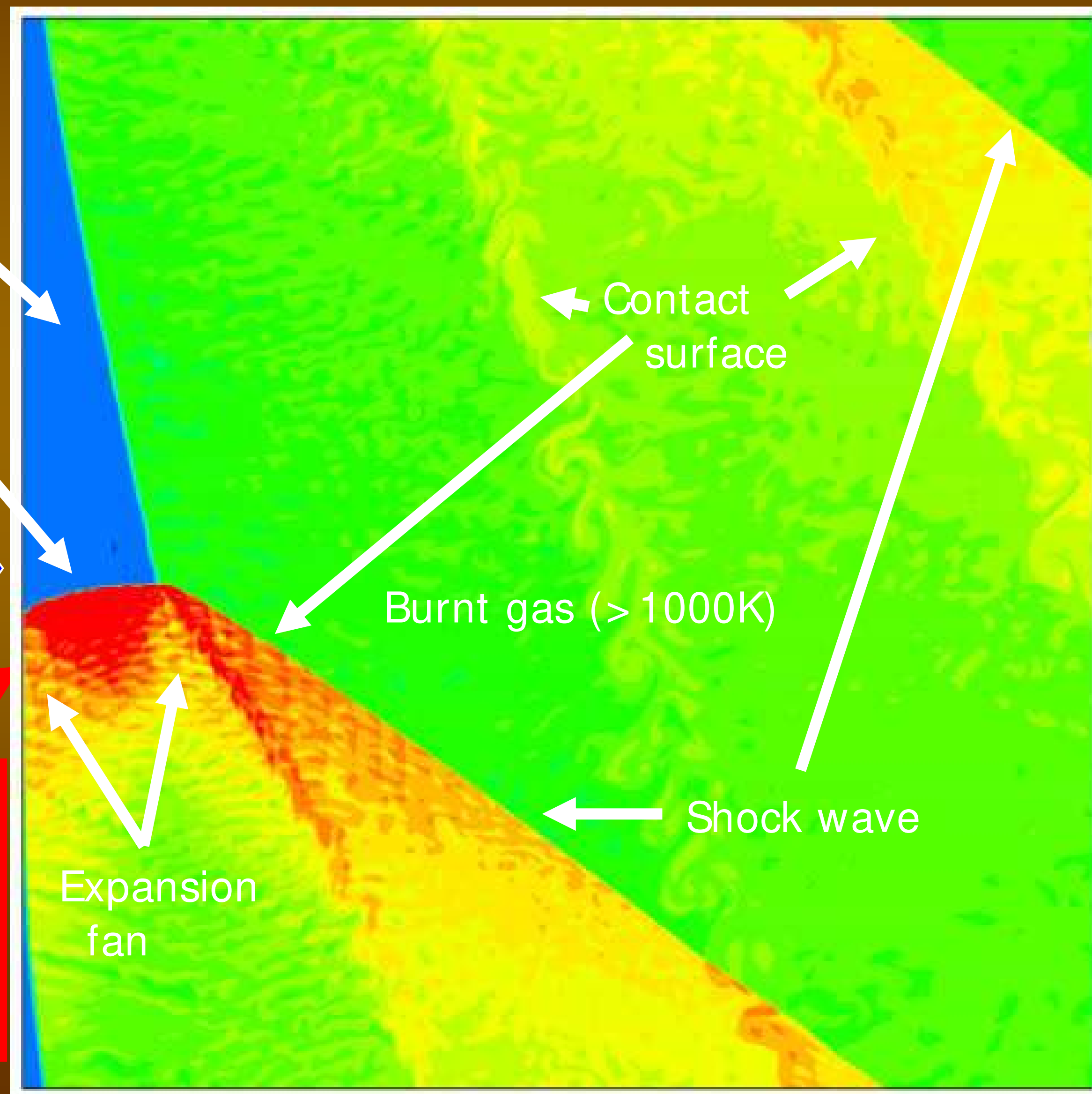




At nearly 1ms after ignition, a detonation rotating azimuthally in channel is seen to propagate steadily.

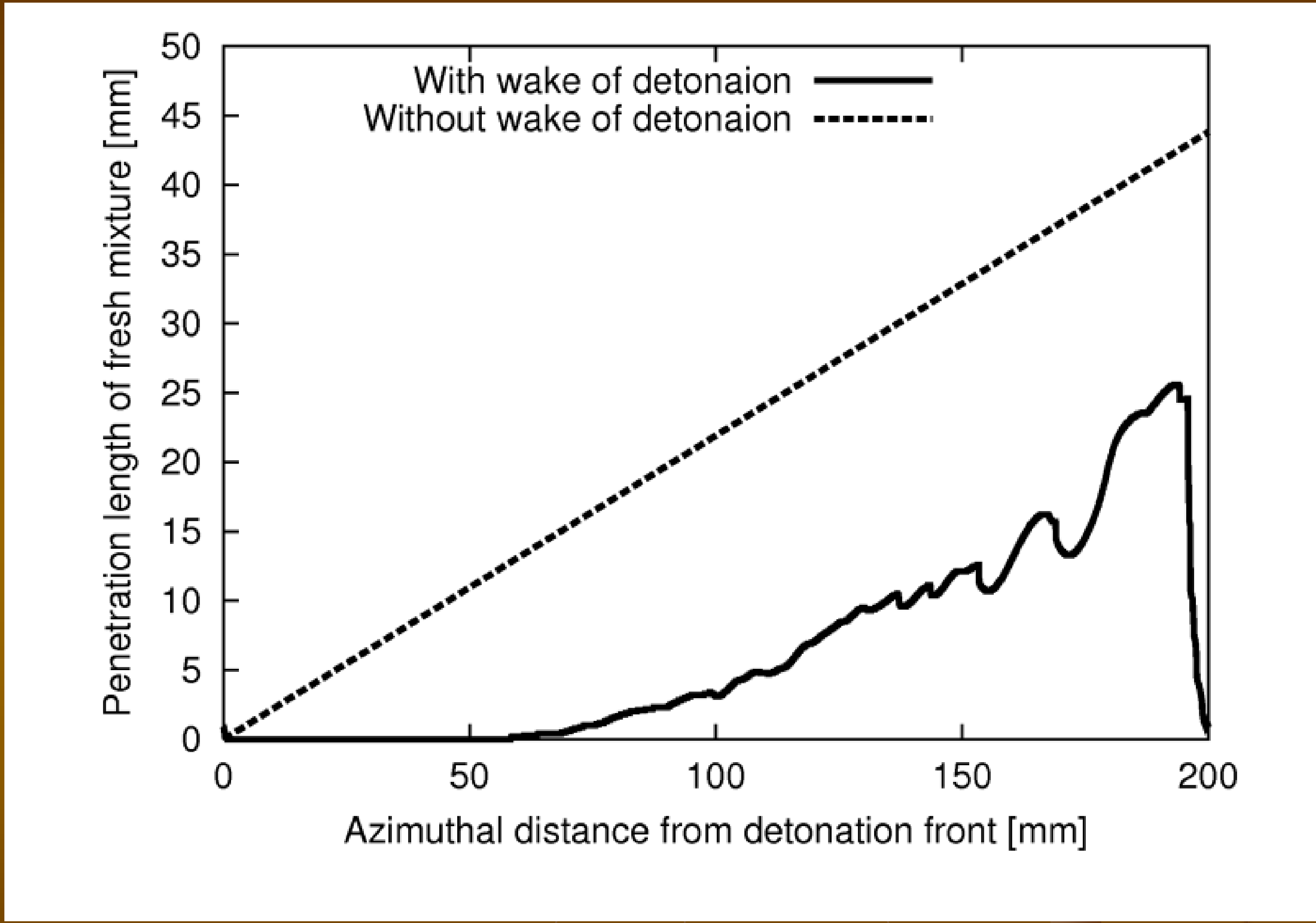
A detailed triple-shock structure is seen on detonation wavelet.

Flow structure in model RDE



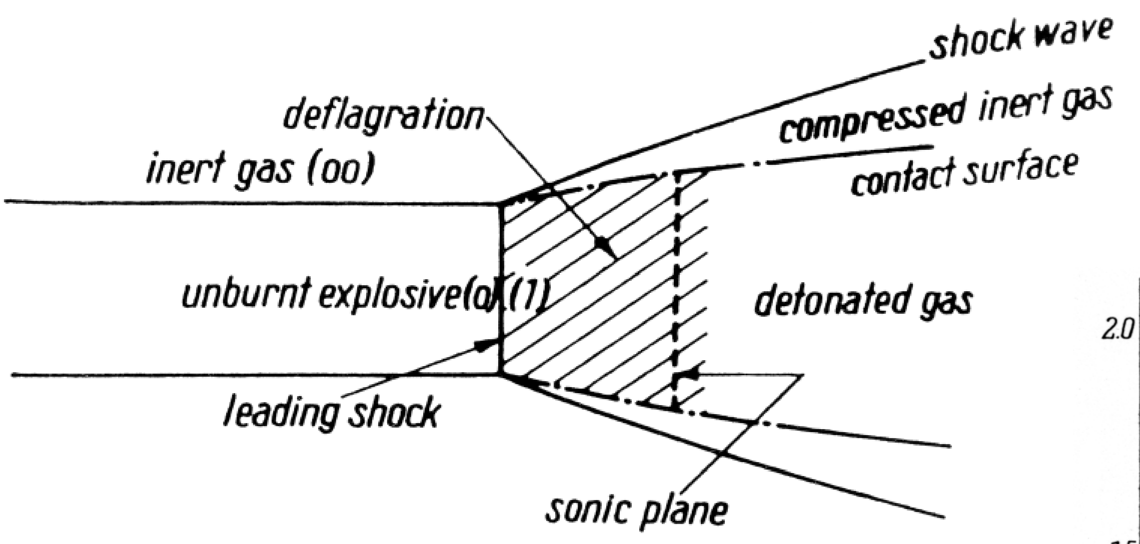
Combustible gas injection is suppressed here due to high pressure right behind rotating detonation.

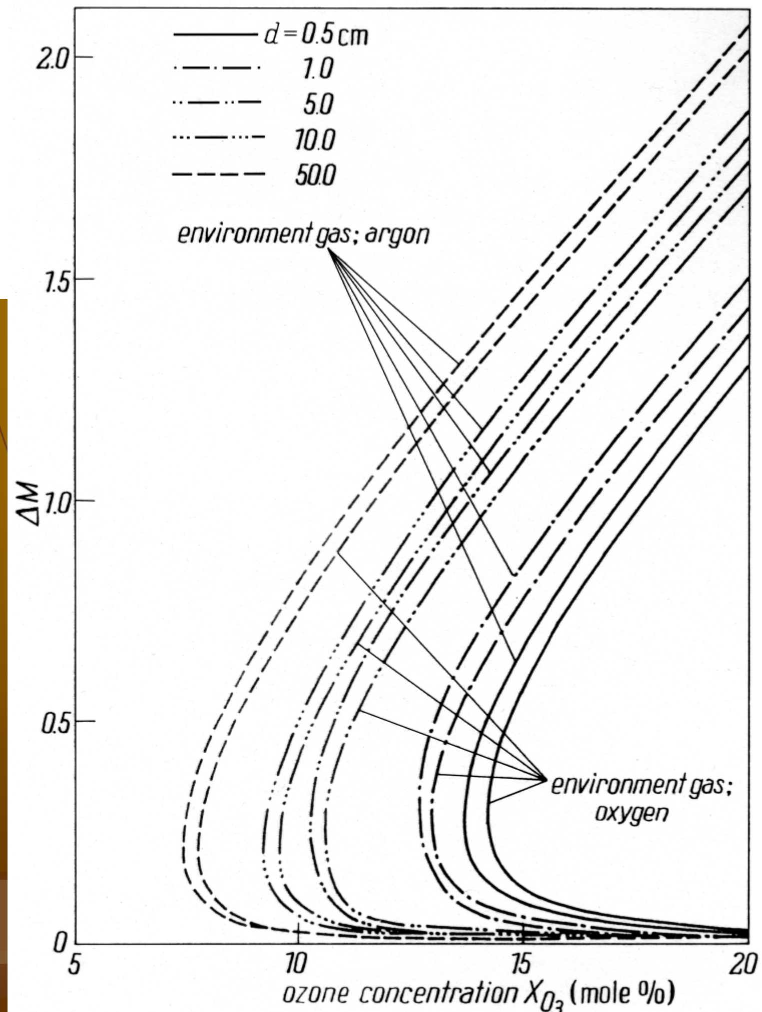
Outline of Combustible Gas Layer: K-H Instability is seen.



Structure of unburnt gas at t=6298.5μsec (during steady rotation). Broken line gives an assumed profile for choking injection where flowfield pressure is low enough to satisfy choking condition between reservoir and flowfield. In reality choking never happens.

A Detonation-Shock Combined Wave

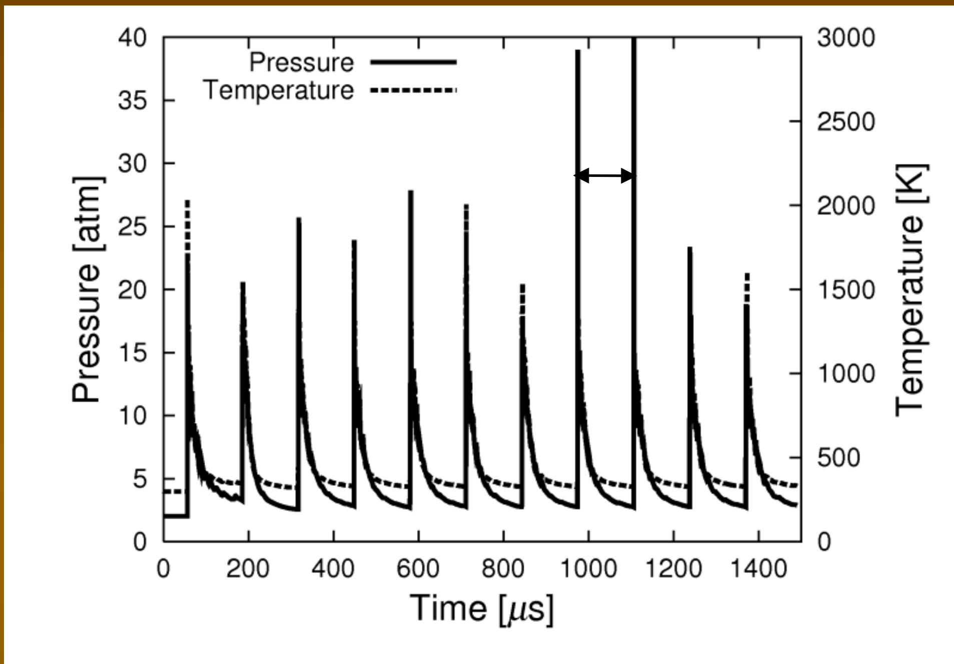




"Detonation wavelet + Shock wave" gives "a detonation-shock combined wave" discussed in by Fujiwara and Tsuge, J.Phys.Soc.Japan, Vol.33, pp.237-241, 1972.

The detonation propagation velocity is given by Generalized C-J Condition, slightly lower than the plane C-J value, depending upon equivalence ratio, wavelet length and environmental gas.

Propagation velocity of rotating detonation



History of pressure and temperature at a position right downstream of combustible gas injection boundary.

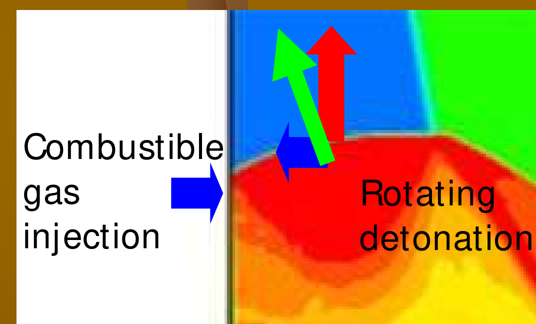
Peaks are fluctuating because the triple points are running along the detonation front and period of data-logging is not synchronized with a cycle of rotating detonation.

Interval between peaks = 132.27μs

Detonation propagation velocity in the azimuthal direction

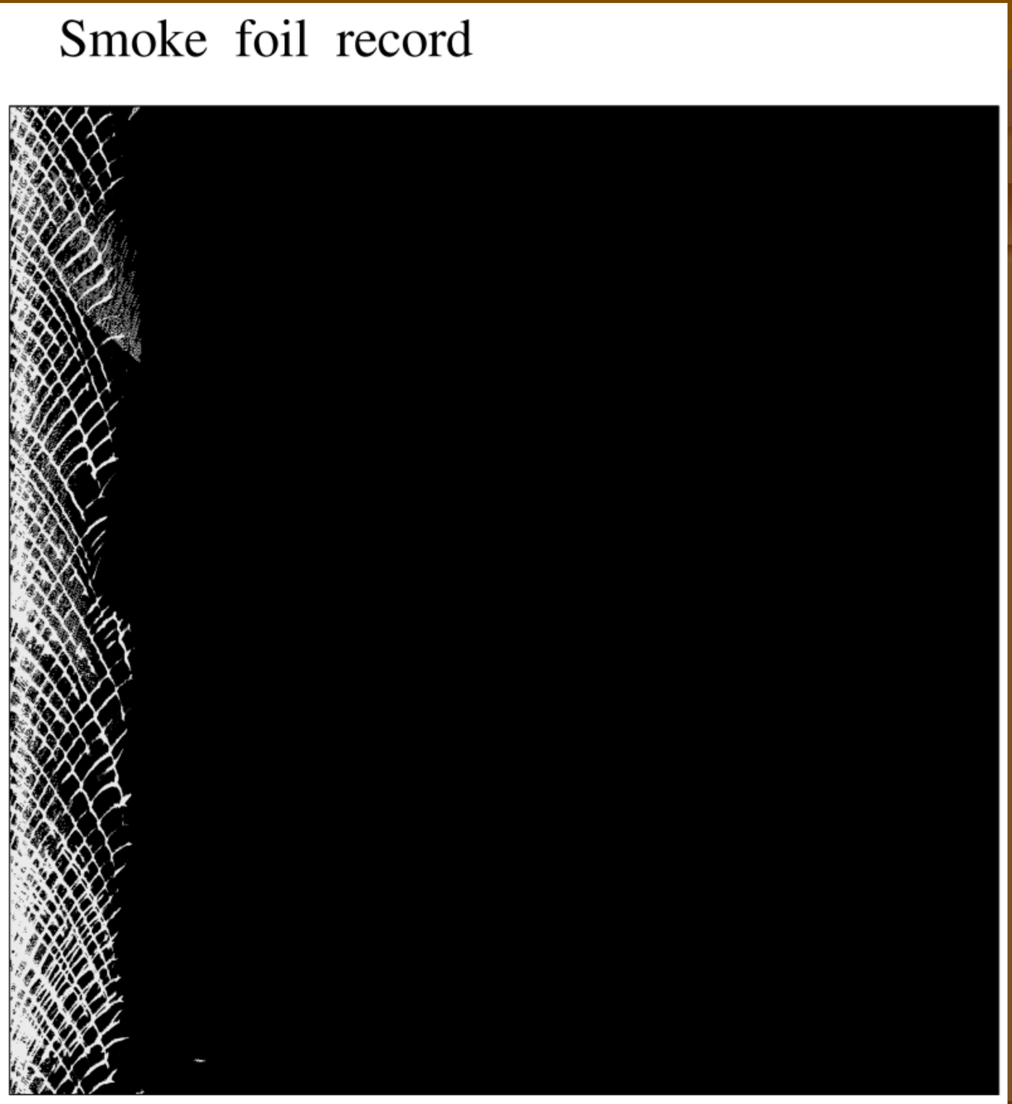
D = 1512.1 m/s

Injection velocity A = 331.4 m/s

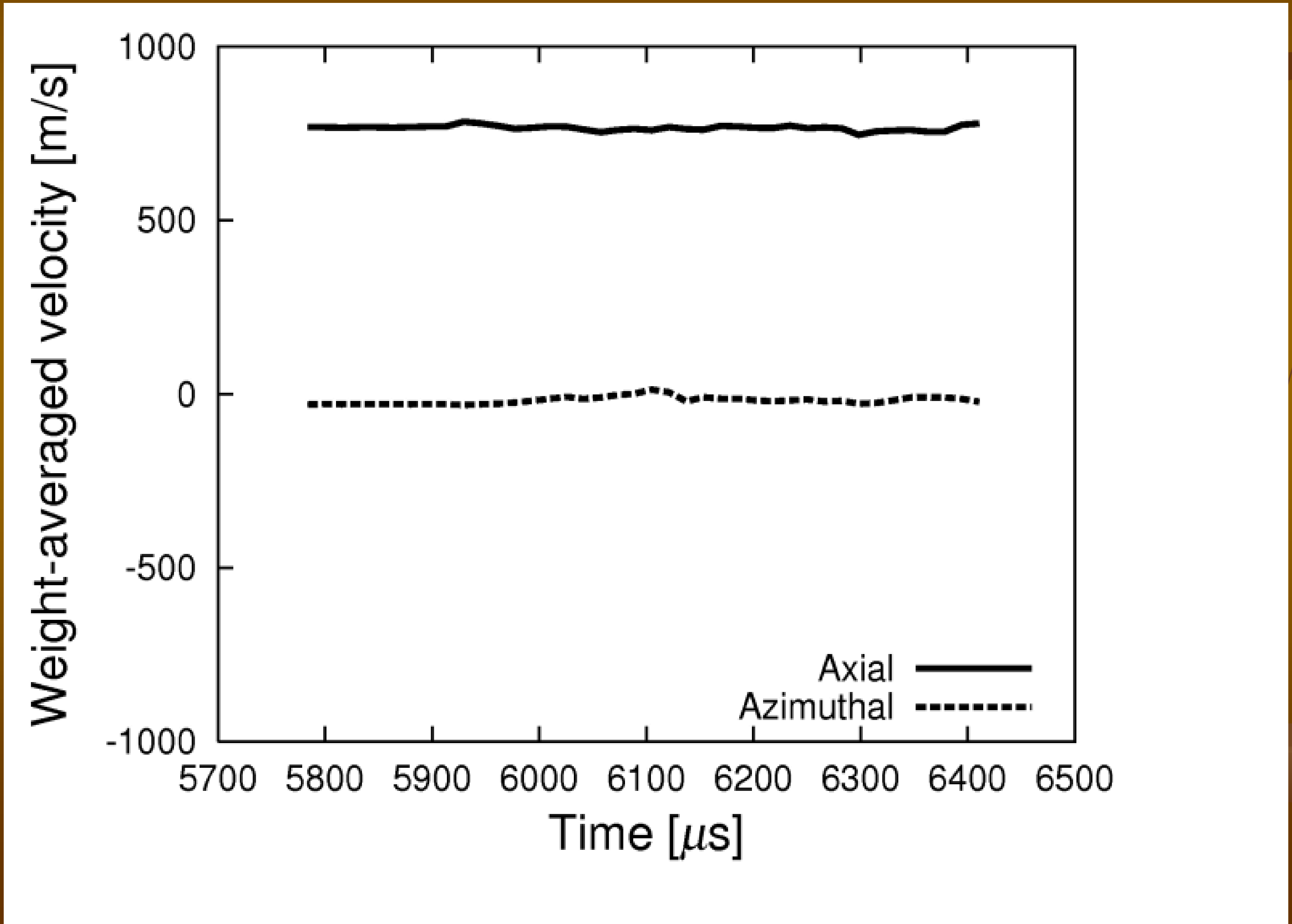


Detonation propagation velocity normal to detonation front B = 1548 m/s (vector sum of D and A) = about 97% of plane CJ value (plane CJ value Dcj = 1591 m/s) probably due to expansion of reaction zone before CJ plane.

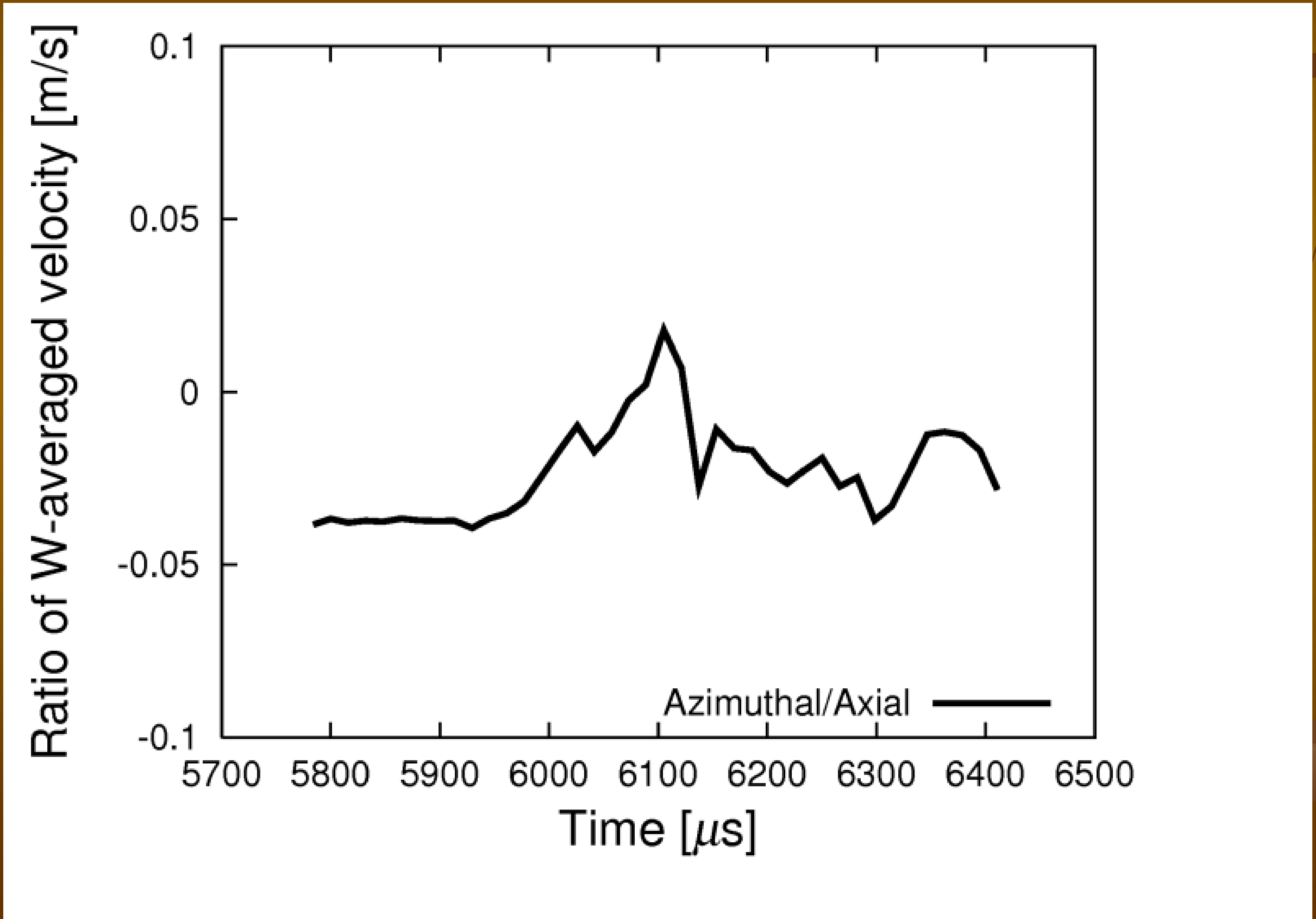
Smoke-foil record written by triple shocks in rotating detonation after t=6250ms (during steady rotation), where white lines are trajectories of pressure higher than 60atm during detonation propagation. Cell size is 3-3.5mm near injection wall, while 4mm in downstream side.



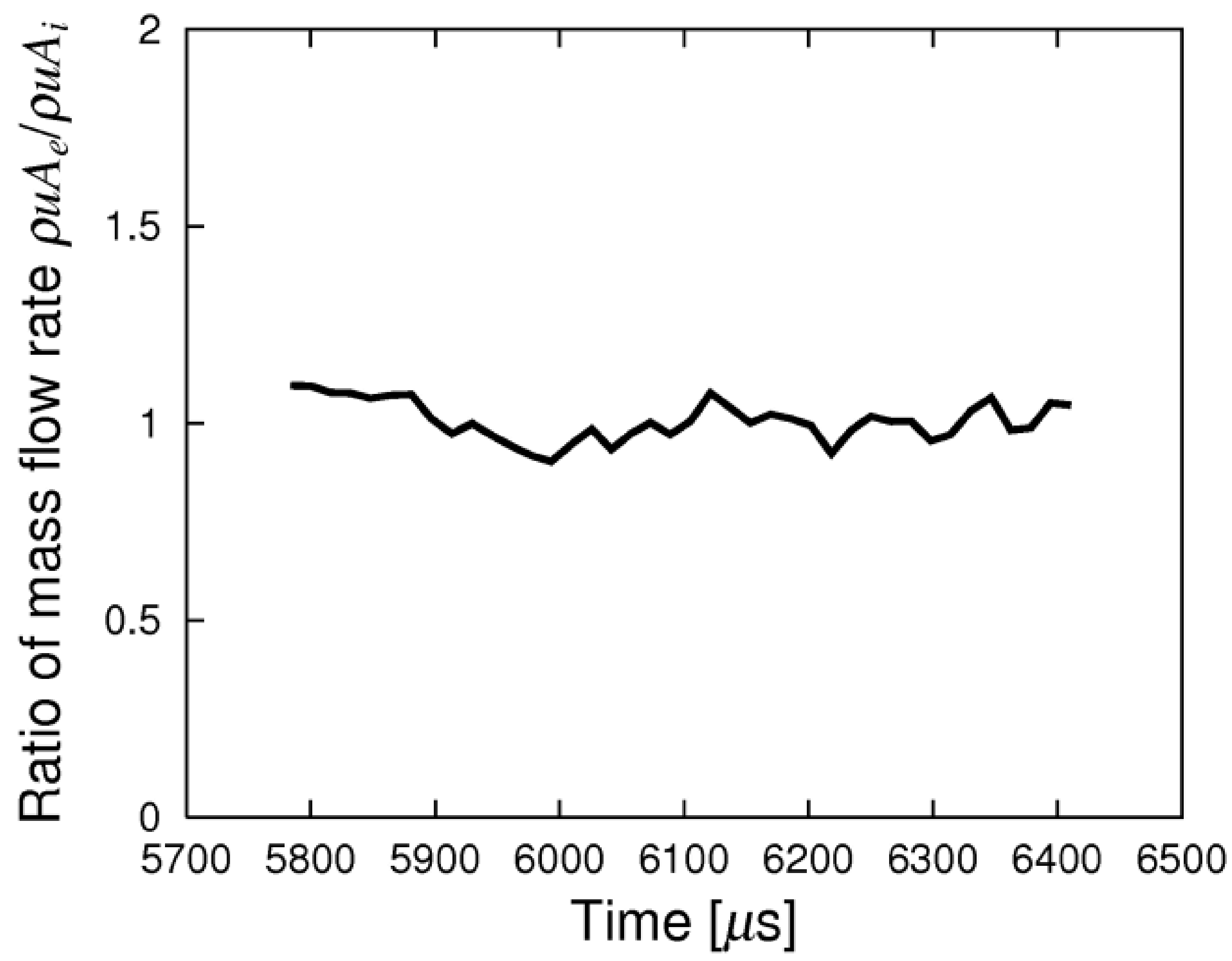
Temporal variation of two velocities density-averaged over exit plane: Angular momentum is conserved



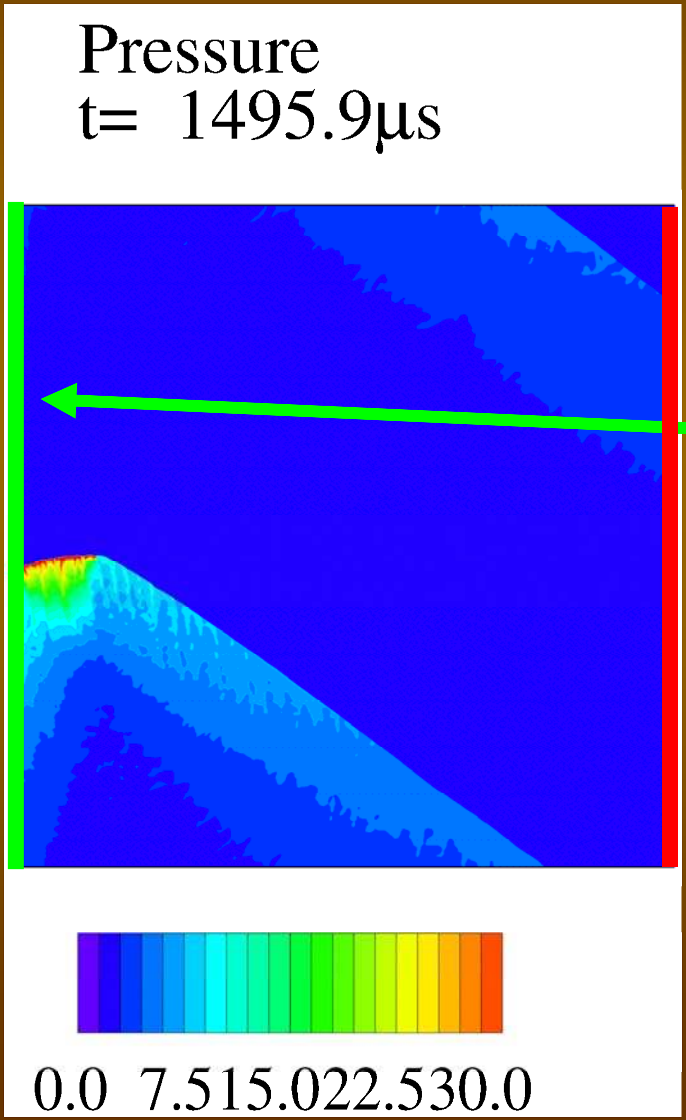
Temporal variation of ratio between density-averaged azimuthal and axial velocities at exit plane – order of 3 %: Angular momentum is conserved.

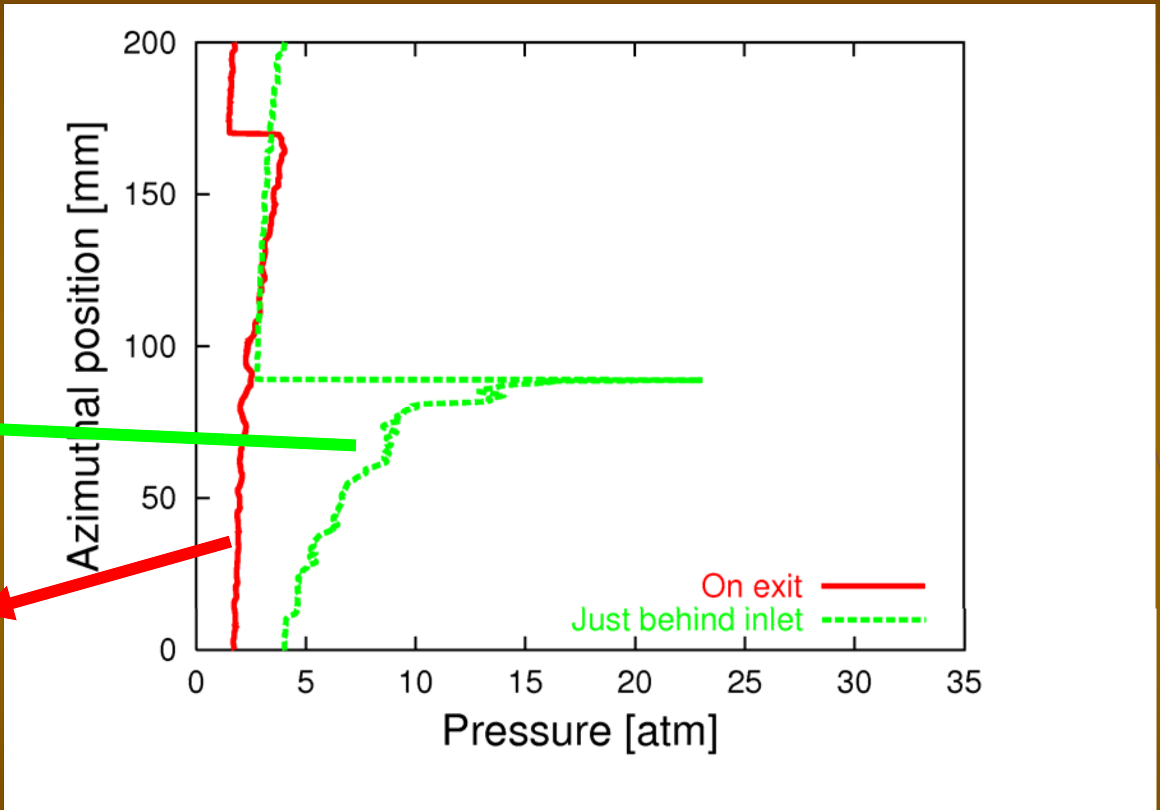


Temporal variation of mass flow ratio between exit and injection planes: Mass is conserved.



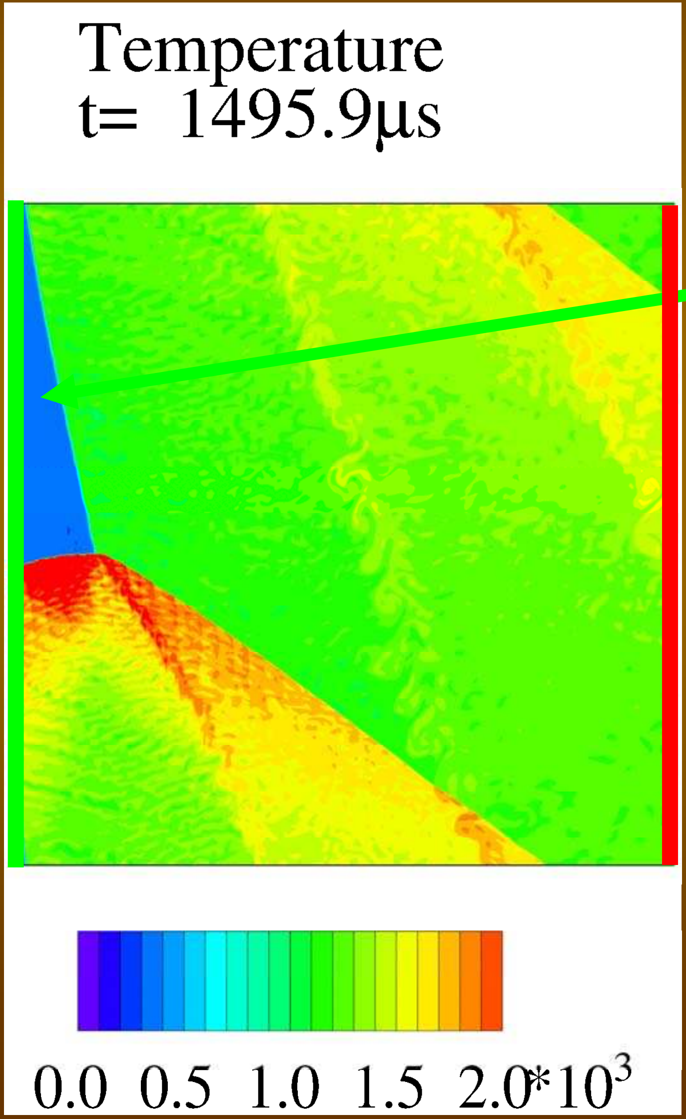
Distribution of pressure along azimuthal direction

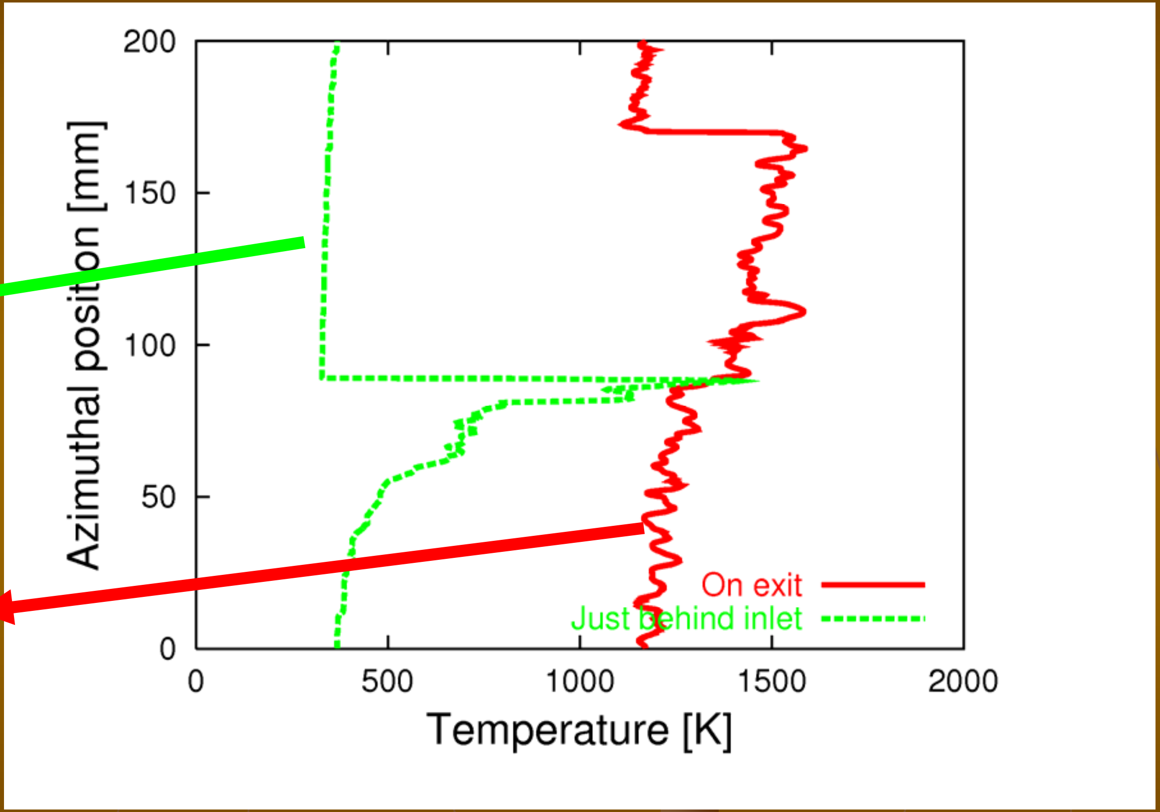




On exit plane, a strong shock followed by expansion wave (red line) still propagates azimuthally. This shock wave weakens toward downstream, changing into a Mach wave far downstream.

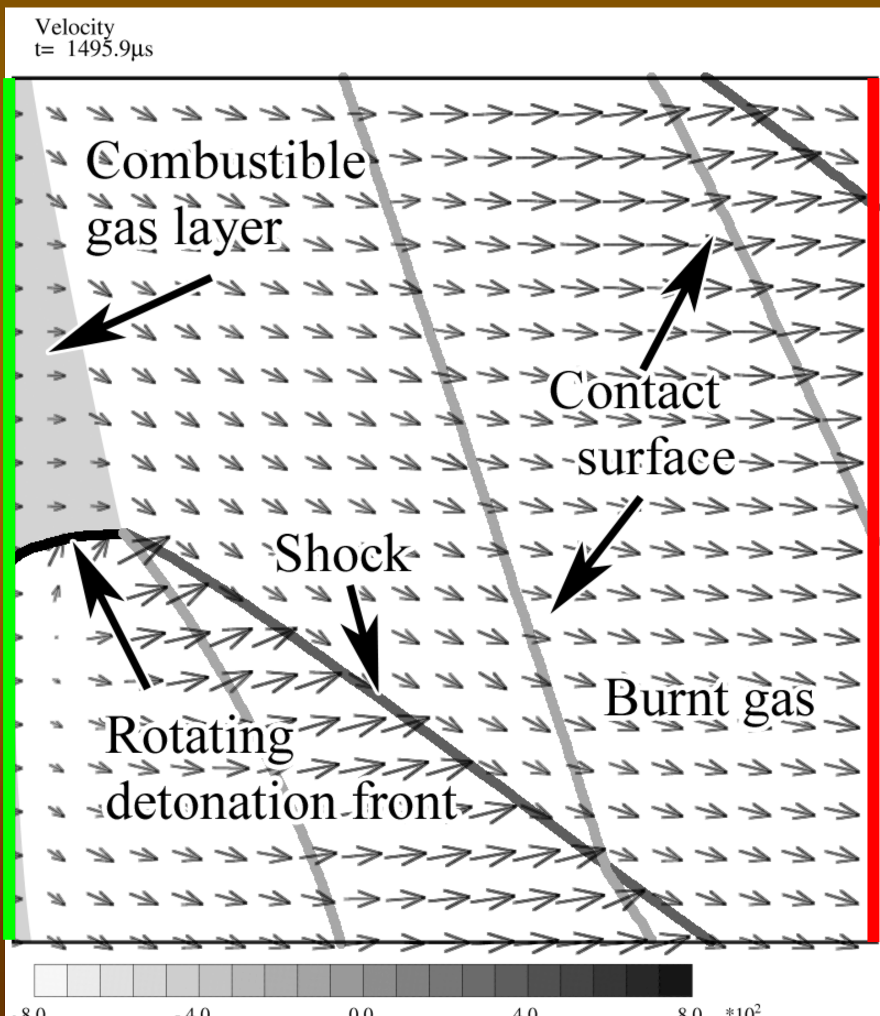
Distribution of temperature along azimuthal direction

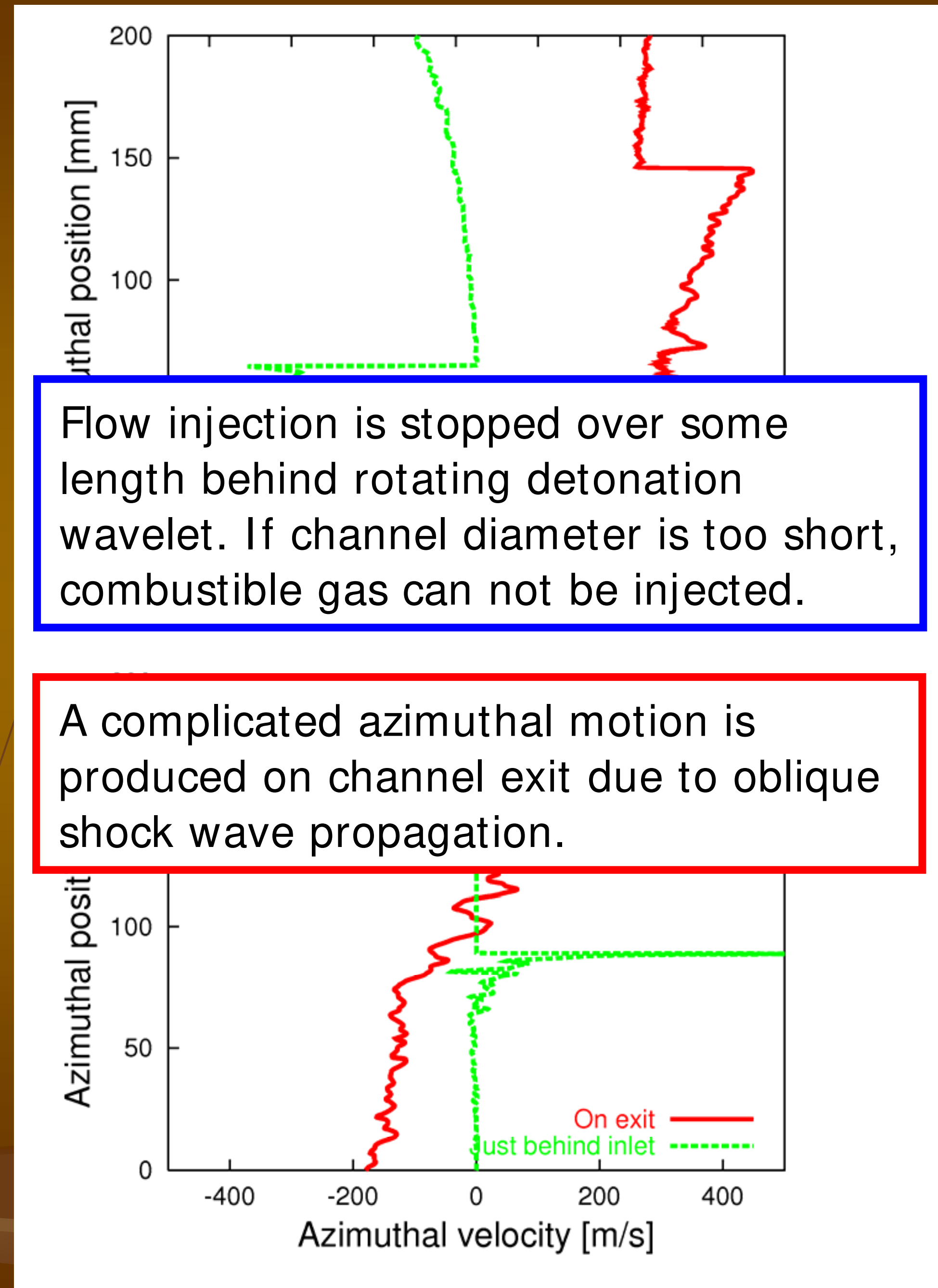




This temperature distribution rotates at a speed near CJ value. Then a turbine, if located behind channel exit, is exposed to a high-frequency (about 7560Hz in this case) temperature fluctuation.

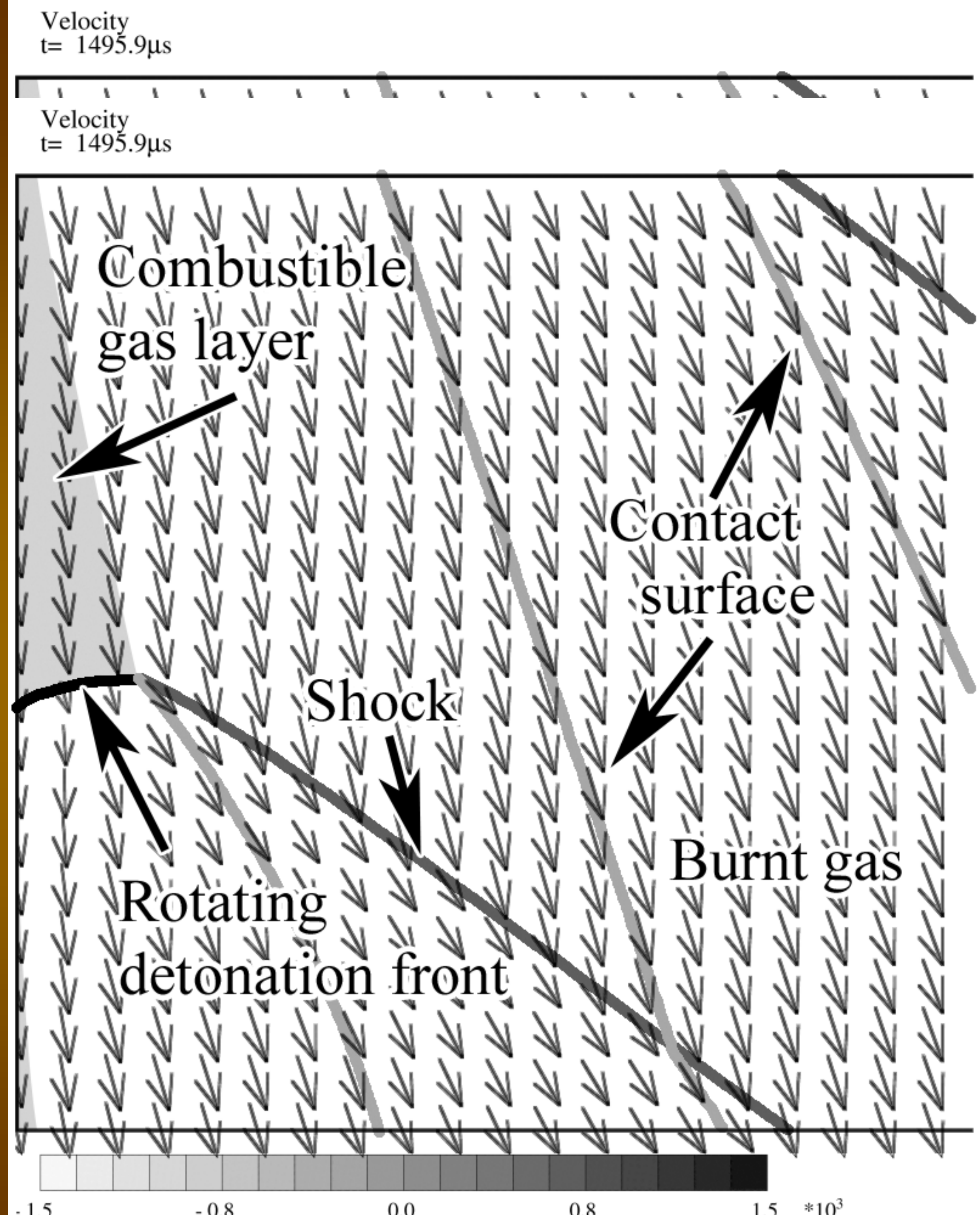
Distribution of velocities
(Laboratory Coordinate System)





Flow injection is stopped over some length behind rotating detonation wavelet. If channel diameter is too short, combustible gas can not be injected.

A complicated azimuthal motion is produced on channel exit due to oblique shock wave propagation.



- Flowfield in Wave Coordinate where detonation front is fixed.

Axial velocity distributions on two planes (injection wall, exit plane) at t=6298.5msec (during steady rotation): 600-900m/sec on exit.

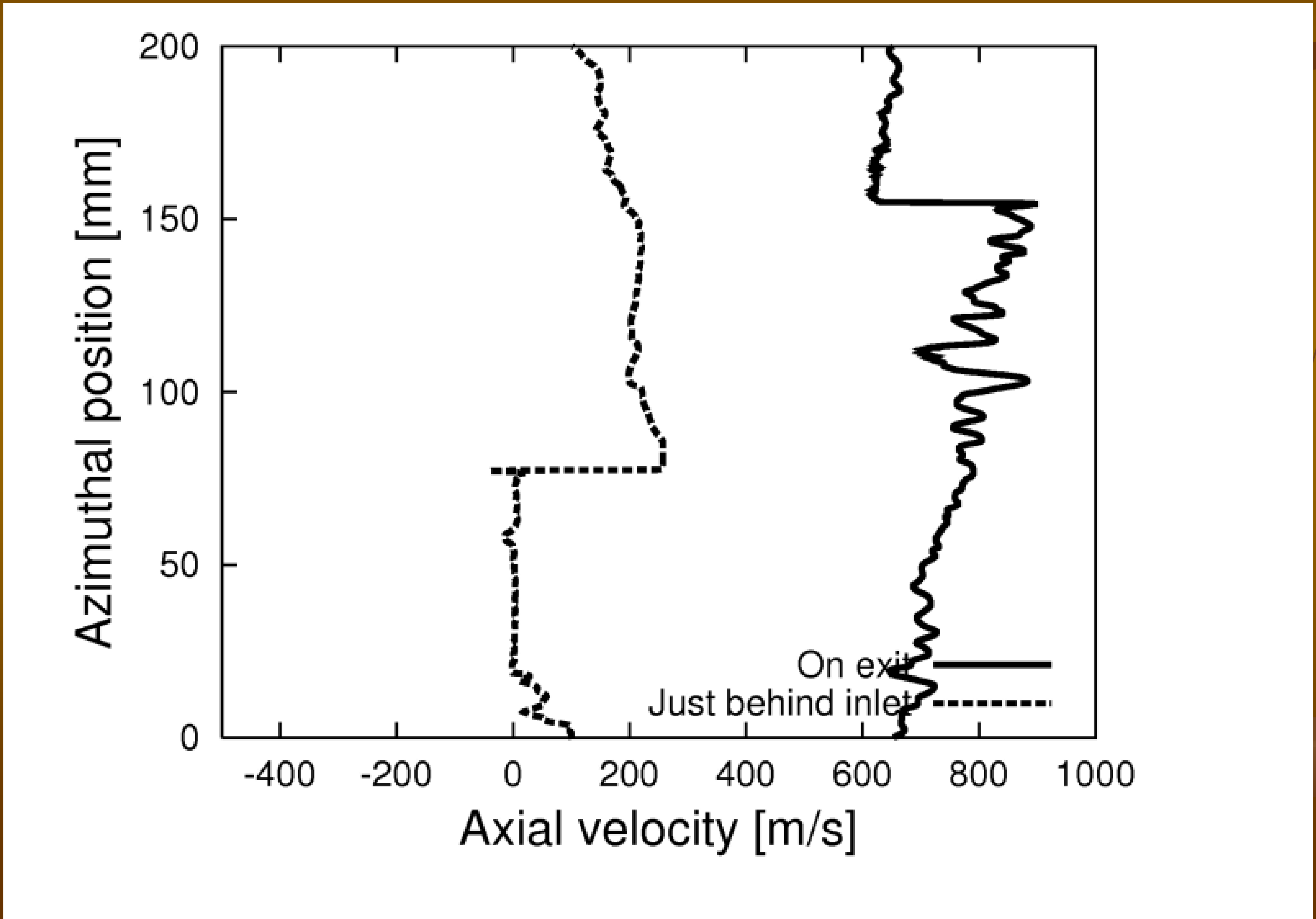
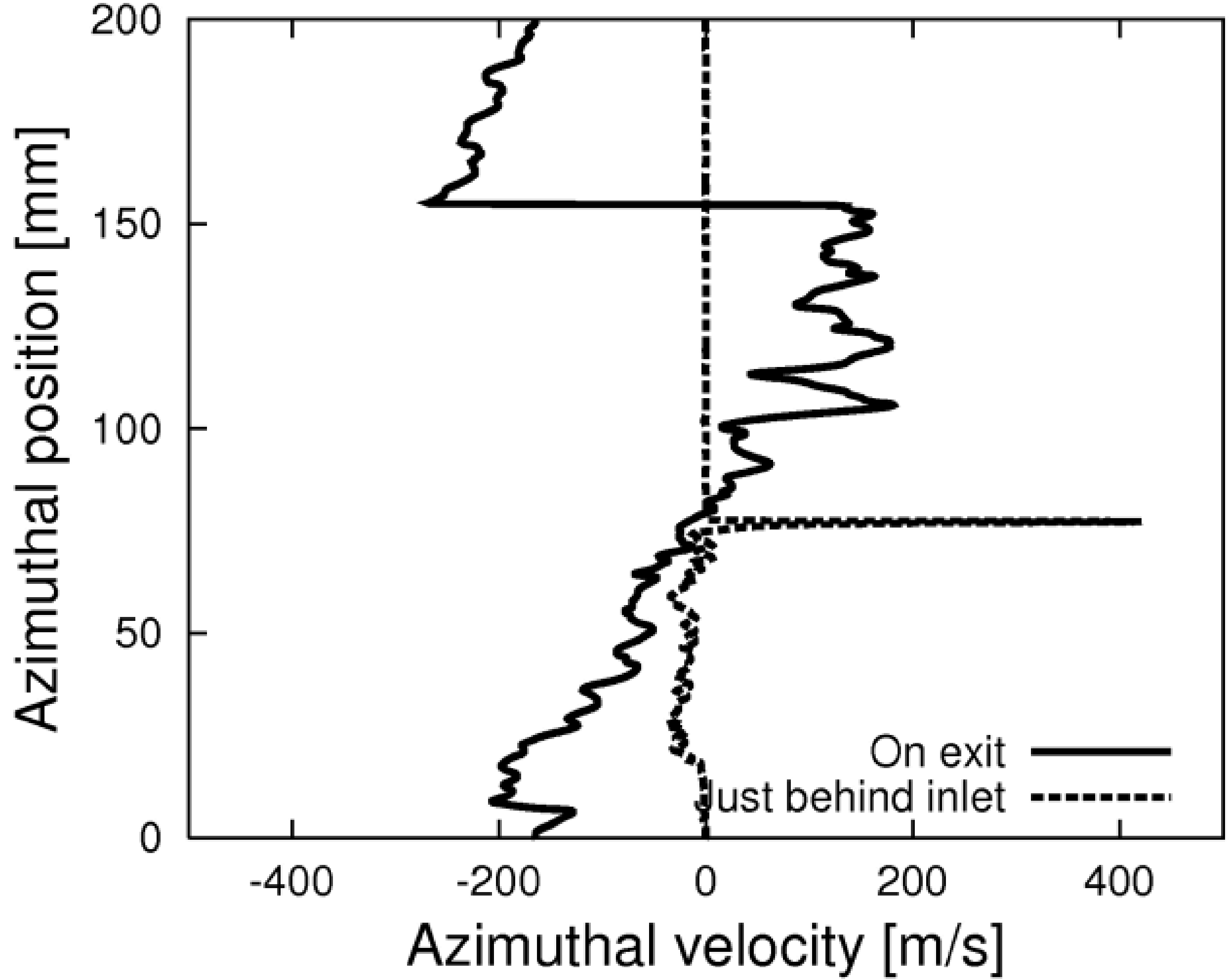
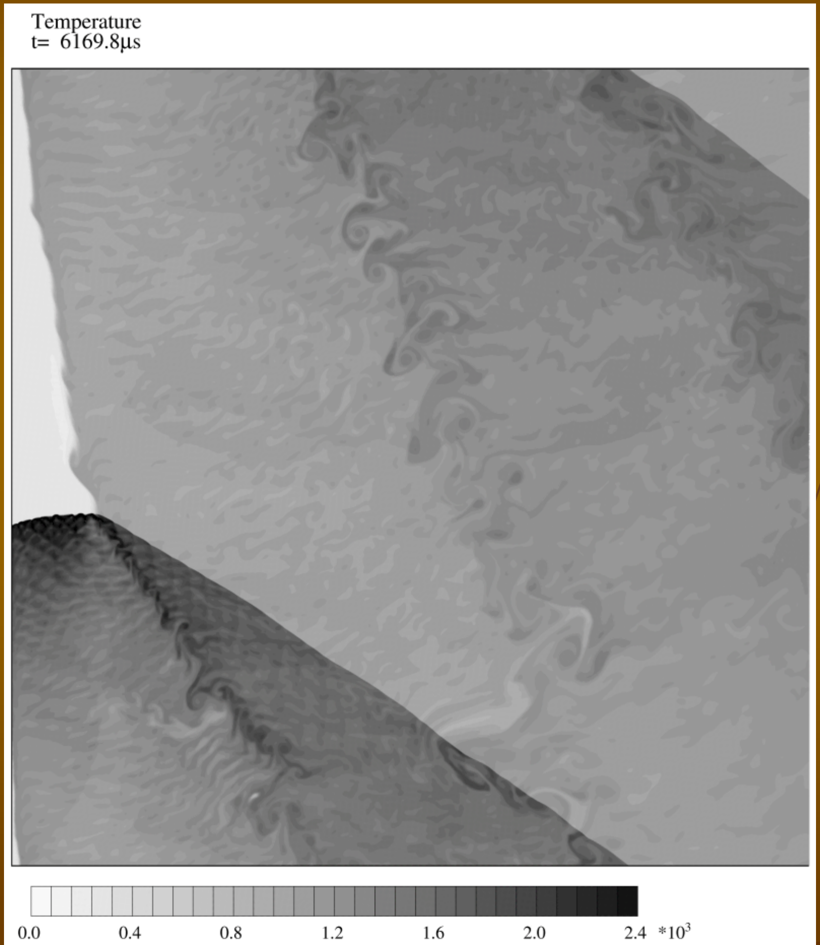


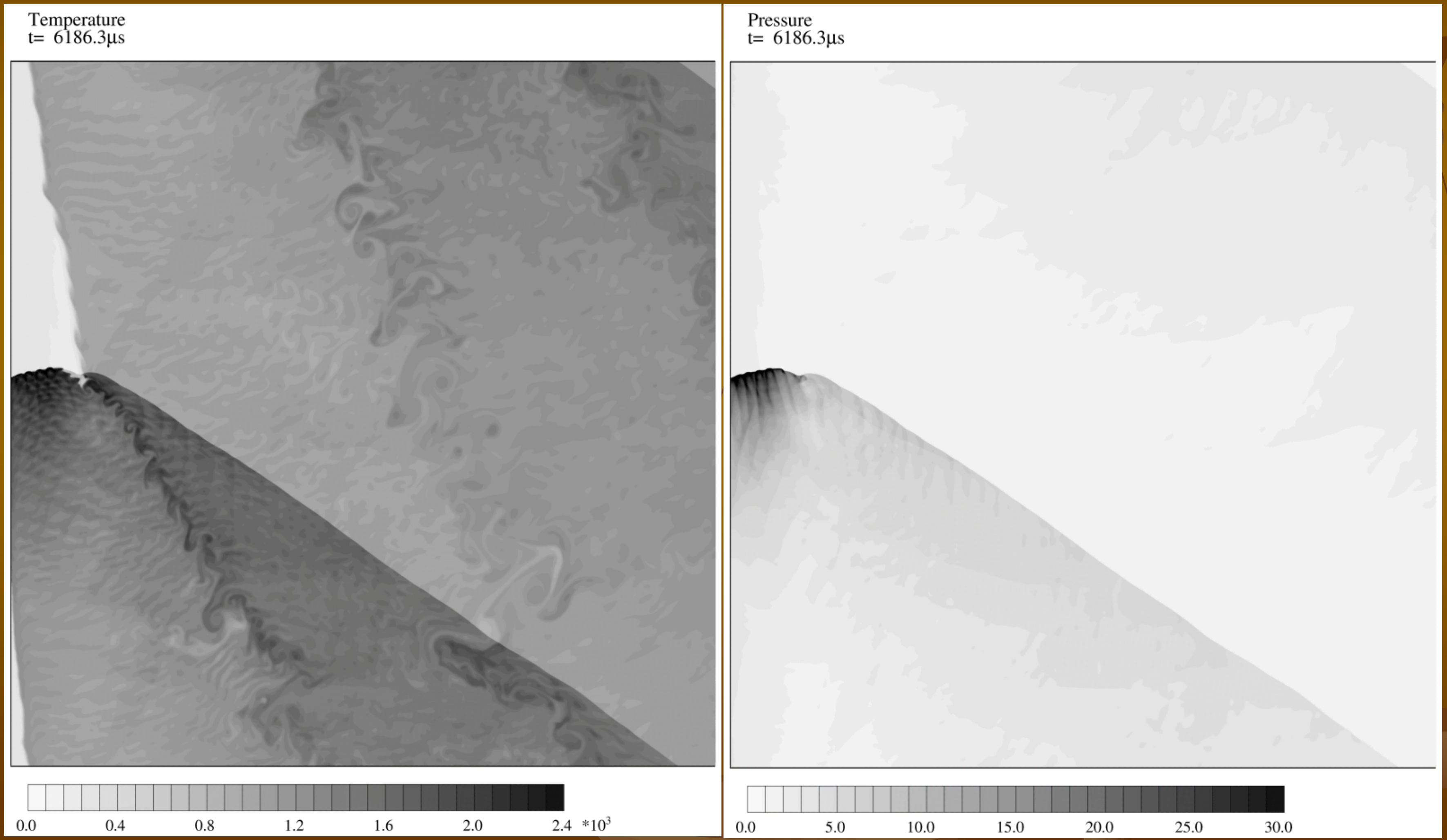
Fig.16 Azimuthal velocity distributions on two planes (injection wall, exit plane) at t=6298.5msec (during steady rotation): Very low.



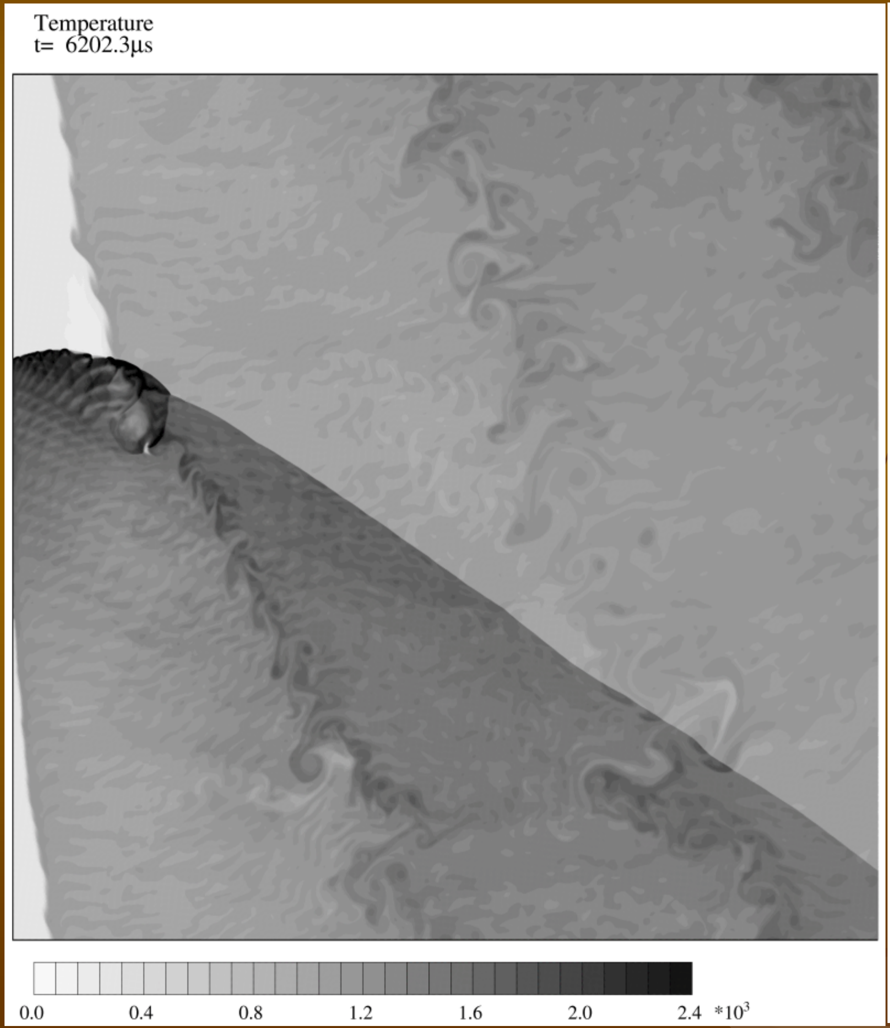
Generation of an unburnt gas pocket explosion caused by K-H instability seen in temperature and pressure distributions at t=6169.8~6202micros (I).



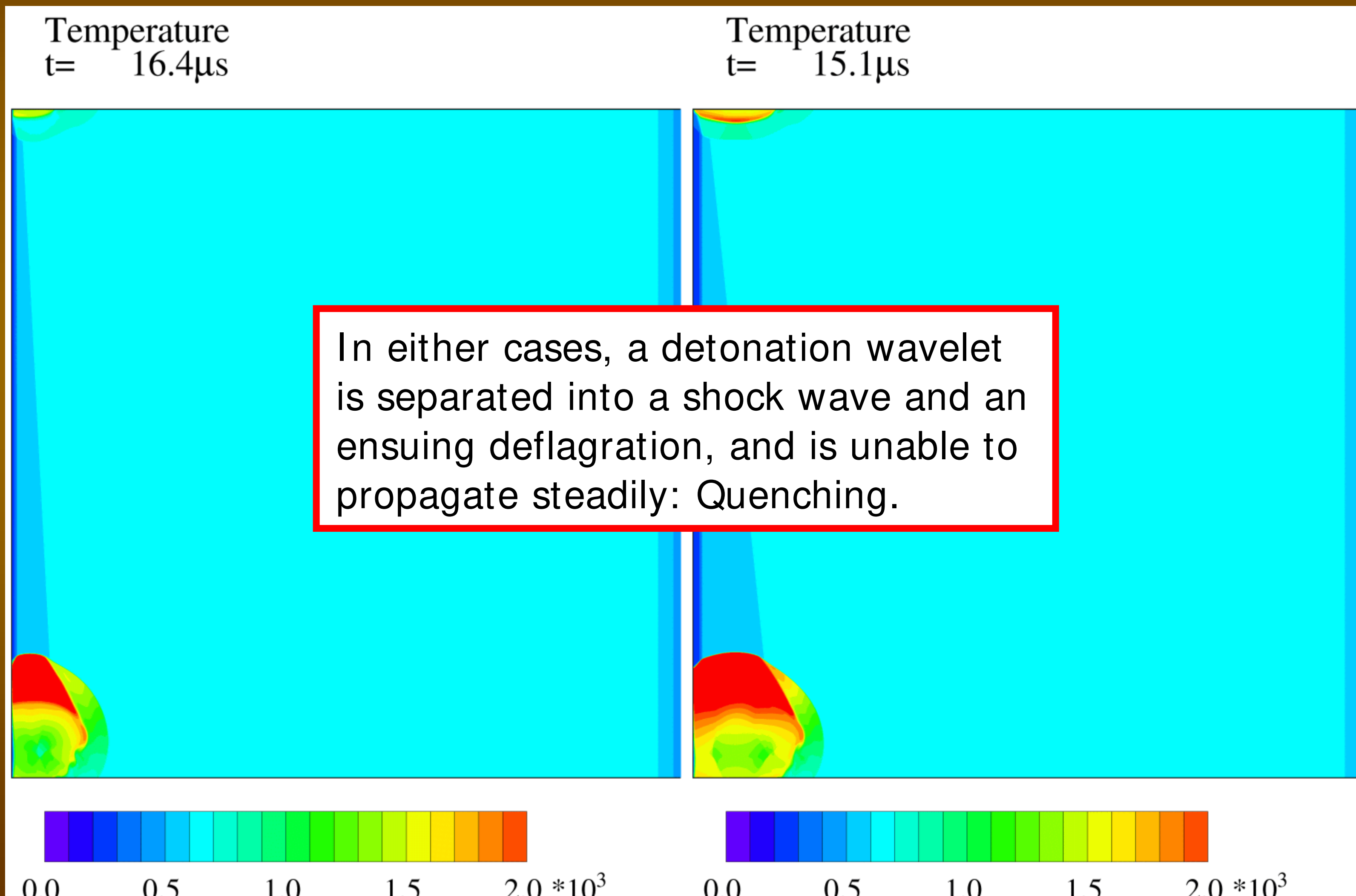
Generation of an unburnt gas pocket explosion caused by K-H instability seen in temperature and pressure distributions at t=6169.8~6202micros (II).



Generation of an unburnt gas pocket explosion caused by K-H instability seen in temperature and pressure distributions at t=6169.8~6202micros (III).



Influence of lower injection velocities on existence of rotating detonation is tested

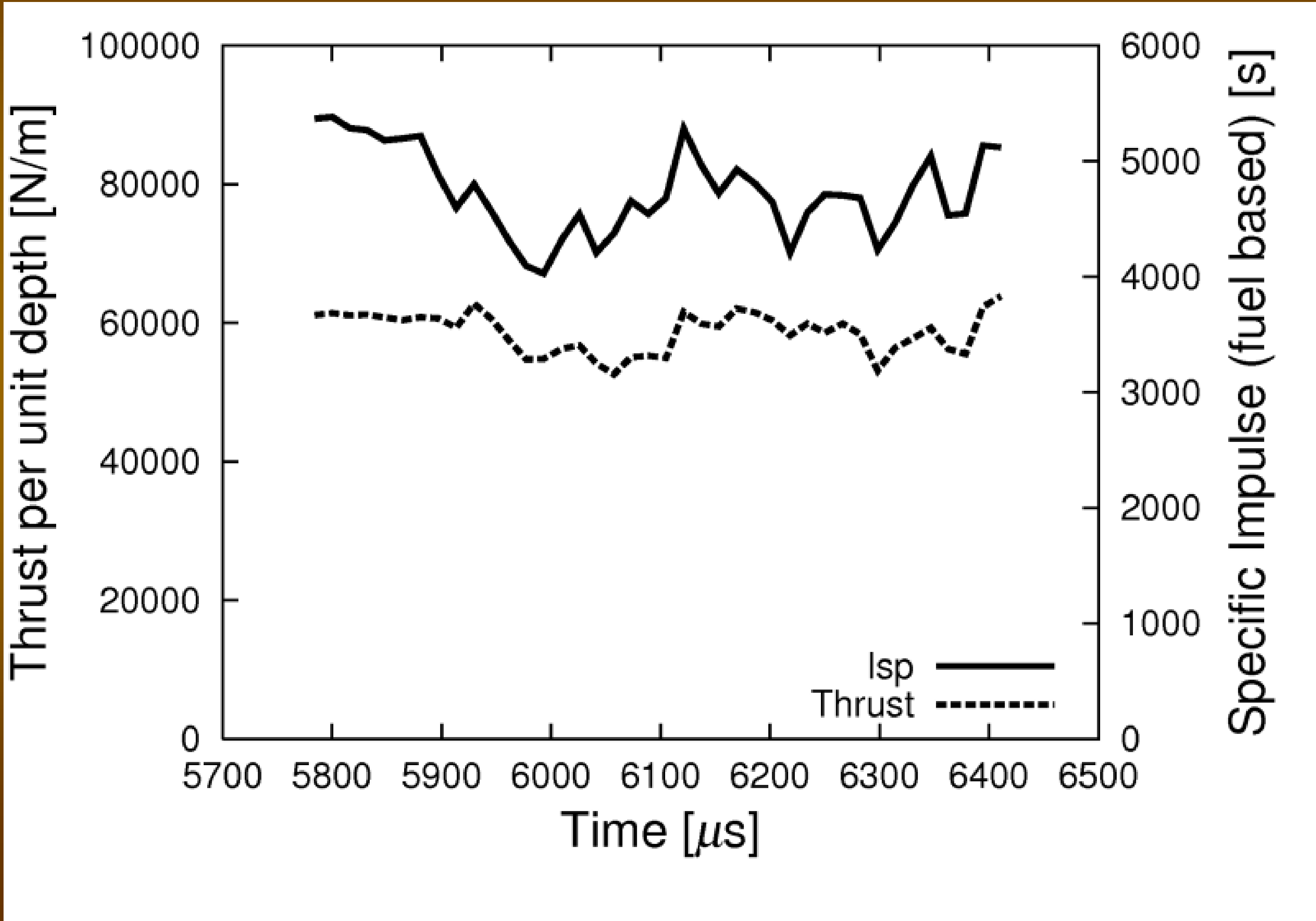


In either cases, a detonation wavelet is separated into a shock wave and an ensuing deflagration, and is unable to propagate steadily: Quenching.

Injection Mach number=0.25

Injection Mach number=0.5

Performance of RDE as thruster: Temporal variations of thrust per unit depth (60000N/m) and specific impulse (4700sec).



Conclusions

- A flowfield in RDE is numerically simulated to give a “steady” or periodical solution, using a reasonable computer time, under assumption that a flow is plane 2-dimensional.
- A rotating detonation wavelet propagates azimuthally at a velocity slightly lower than plane CJ value, with an oblique shock wave trailing downstream, as “a free detonation”. This shock wave changes direction of burnt gas flow from azimuthal to axial.
- At exit of short RDE, flow is still a few % nonuniform in pressure and temperature fluctuations.
- Mass and angular momentum are conserved.
- K-H instability causes unburnt pockets that lead to violent explosion
- A standing detonation can be obtained basically for incoming mixture velocity zero to infinity.
- I_{SP} = 4700sec for a diluted H_2-O_2 stoichiometric mixture.