Basics of Pulse Combustion Technology

Prepared by

WU Zhonghua Jan 2006

Outline

- What is pulse combustion (PC)
- Types
- Advantages
- Limitations
- Applications
- Models of PC
- Typical numerical solutions
- Experimental validation

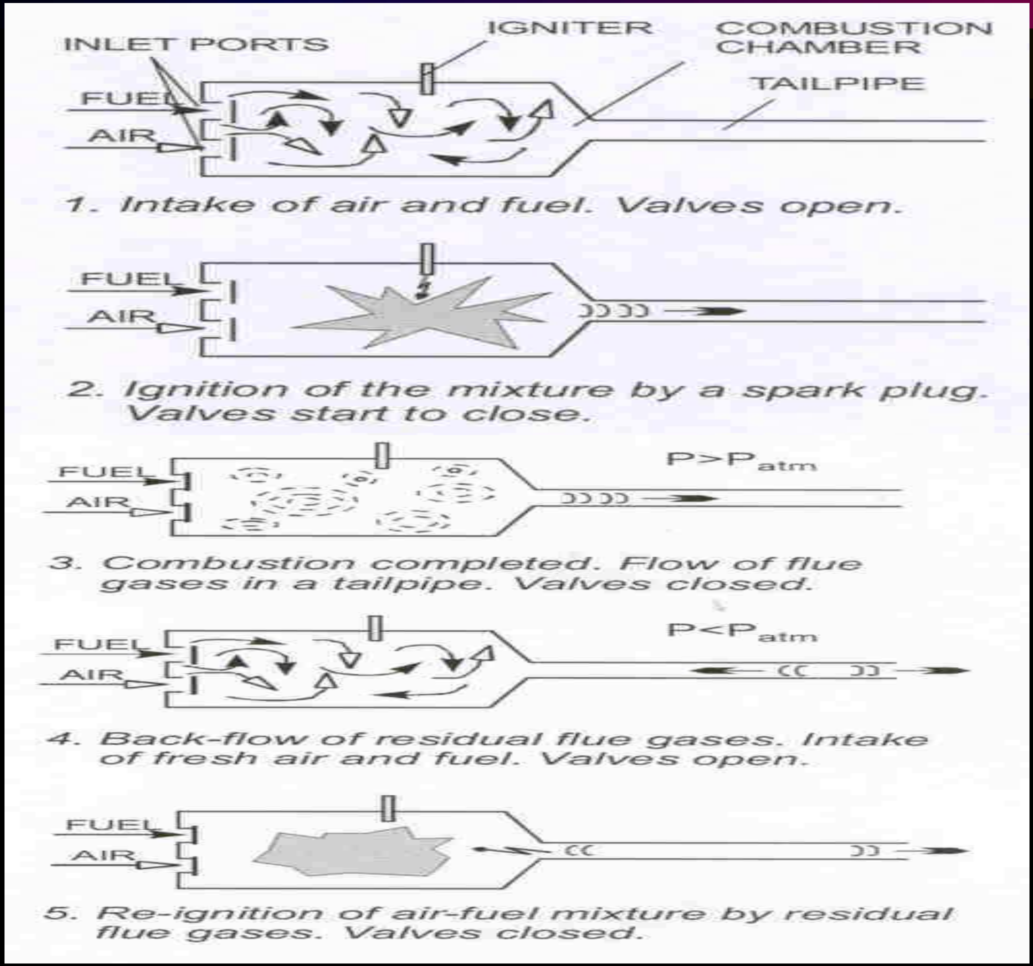
Why and what is pulse combustion?

- **Combustion-driven oscillation** often causes boring noise, non-designed working conditions and even structural failure of the combustion system
- However, such instabilities have some merits such as enhancing heat transfer, increasing combustion intensity and reducing NO_X pollutants.
- **Pulse combustion** is a positive use of the combustion-driven oscillations.
- Pulse combustion is intermittent (periodic) combustion of gaseous, liquid and solid fuel.

Basic information of PC

- Pulse combustors generally consist of an air/ fuel inlet valve, a combustion chamber and a resonance tube (tailpipe) for exhausting the combustion products.
- Pulse combustor can used:
  - gases fuel: natural gas, LPG, Propane, etc
  - liquid fuel: gasoline, coal oil, heavy oil, alcohol, etc
  - solid fuel: pulverized coal, wood coal, coal in water slurry, etc
- Pulse combustion is self-actived

Operating principles of PC



1. Intake of air and fuel. Valves open.

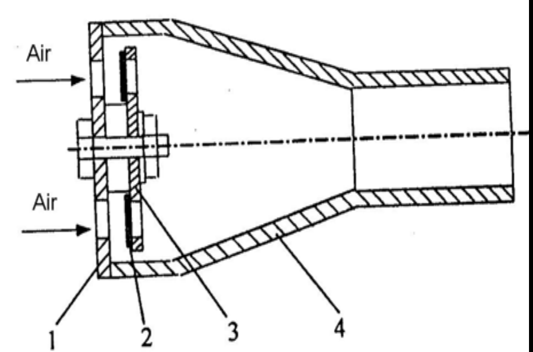
2. Ignition of the mixture by a spark plug. Valves start to close.

3. Combustion completed. Flow of flue gases in a tailpipe. Valves closed.

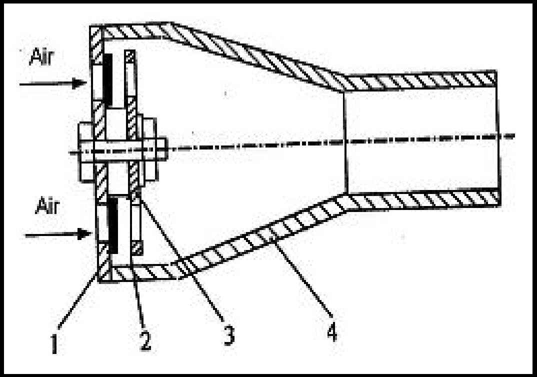
4. Back-flow of residual flue gases. Intake of fresh air and fuel. Valves open.

5. Re-ignition of air-fuel mixture by residual flue gases. Valves closed.

Figure 1 the operation principle of a valve pulse combustor



Air valve open



Air valve closed

Types of pulse combustor

- Operating principles
  1. Schmidt type (Based on the principles of the quarter-wave sound resonator)
  2. Helmholtz type (Operated under the principles of the standard acoustic Helmholtz resonator)
  3. Rijke type (Based on the operating principles of the Rijke tube)
- Valve and valveless PC
  1. Flapper and Reed type valves
  2. Rotary valves
  3. Aerodynamic valves

Comparison of steady –state and pulse combustion

Table 1 Comparison of steady and pulse combustion[8]

Process parameters	Steady state	Pulse
Combustion intensity (kW/m^3)	100-1000	10000-50000
Efficiency of burning (%)	80-96	90-99
Losses due to chemical underburning (%)	0-3	0-1
Losses due to mechanical underburning (%)	0-15	0-5
Temperature level (K)	2000-2500	1500-2000
CO concentration in exhaust (%)	0-2	0-1
NOx concentration in exhaust (mg/m^3)	100-7000	20-70
Convective heat transfer coefficient (W/m^{2}k)	50-100	100-500
Time of reaction (s)	1-10	0.01-0.5
Excess air ratio	1.01-1.2	1.00-1.01

Advantages

- Pulse combustion can result in
  - Increased heat and mass transfer rate (by a factor 2 to 5)
  - Increased combustion intensity as quantified by the gas mixing index (by a factor of up to 10)
  - Higher combustion efficiency with low excess air
  - Reduced pollutant emissions (especially NO_x, CO and soot)
  - Improved thermal efficiency (by up to 40 %)
  - Reduced space requirements for the combustion equipment.

Limitations

- High noise
  - Even larger than120 db
  - Can be reduced to 60~80db now.
- Limitation of higher pressure oscillation
  - Compressed air/fuel mixture
  - Scale up of the combustion chamber

Applications of pulse combustor

- Applications :
  - Water/ space heaters, heat exchanger ….
  - Engines such as V-1 “buzz” flying bomb, aircraft…
  - Combustor for central heating systems, boiler, etc
  - Others such as smoke generator, atomizer…
- Some applications in drying
  - Spray drying (PCSD)
    - chemical and pharmaceutical products food, polymers…
  - Fluid Bed drying
    - Acid wastes, Sawdust, Urban waste,…
  - Flash drying
    - wood wastes…

Types of PCD

Spray drying

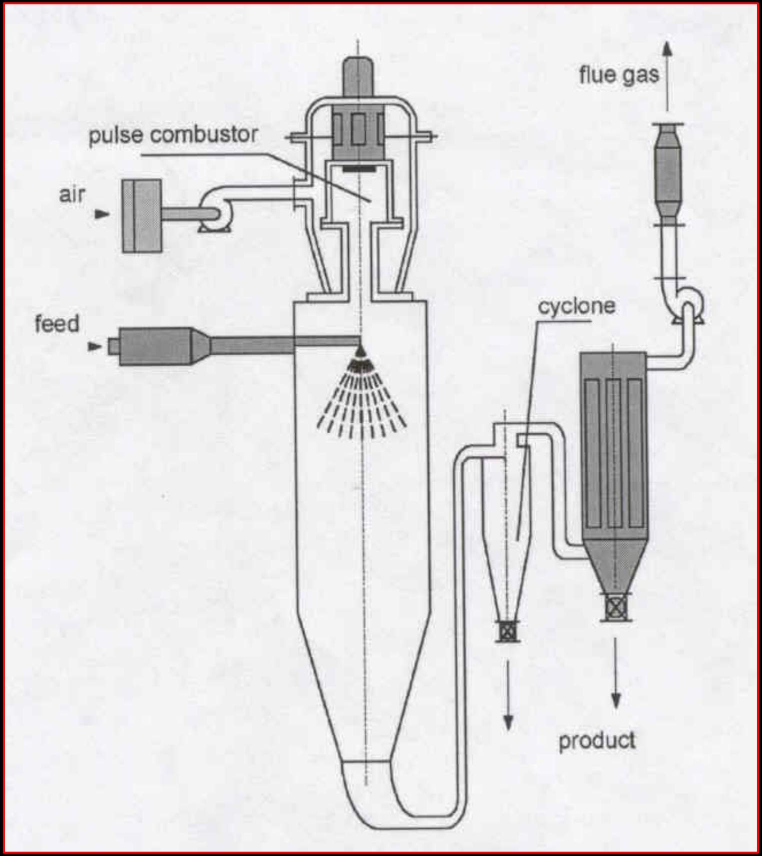
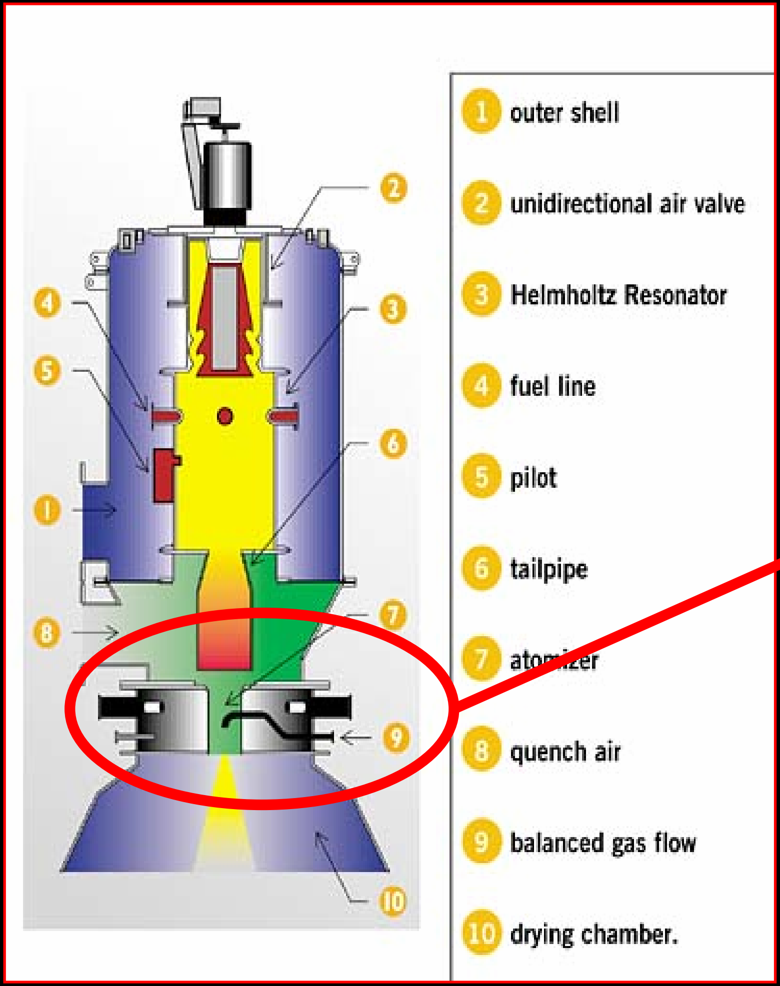


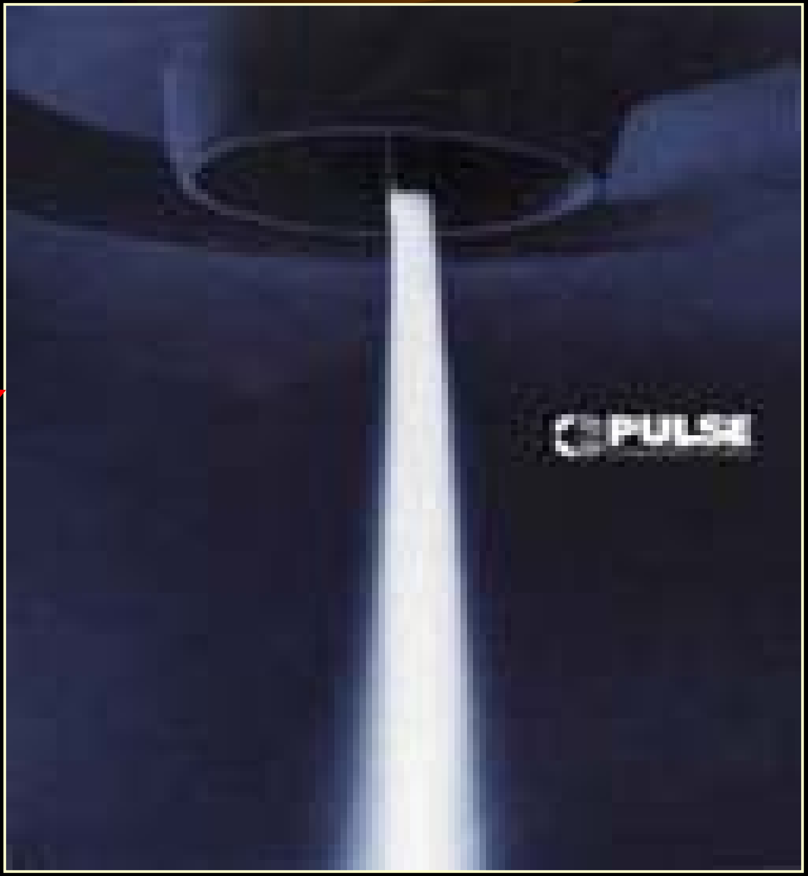
Figure 3 Hosokawa Bepex Corporation drying system[1]

- Pulse combustion frequency ranges from 80 to 150 Hz and heat release rate achieved up to 300 kW.
- Over 60 different materials are tested; equal or better quality observed.
- For some materials such as biopesticides, antibiotics, products with 8-11% higher potency than spray-dried products reported.

PC spray dryer



1. outer shell
2. unidirectional air valve
3. Helmholtz Resonator
4. fuel line
5. pilot
6. tailpipe
7. atomizer
8. quench air
9. balanced gas flow
10. drying chamber.



Types of PCD

Fluidized bed drying

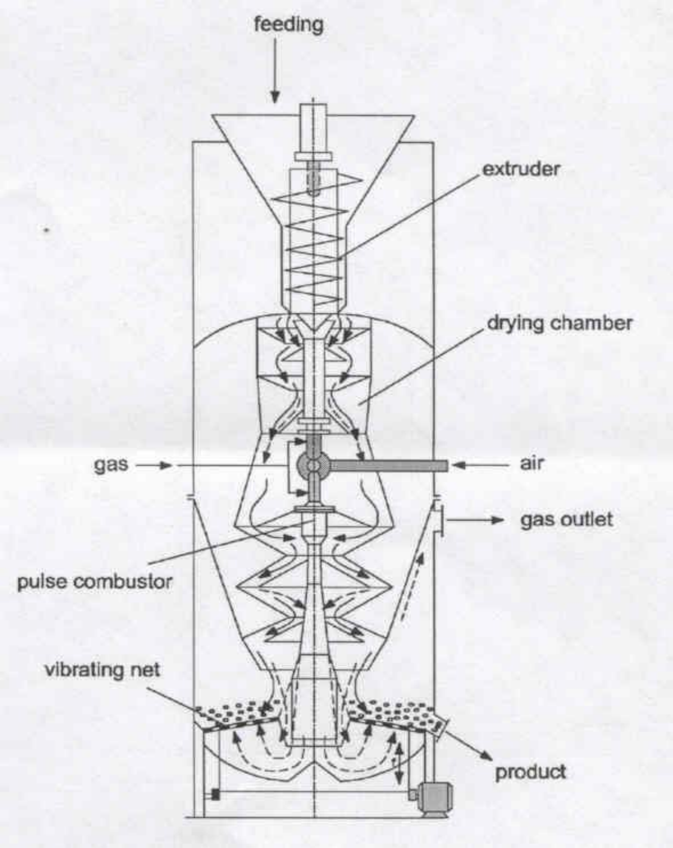


Figure 4 IMPULS vibrofluidized bed dryer[1]

- This device is used to dry industrial waste
- Has capacity of 20,000 t per year of evaporated water[1]
- Acid wastes, biological deposits, toxic wastes, sawdust, urban wastes, sludges and many more can be dried using pulse fluidized bed drying

Types of PCD

Flash drying

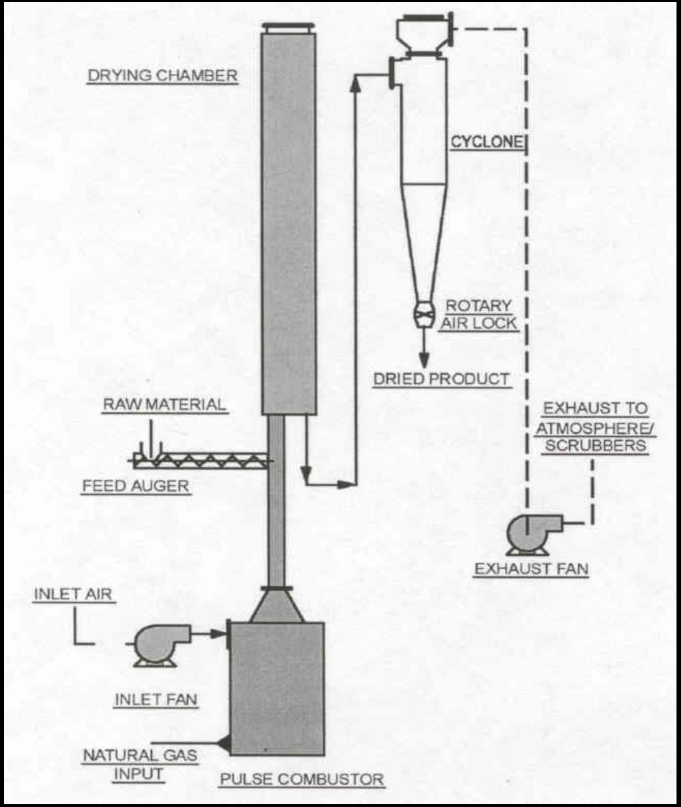


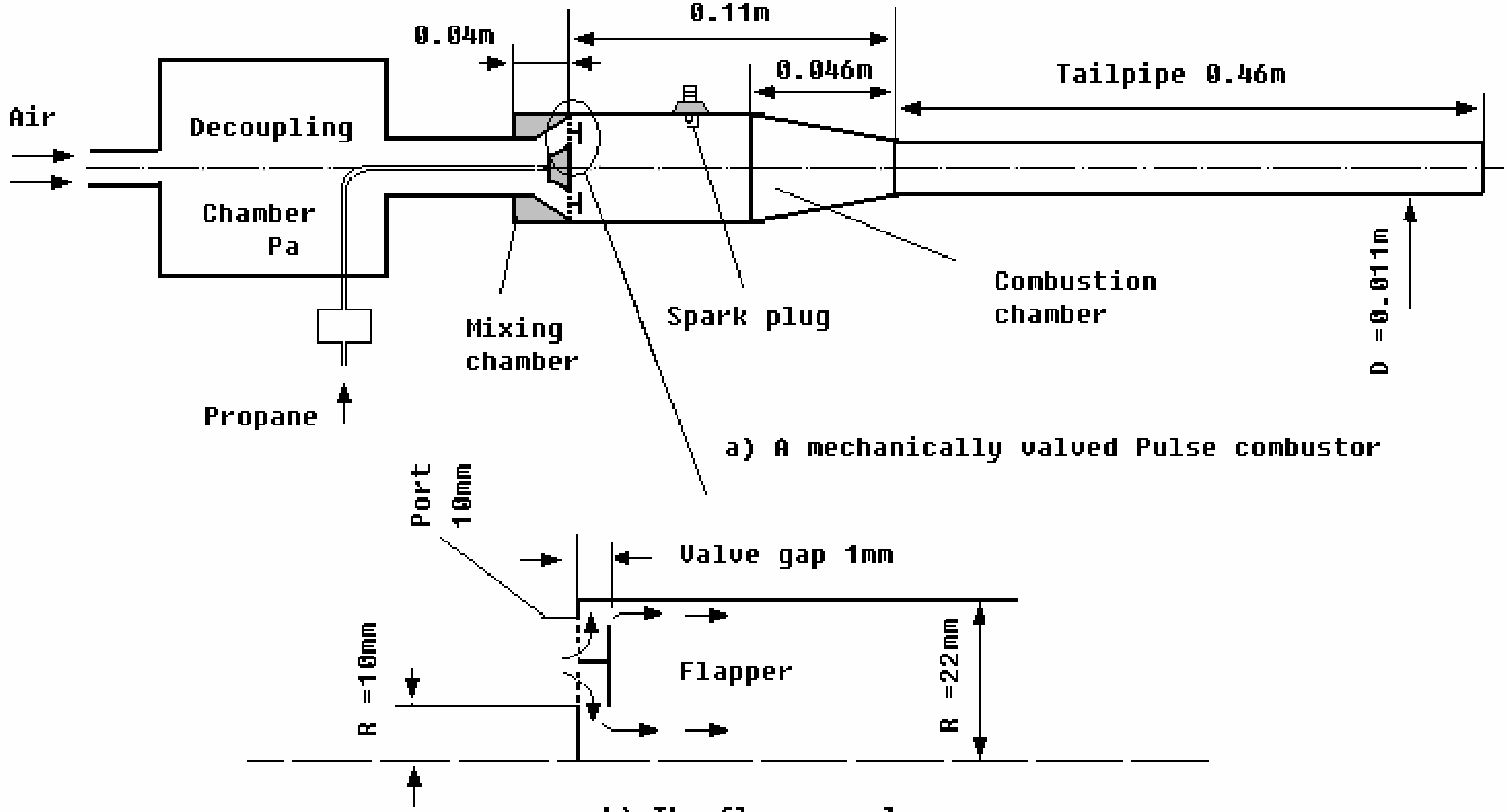
Figure 5 Novodyne Ltd. Flash dryer drying[1]

- This flash dryer was studied for sawdust and waste drying
- Materials can be dried from moisture content of 50% to 30% in single pass
- Evaporation rate ≈ 230 kg H_2o/h
- Capital costs are projected to be10-15% less than classical flash dryer.

Modeling of PC

- To develop a novel CFD model for the Helmholtz type pulse combustors with a proper and simple inflow condition .
- To investigate the pulse combustion process and effects of operation parameters on combustion performance.
- To provide guidelines for design a small-scale pulse combustor.

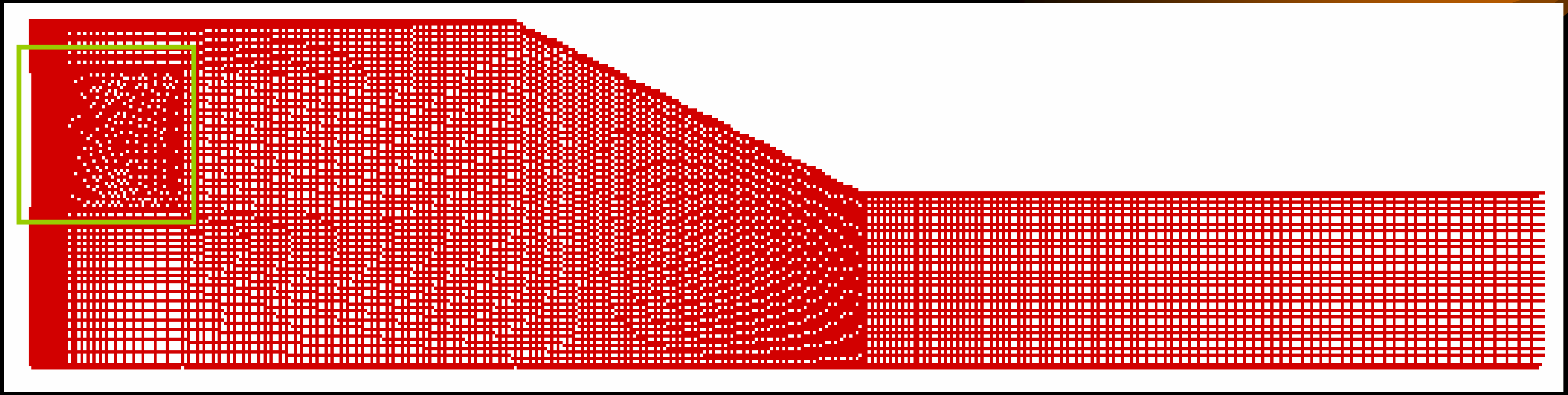
Schematic of the simulated mechanical valved pulse combustor



a) A mechanically valved Pulse combustor

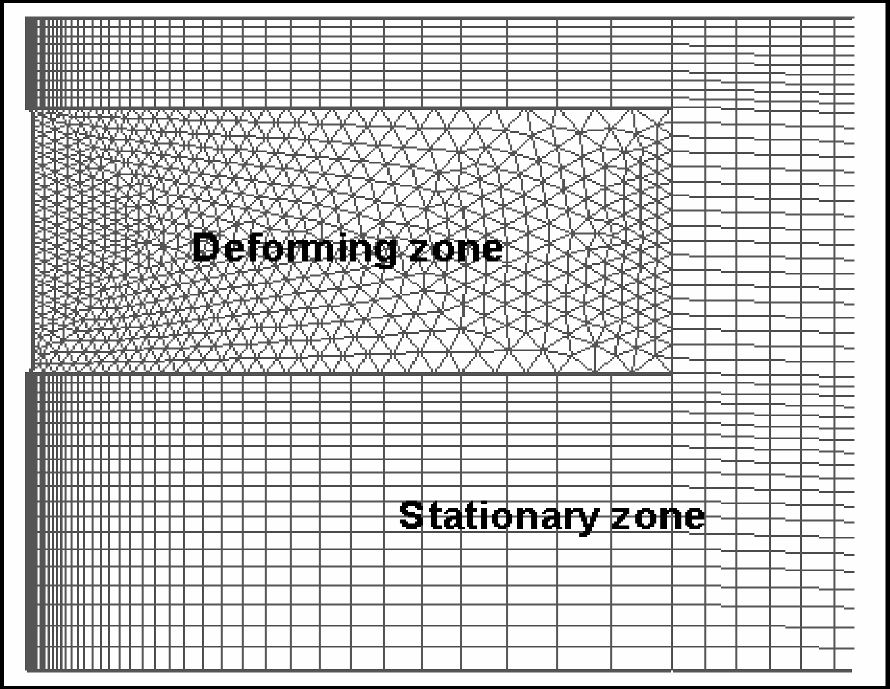
b) The flapper valve

Mesh generation

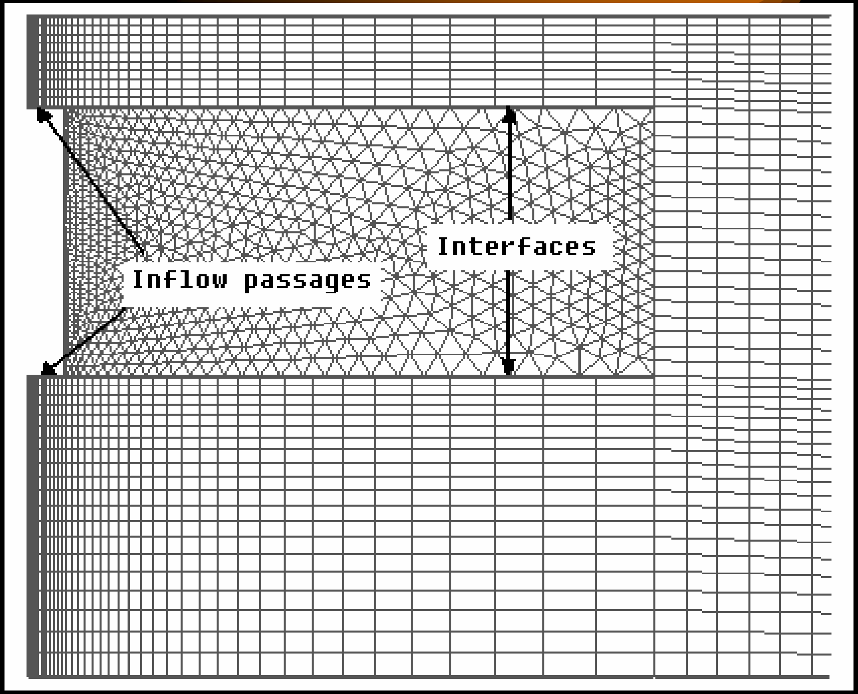


- Mesh is denser near the combustion chamber, specially near the inlet.
- In the marked zone, dynamic mesh is used to capture the movement of the flapper.
- A Two-dimensional, axis-symmetric mesh is applied .

Dynamic mesh



a) Dynamic mesh when the flapper valve closes (valve gap=0.0 mm)



b) Dynamic mesh when the flapper valve opens completely (gap=1mm)

Dynamic mesh (2)

The flapper movement is driven by the pressure difference integrated cross the cells of the valve surface and when friction is ignored

$$m\frac{du}{dt}=\int_{R_1}^{R_2}2\pi(P'_{0sj}-P_{csj})rdr$$

$u=0$ and

The variation of the flapper displacement can be calculated as

$$\Delta L=\int_{t^n}^{t^{n+1}}udt$$

$$\sum\Delta\vec{x}_i^{n+1}=\Delta L=L^{n+1}-L^{n}$$

When displacement of valve plate is in between 0 and 1 mm, the mesh deforms and the axial positions of its nodes are updated

When X= 0 and 1 mm: $u=0$ $\Delta L=0$

Equations of PC model

- Mass balance

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v_x) + \frac{\partial}{\partial r}(\rho v_r) + \frac{\rho v_r}{r} = M$$

- Species equations (ith species, propane, N_2,O_2, H_2O, CO_2 , etc,)

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial}{\partial x}(\rho_i v_x) + \frac{\partial}{\partial r}(\rho i v_r) + \frac{\rho_i v_r}{r} = M_i$$

- Momentum equations (x-direction)

$$\frac{\partial}{\partial t}(\rho Y_i) + \frac{1}{r}\frac{\partial}{\partial x}(r\rho_i v_x Y_i) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho_i v_r Y_i) = \frac{1}{r}\frac{\partial}{\partial x}\left[r\left(\rho_i D_i + \frac{\mu_t}{Sc_t}\right)\frac{\partial Y_i}{\partial x}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho_i D_i + \frac{\mu_t}{Sc_t}\right)\frac{\partial Y_i}{\partial r}\right] + S_i$$

Equations of PC model

- Energy equation

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{r\partial x}(r\rho h v_x)+\frac{\partial}{r\partial r}(r\rho h v_r)=\frac{\partial}{r\partial x}\left(rk_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{r\partial r}\left(rk_{eff}\frac{\partial T}{\partial r}\right)$$

$$+\frac{1}{r}\frac{\partial}{\partial x}\left[r\left(\rho D_i+\frac{\mu_t}{Sc_t}\right)\frac{\partial h_iY_i}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho D_i+\frac{\mu_t}{Sc_t}\right)\frac{\partial h_iY_i}{\partial r}\right]+S_h$$

- K-epsilon turbulence model

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{r\partial x}(r\rho k v_x)+\frac{\partial}{r\partial r}(r\rho k v_r)=\frac{\partial}{r\partial x}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right]+\frac{\partial}{r\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right]+G_k-\rho\varepsilon$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{r\partial x}(r\rho\varepsilon v_x)+\frac{\partial}{r\partial r}(r\rho\varepsilon v_r)=\frac{\partial}{r\partial x}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial x}\right]+\frac{\partial}{r\partial r}\left[r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial\varepsilon}{\partial r}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Combustion model

In this work, the following one-step propane combustion chemistry is assumed

$$C3H8 + 5O2 \rightarrow 3CO2 + 4H2O$$

The form for the Arrhenius law used is the one proposed by Westbrook and Dryer

$$C_3H_8[kgmol/(m3\cdot s)] = 4.836\times10^9 \cdot \exp[-\frac{1.256\times10^8\ J/kgmol}{RT}]\cdot[C_{C_3H_8}]^{0.1}\cdot[C_{O_2}]^{1.65}$$

The form of the turbulent reaction rate is

$$R_i = A\rho m^* \left(\frac{\varepsilon}{k}\right)$$

$$m^* = \min\left\{\left(\frac{m_j}{v_j M_j}\right)_{reac\ tan\ ts},\ B\sum_{products}\left(\frac{m_k}{v_k M_k}\right)\right\}$$

Boundary conditions

Wall: non-slip, heat loss is considered as

$$q_i = h(T_{wi} - T_a) + \xi\sigma(T_{wi}^4 - T_a^4)$$

Outlet: atmospheric pressure is specified and the remaining variables are calculated assuming far-field conditions

Axis: The symmetry boundary condition

Working fluid: air/ propane mixture, Prosperities such as viscosity is temperature-dependent

Boundary condition (2)

- Inlet: total pressure of fuel/air mixture of 2600 Pa, the initial total temperature T_0, of 300 K, the initial mass fraction of propane with 0.054 and thus the excess air ratio of 1.123 are specified .

The cross-sectioned area of the fuel/ air mixture inflow passage is calculated as

$$A_{Inlet} = 2\pi \times R_1 \times L + 2\pi \times R_2 \times L$$

The mass flux of fresh mixture inflow

$$\dot{M} = \rho v A_{inlet} = 2\pi\rho v \times (R_1 + R_2) \times L$$

Solution

The pressure–velocity coupling is discretized using the "SIMPLE" method.

The momentum, species, and energy equations are discretized using a second-order upwind approximation.

The criteria to judge when the computation can be stopped is that the pressure amplitudes in the following cycles are the same (cyclic steady state).

Three time-step sizes are set: 1×10-5, 1×10-6, and 5×10-7s and finally ,time-step size of 1×10-6 s was selected .

Solutions (2)

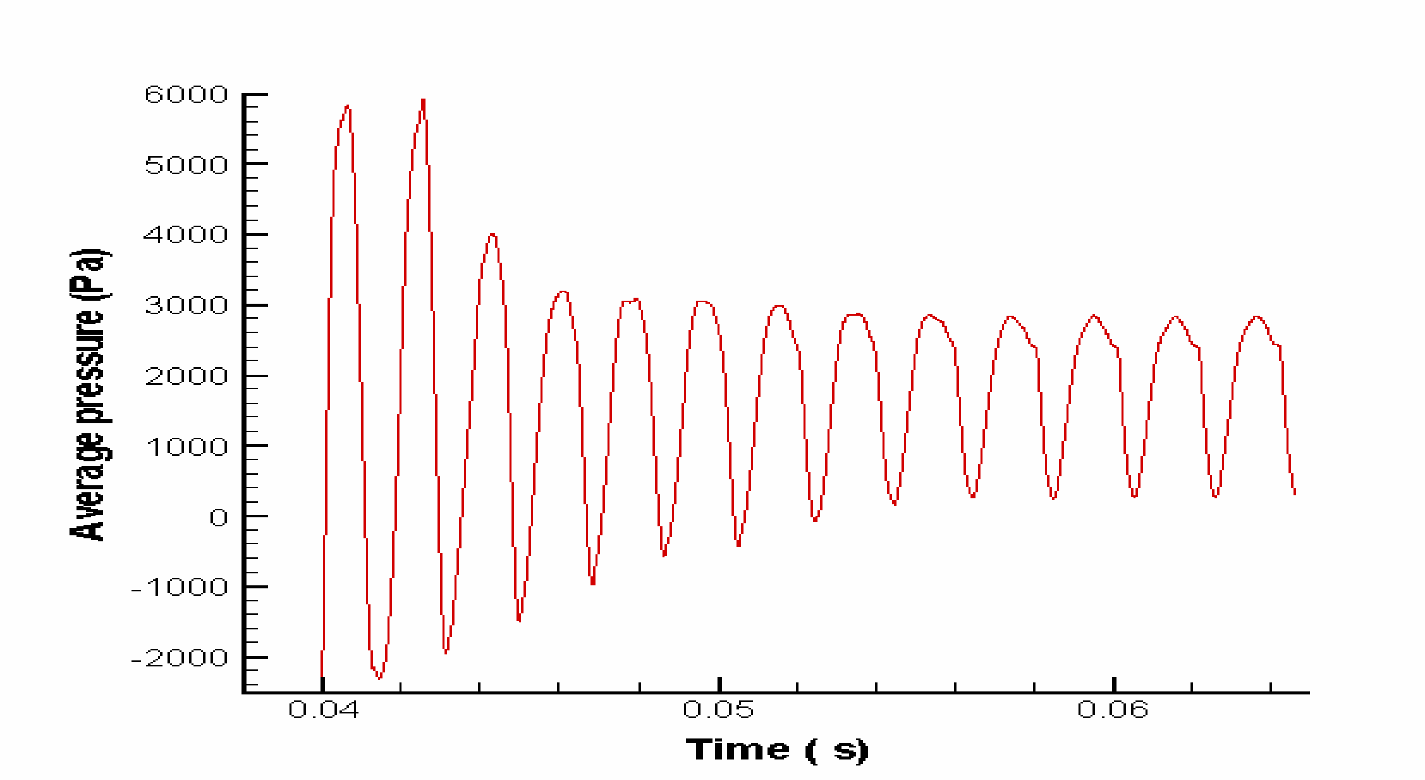
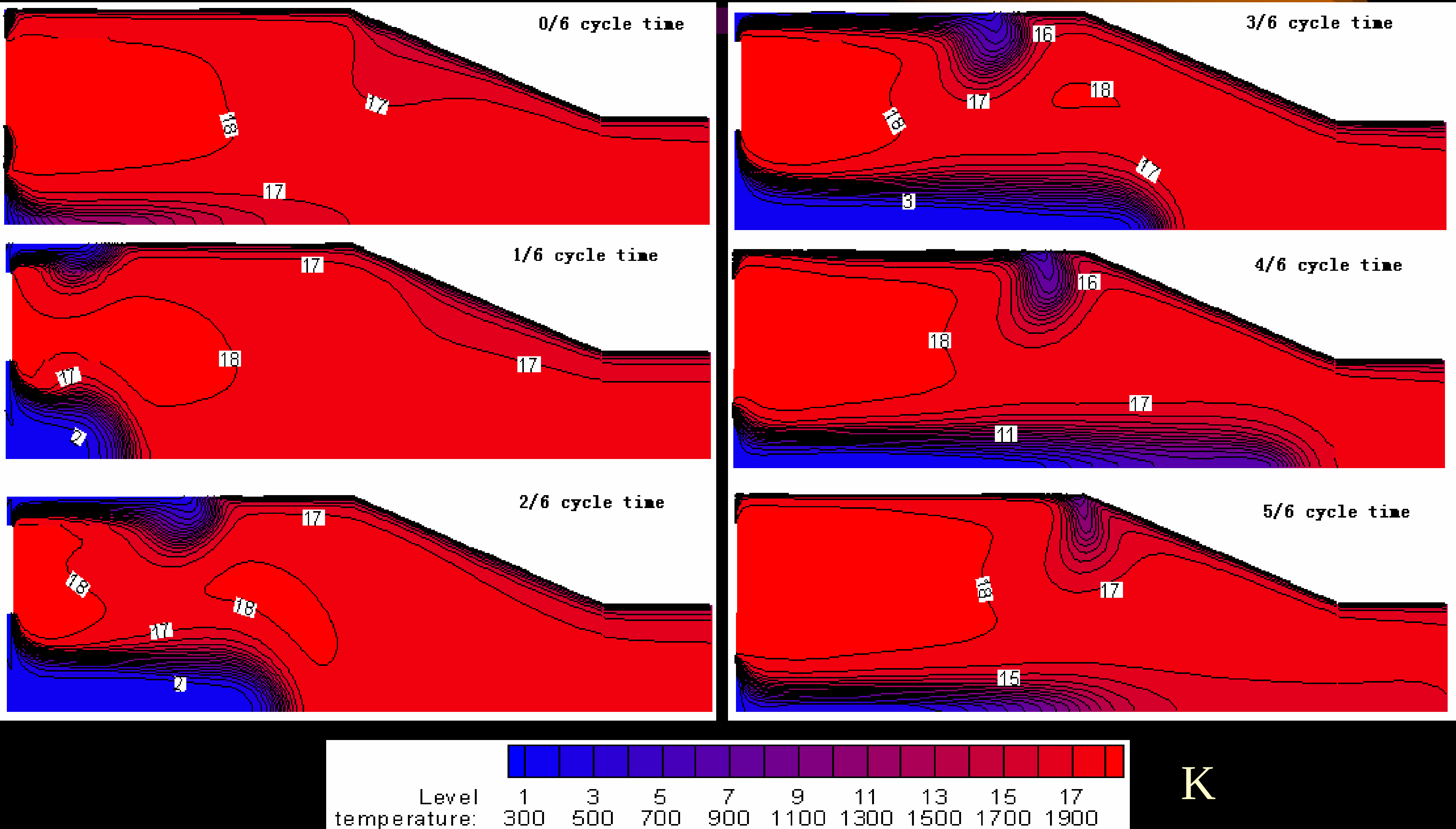
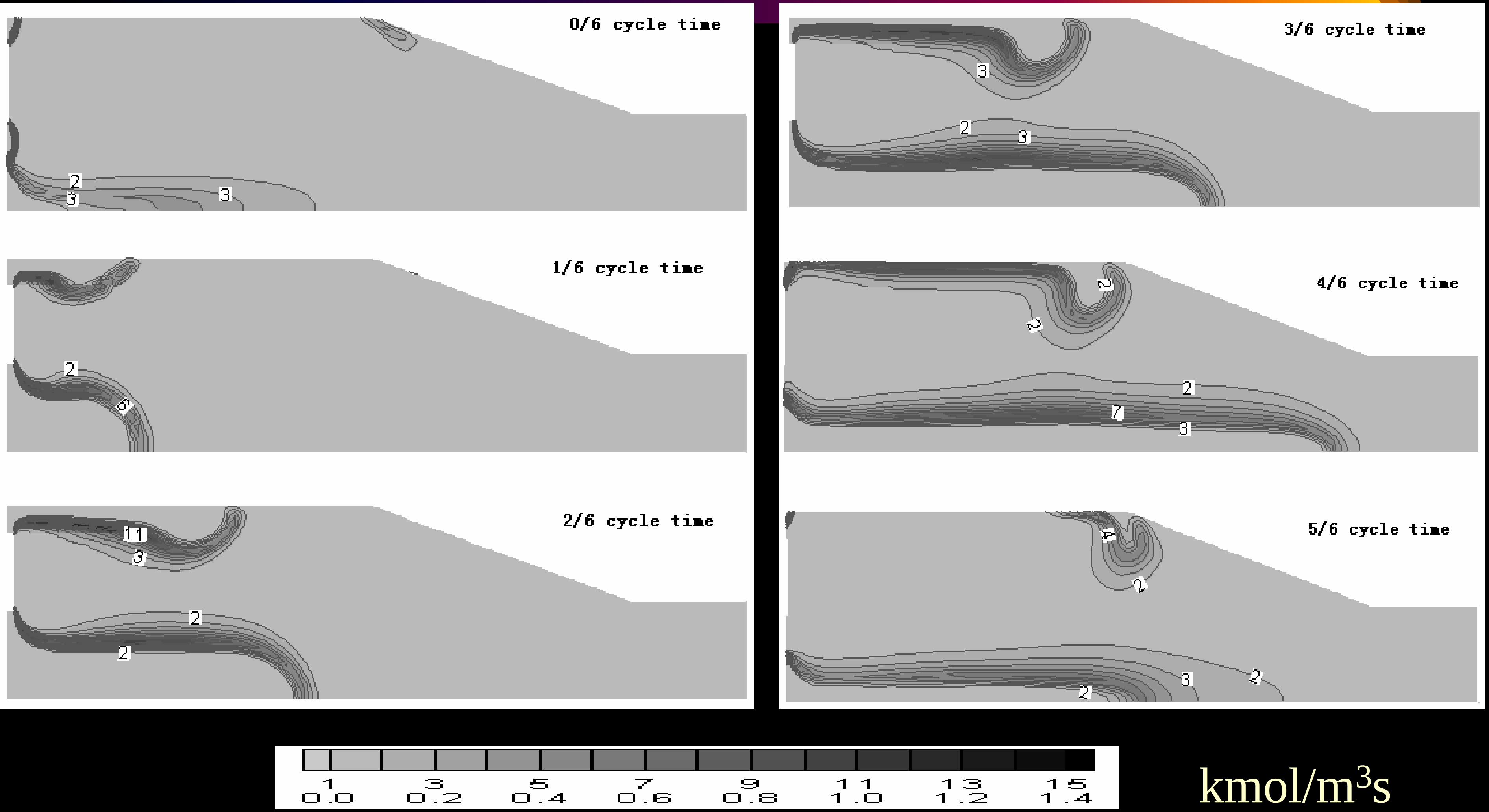


Figure 3 Convergence history of average gas pressure in combustion chamber (without heat loss, time step size: 1×10^{-06}s)

Gas temperature oscillation in the combustion chamber



Flame front during a cycle

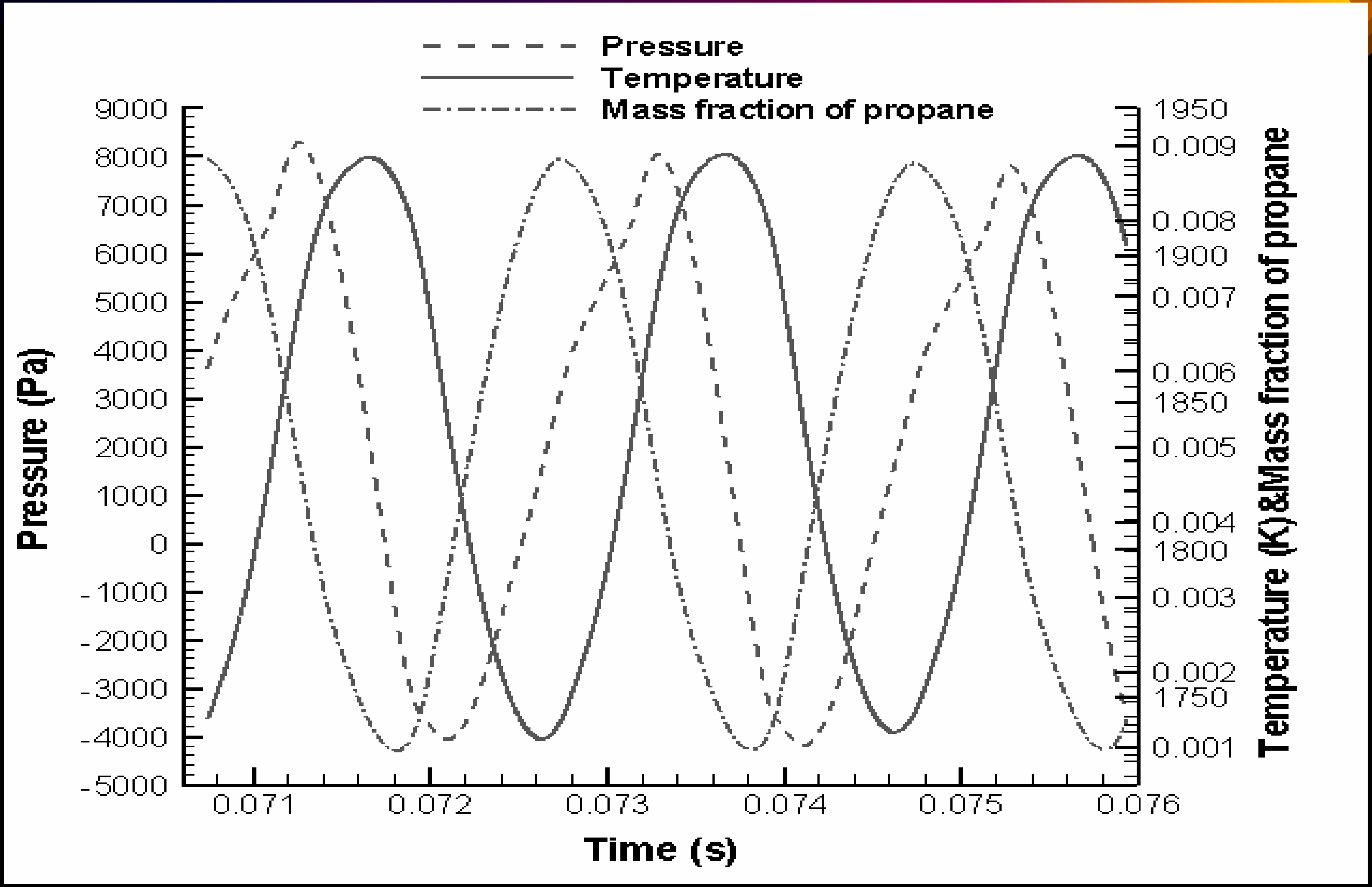


kmol/m^{3}s

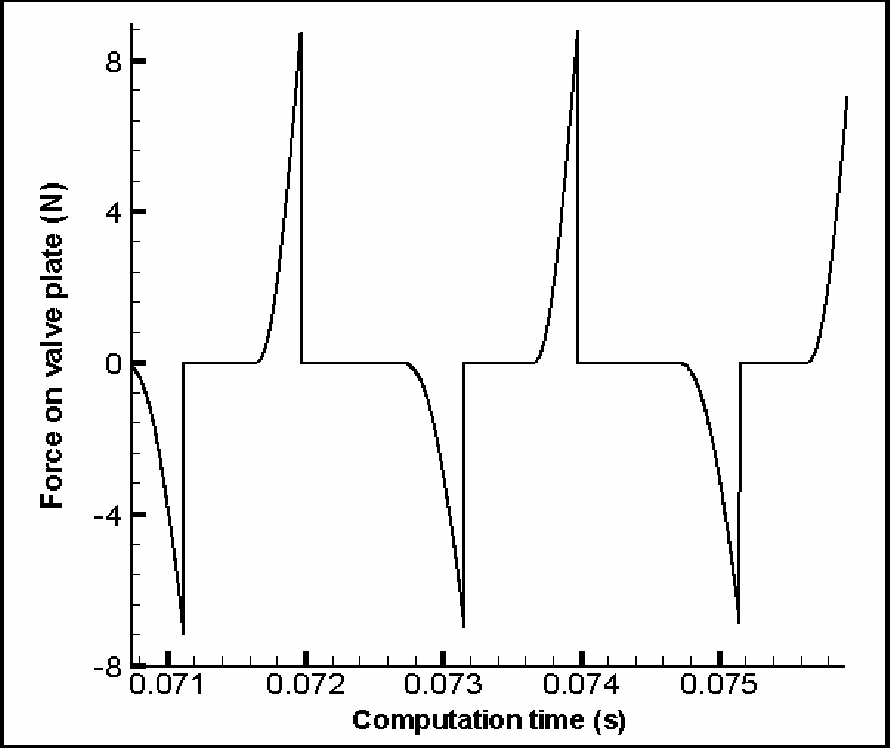
A sustained PC process

- The flame was anchored in two positions: a small one near upper wall and another big one at the centerline near the inlet.
- The flame was a narrow band surrounding the mixture of fuel and air.
- Between the two flame zones, a hot remnant gas zone existed near the back of the inlet valve
- most combustion was completed in a pulse cycle while there was still some unburned fuel at the centerline.
- There are two possible re-ignition sources
  - High temperature wall
  - hot remnant gas
  - Remaining flame

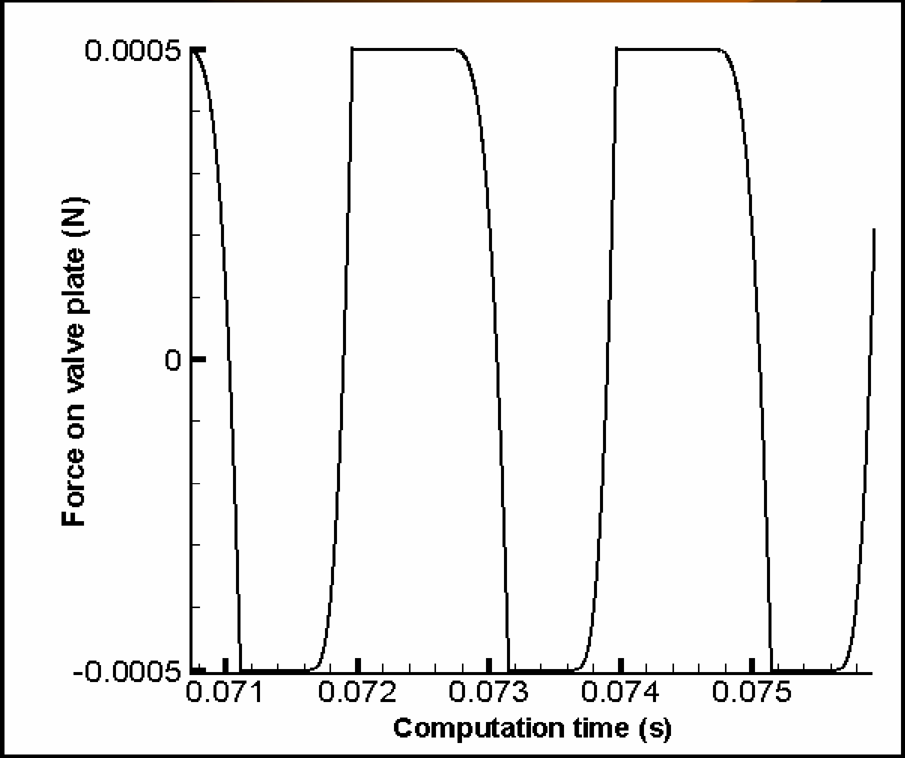
Phase relations between gas pressure , temperature, and fuel concentration



Dynamic of flapper

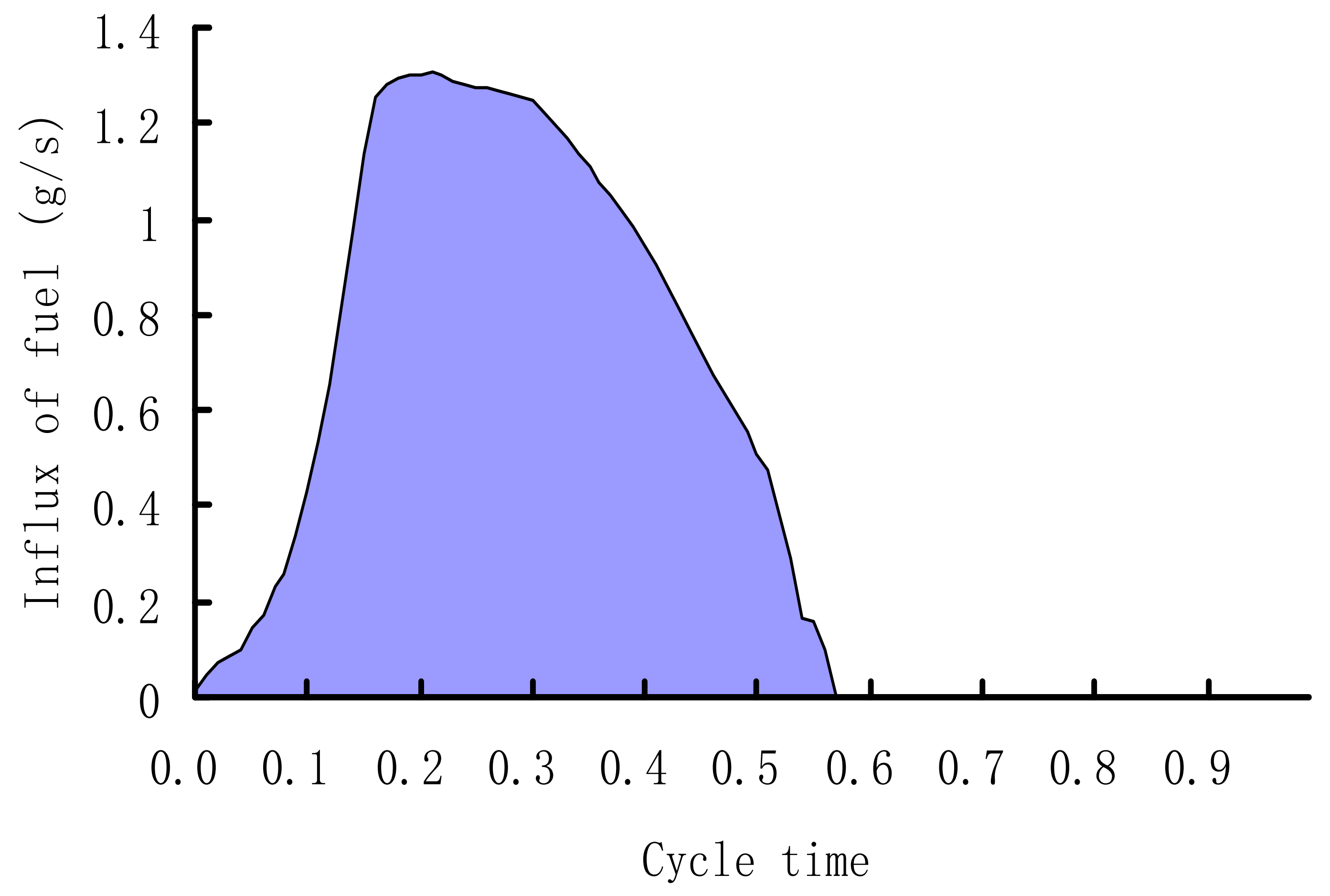


Time trace of the velocity of the flapper

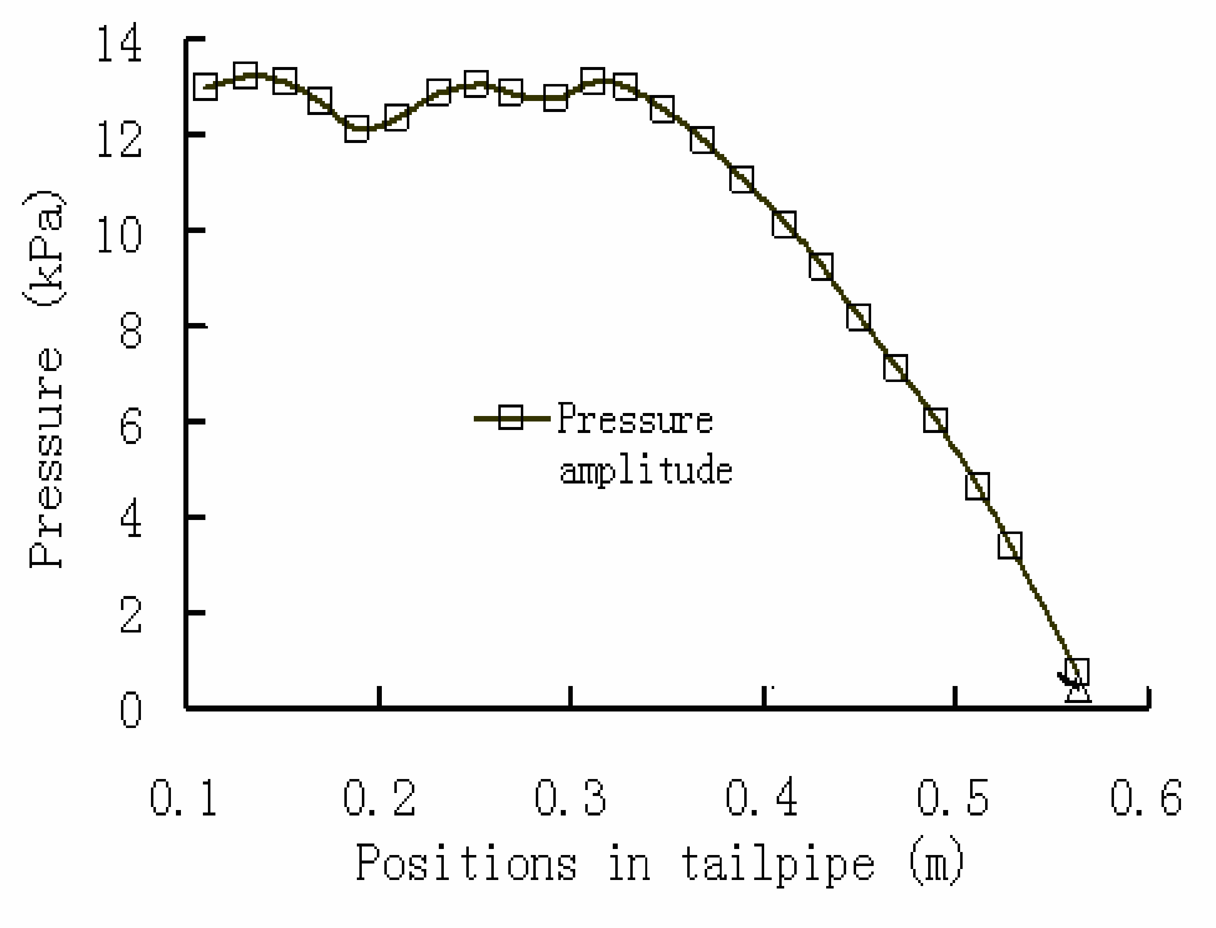


Time trace of the valve plate position (valve closed: -0.0005m, valve opened: 0.0005m)

fuel influx during a cycle

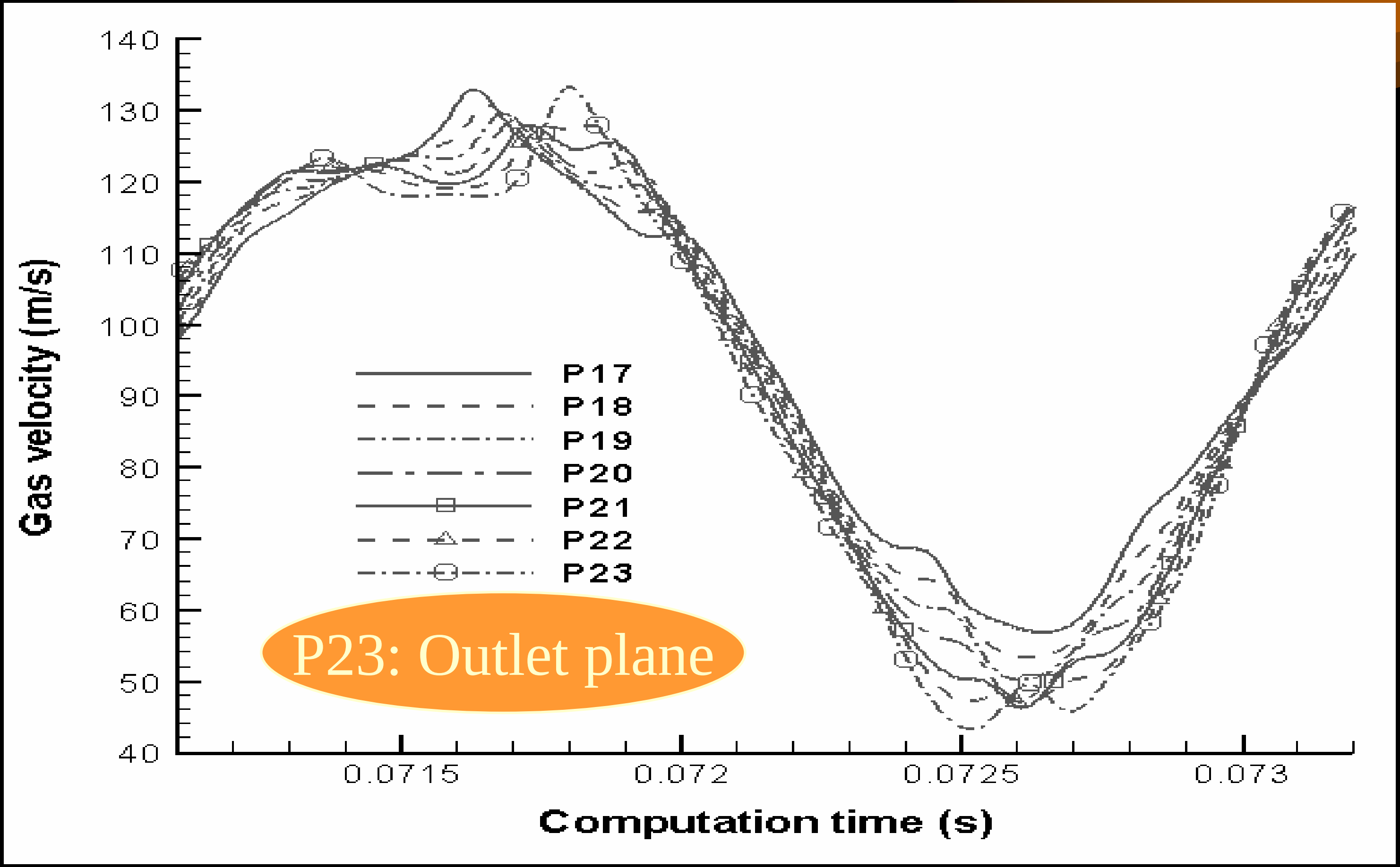


Gas dynamic in tailpipe(1)



Gas pressure amplitude distribution along tailpipe

Gas dynamics in tailpipe (2)



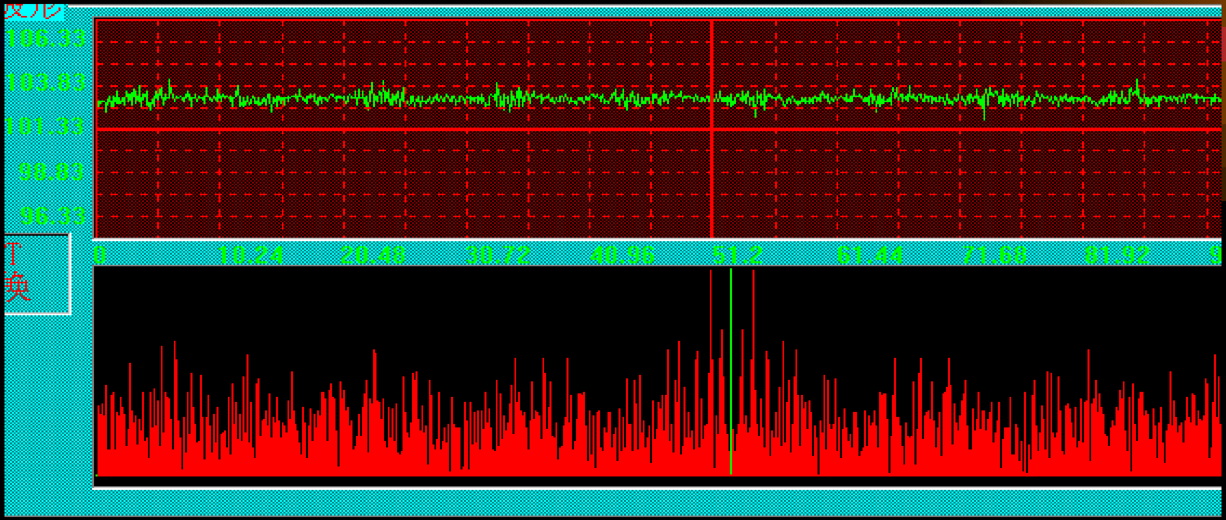
Gas velocity oscillation near tailpipe outlet

Conclusions

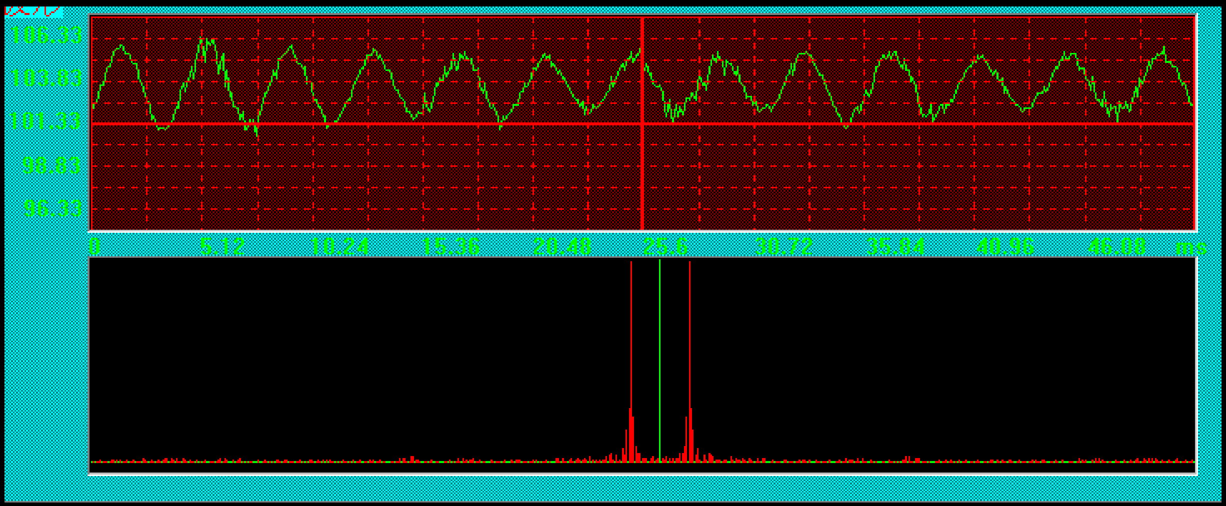
- The proposed PC is simulated and a self-sustained pulse combustion process is achieved.
- The predicted phase delay between gas pressure , temperature, and heat loss is consistent with phase relation described by Rayleigh’ criterion
- The predicted PC have a pulse frequency of 250 Hz, exit velocity of 40~125 m/s, pressure amplitude of 12 kPa
- The novel CFD model using a dynamic mesh have an ability to simulate the dynamics of inlet valve and its resulting fuel influx.
- The coupling of dynamic of the flapper, influx of fuel, acoustic pressure was simulated by novel CFD model

The fabricated small-scaled mechanical valved pulse combustor

Transient pressure monitored in the combustion chamber



Control team
(no fuel inflow)



Fuel 0.055m^3/h

Amplitude: 101.33~105.08 kPa (3.8 kPa)

Frequency:250 Hz

Operational conditions

- Pulse combustor:
  - length 570 mm, chamber diameter: 44 mm tailpipe diameter: 22
- Flapper :
  - Materials: spring steel, 0.2 mm thickness.
- Fuel: LPG (~60% propane)
- Fuel flow rate : 0.055~0.12 m3/h, 8~25.2 mmH_2O
- The design is based on the numerical results of base case and parametric research.
- The successful operation of the fabricated small-scale PC partly validated the novel CFD model

Basics of Pulse Combustion Technology

Thank you for attention !

NUS
National University of Singapore