# NUMERICAL APPROACH IN COMBUSTION AND PROPULSION TECHNOLOGIES

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A recent trend in numerical simulation in combustion and propulsion technologies is presented. One characteristic of simulation of combustion flow is huge numbers of species and elementary reactions related to combustion reaction. For example, a full chemical kinetics for heptane fuel ($C_7H_{16}$) which is a typical component of a gasoline fuel involves more than 500 species and more than 3,000 elementary reactions. Therefore, to simulate a flame dynamics of such a large hydrocarbon fuel, a supercomputer with high speed and large memory is strongly required. An algorism for automatically reducing numbers of species and reactions is also under development by many researchers. The other characteristic of combustion analysis is a necessity of coupling between fluid dynamics and chemical reactions. Non-linearity in both of equation of fluid dynamics such as Navier-Stokes equation and chemical reaction terms in conservation equations for species makes the combustion analysis complicated and the simulation consumes very long computation time because of a small time step. Moreover, a research of a supersonic ramjet (scramjet) engine is introduced as one topic in the propulsion field. The scramjet engine is considered to be a new propulsion system in hypersonic vehicles or space planes. The key technology for the success of development of the new engine is an achievement of mixing, ignition and combustion within 1 millisecond in a supersonic flow. The author has numerically and experimentally conducted development of ignition and combustion enhancement technique by using plasma in a supersonic flow for several years. A CFD analysis of plasma jet (PJ) ignition in a supersonic flow is demonstrated in the presentation. The PJ ignition includes various phenomena such as chemical reactions, turbulence, shock waves, and plasma physics. The numerical model was validated by a comparison with experimental results.

# Numerical approach in combustion and propulsion technologies

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# Combustion technology

**More than 80 % of energy for domestic heating, power generation, and transportation is obtained by combustion of fossil fuel.**

**Only chemical (combustion) propulsion system can get large power to go to space.**

**improvement of energy efficiency**
**increase in fuel economy**
**reduce of pollutant emission and $CO_2$**

**contribute to environmental issues, energy problems, space technology**

# Combustion reaction(1)

**Overall reaction**

$2H_2 + O_2 = 2H_2O$, $C_3H_8 + 5O_2 = 3CO_2 + 4H_2O$

**many species, many elementary reactions**

$H_2 + O_2 = HO_2 + H$
$H + O_2 = OH + O$
$O + H_2 = H + OH$
$H_2 + OH = H_2O + H$
:
:

| Fuel | Species | Reactions |
|---|---|---|
| $H_2$ | 9 | 20 |
| $CH_4$ | 20 | 100 |
| $C_3H_8$ | 50 | 300 |
| n-$C_7H_{16}$ | 500 | 3000 |

# Combustion reaction(2)

**LES and DNS can be applied for only $H_2$ and $CH_4$.**

**Combustion researchers strongly need**

**Topics**

***Establishment of Skeltal (reduced) reaction mechanism for large hydrocarbons**

***Algorithm for automatically reducing numbers of species and elementary reactions from full kinetics**

e.g. Computational singular perturbation (CSP) method
Direct related graph (DRG) method

# Combustion reaction(3)

**Coupling of combustion reaction and fluid dynamics**

**Strong non-linear phenomena**

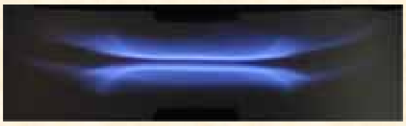
## 20th century

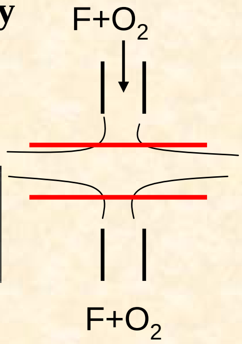
**2D or 3D analysis**
**with 1-step reaction model**
**flame-sheet model (flame thickness is 0)**

**F + O => P**
**$k = A\,[F]^p[O]^q \exp(-E/RT)$**

**1D analysis**
**with full chemistry**

**planar flame**



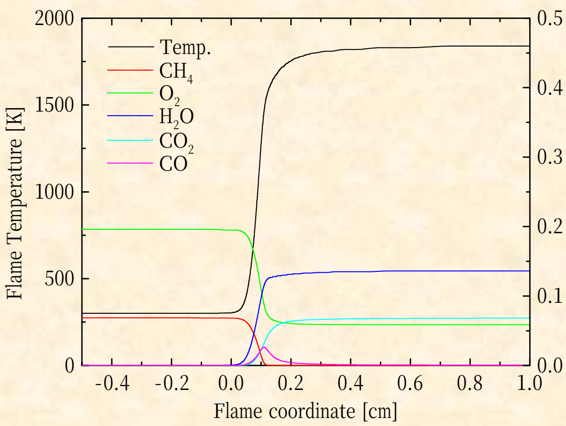


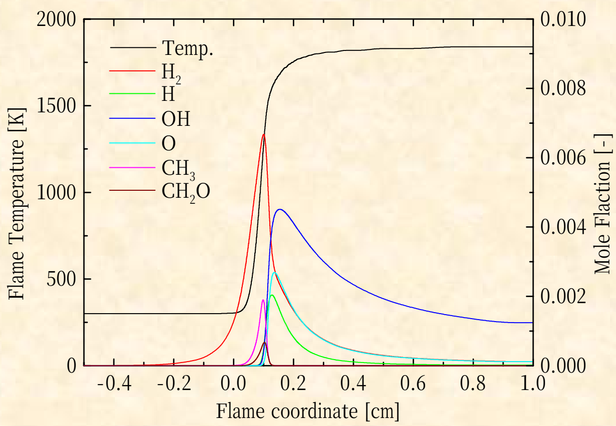

## 21st century

**DNS or LES with full chemistry of large hydrocarbon fuel**

# Flame structure

**flame thickness = 0.01mm – 0.1 mm**




**flame thickness is in inverse proportion to pressure and temperature.**

**high pressure and high temperature are keywords in new technology**

# Scramjet engine (1)

**SCRamjet (<u>S</u>upersonic <u>C</u>ombustion Ramjet) engine**


Combustion occurs in a supersonic flow

**a new air-breathing engine for**

**space plane**
**hypersonic airplane for intercontinental transportation**

# Scramjet engine (2)

**Why do we go to space by an air-breathing engine ?**

**<u>Rocket engine</u>**

carry fuel and oxidizer
(e.g. H2 Rocket, Space shuttle---$H_2/O_2$)
mass of oxidizer is more than 30% in total
9 to 35 times of pay-load

**<u>Air-breathing engine</u>**

do not need load oxidizer
can increase pay-load

**many technical issues in operation of air-breathing engine in high Mach No.**

***Mach number = (flow velocity)/(sonic velocity)**

# Scramjet engine (3)

Why do we need to burn fuel in a supersonic flow in the engine ?

$$\frac{1}{2}mv^2 \xrightarrow{V=0}$$ **heat (increase in temperature of gas)**

High seed flow has a large kinetic energy. This large kinetic energy is converted to a thermal energy (increase in temperature of a flow) in the engine.

**M -> 0**

**M = 1** → **T = 360 K**

**M = 5** → **T = 1800 K**

**M = 10** → **T = 6000 K**

$$T = T_0\left(1+\frac{\gamma-1}{2}M^2\right)$$

heat

$H + OH = H_2O$ (recombination)

↓

H,O,OH

**dissociation of products progress**

**heat release can not be obtained**

**no thrust**

**material problem**

# Scramjet engine (4)

## <u>Situation of development of scramjet engine</u>

### U.S.A.

**Hyper X-43A program (~2004) flight test**

**succeeded in acceleration to M=9.6 with a scramjet engine**

**HiFire, X-51 programs in progress**

### EC (ESA, ONERA, DLR)

**LAPCAT program**

**hypersonic vehicle (M=8) for intercontinental transportation**

**(4 hours from Brussels to Sydney)**

### Asia (China, India, Korea), Australia, …

**fundamental research is in progress**

### Japan (JAXA Kakuda)

**confirmed net thrust in M=4, 6, 8 flows by the engine test on ground**

**flight test of the engine was conducted in March, 2006**

# Scramjet engine (5)

## research of scramjet in Tohoku University

experimental and numerical study of ignition and combustion enhancement by using plasma

**Supersonic wind tunnel**

**test Mach no.:**
**M=1.0, 1.8, 2.3**
**test section size:**
**30 mm x 30 mm x 300mm**

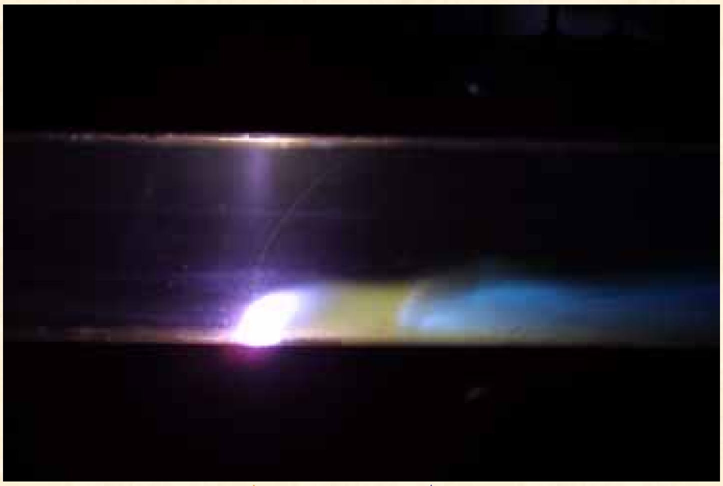
**duration of test:**
**about 30 s**

# Scramjet engine (6)

## ignition and combustion enhancement by plasma

**ignition of ethylene ($C_2H_4$) fuel by a PJ torch in a supersonic flow**

**M=2.5**



30 mm

**PJ** **Fuel**

**Plasma Jet (PJ)**
**Torch igniter**

# Scramjet engine (7)

## Numerical method

**Governing equations:**

Raynolds-averaged three-dimensional Navier-Stokes (RANS) equations in the generalized curvilinear coordinate for multispecies

**Scheme:** third-order SHUS scheme scheme for convective terms
second-order central-difference scheme for diffusive terms

**Time integral:** Matrix-free LU-SGS method

**Combustion model:**

$H_2$ combustion model----------9 species, 33 elementary reactions

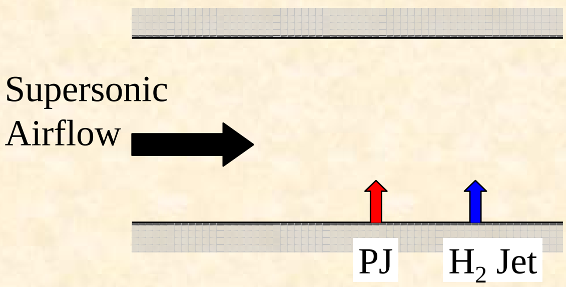
**Turbulence model:** k-ω SST two equations model

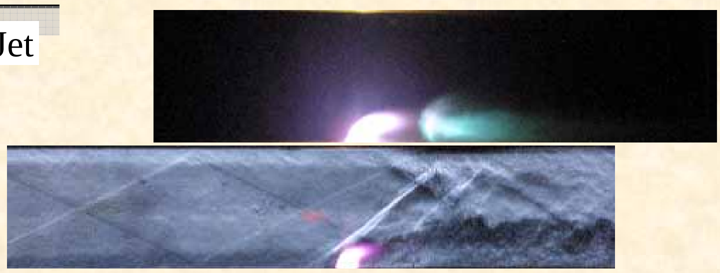
**Size of area in computation:** x (30mm), y (30mm), z (300mm)
same as experiment

**Mesh number:** 157 x 55 x 71 (total 613,085)

# Scramjet engine (8)

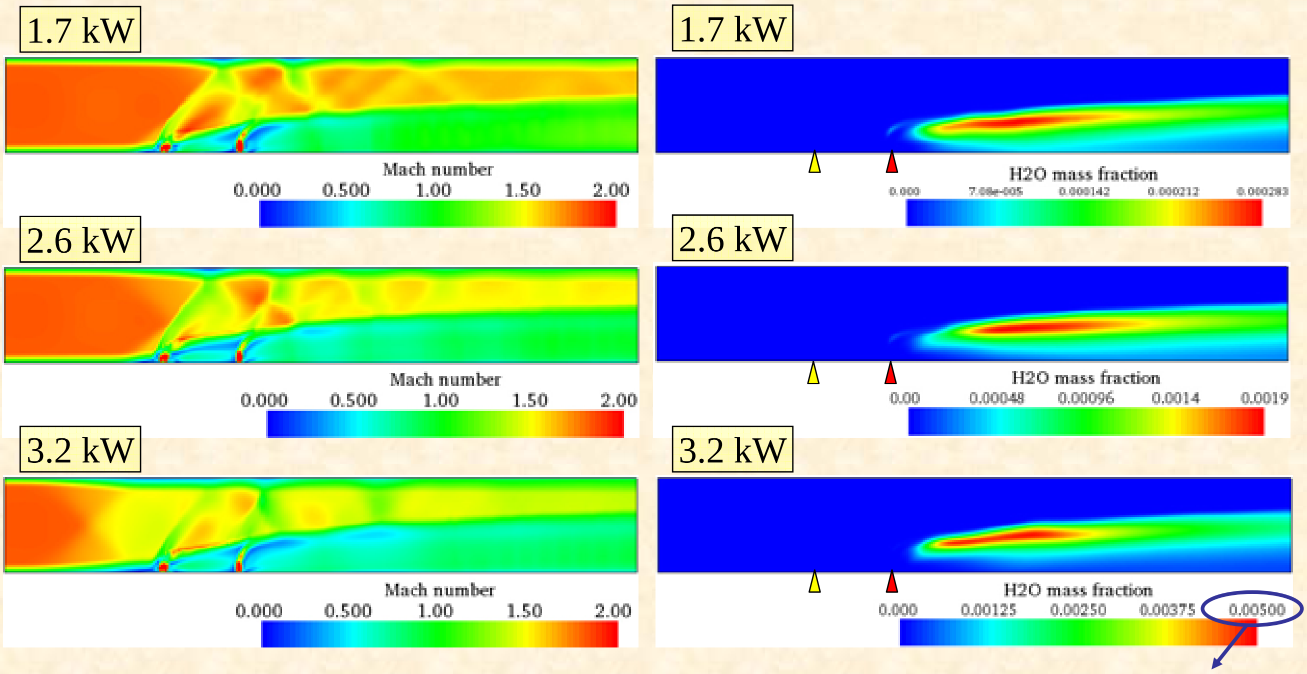
## downstream fuel injection



# Scramjet engine (9)

## simulation of downstream fuel injection

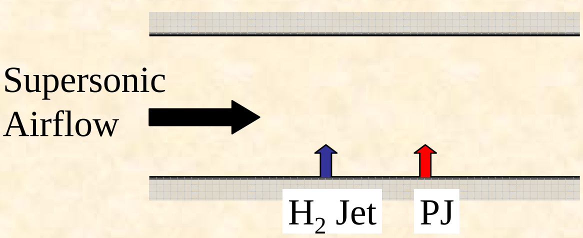


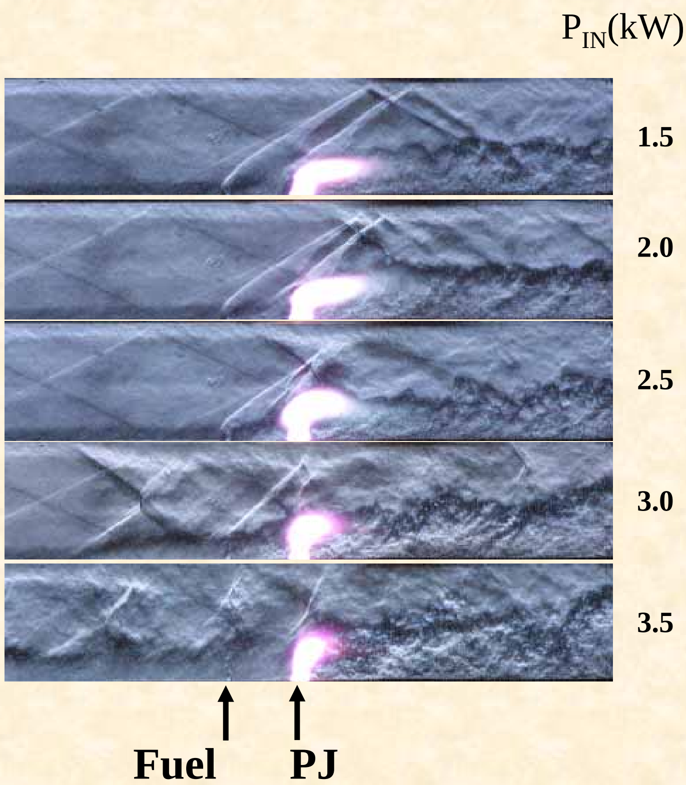

**Mach number**

**$H_2O$ mass fraction** **0.5 %**

# Scramjet engine (10)

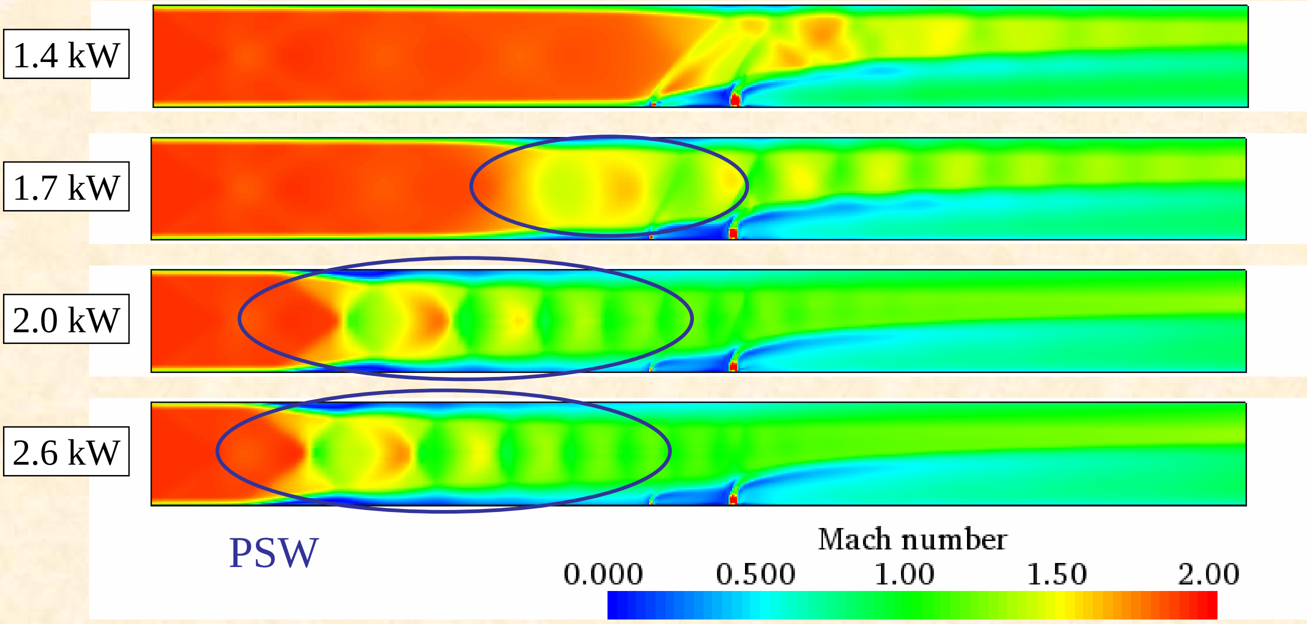
## upstream fuel injection



# Scramjet engine (11)

## simulation of upstream fuel injection (1)

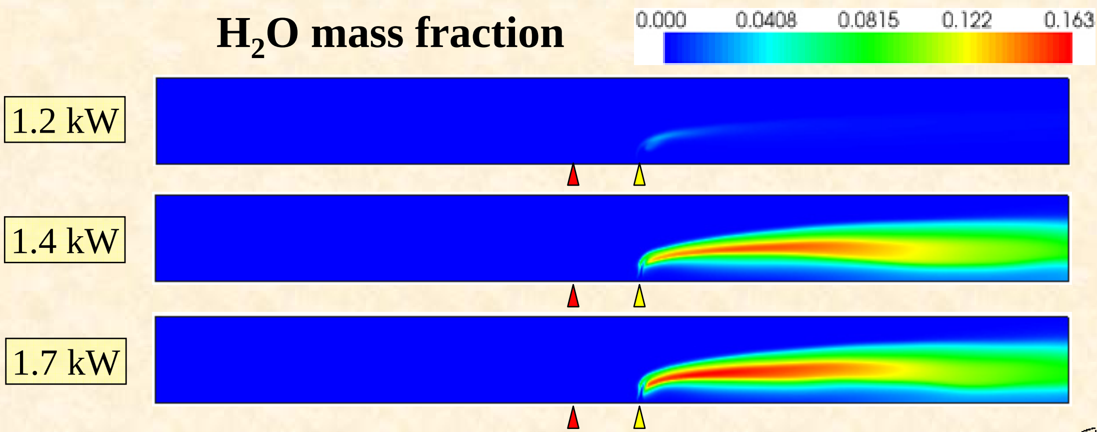


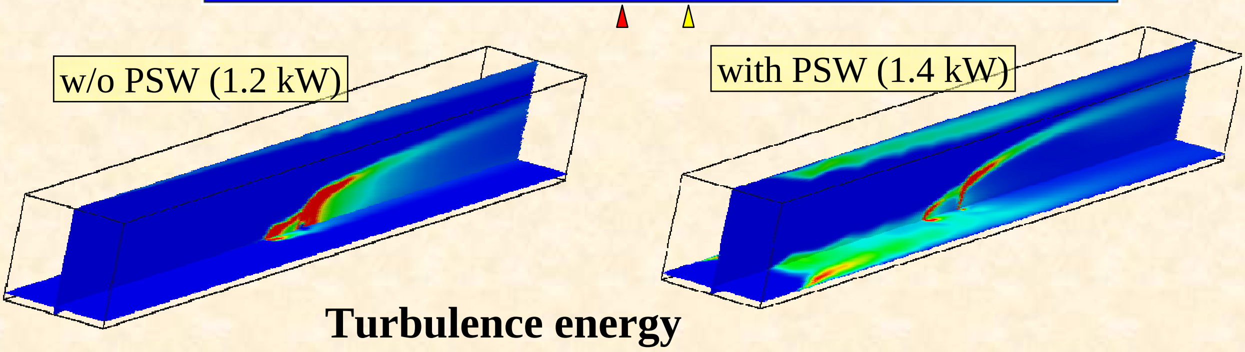

**Mach number**

# Scramjet engine (12)

## simulation of upstream fuel injection (2)

**$H_2O$ mass fraction**




**Turbulence energy**

# Future problems

**1 Simulation of combustion under severe conditions**

high pressure, high temperature conditions (sometimes, beyond critical point)
e.g.) Rocket engine (H2A, …), Automobile,

**2 Simulation of large hydrocarbon fuels**

C3, C4, C5, C6, C7,….
development of reduced reaction mechanism is important

**3 LES analysis of supersonic turbulent combustion flow**

**4 Including plasma chemistry in analysis of combustion flow**