Research on Vacuum Plume and Its Effects

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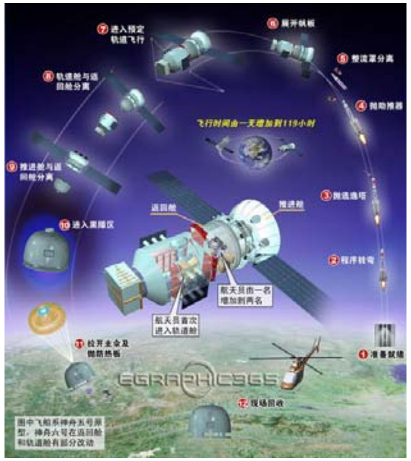
- Introduction
- Numerical Simulation
- Experimental Validation and Research
- Plume WorkStation (PWS)
- Application
- Conclusion

Introduction

- Over the past five decades, great success has been achieved in space technology.
- Space technology have greatly advanced the development of society.
- Currently, about 800 satellites are in orbit. 48 satellites were launched in 2005.



Vacuum Plume and Its Effects

Spacecraft

↓

Impulse control device

↓

Plume

Orbit adjustment

Attitude keeping

Attitude control thruster

Orbit control thruster

Contamination

Aerodynamic force

Aerodynamic thermal

Accidents Caused By Plume Effects

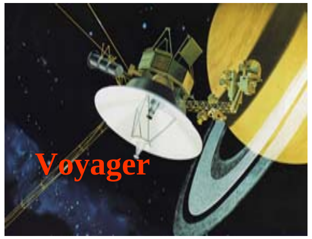
BUAA

Gemini

Observation windows contaminated.

BSE-1

Solar cell surface contaminated.



Voyager

Thrust decreased 22% on average. Torque lost 60%.

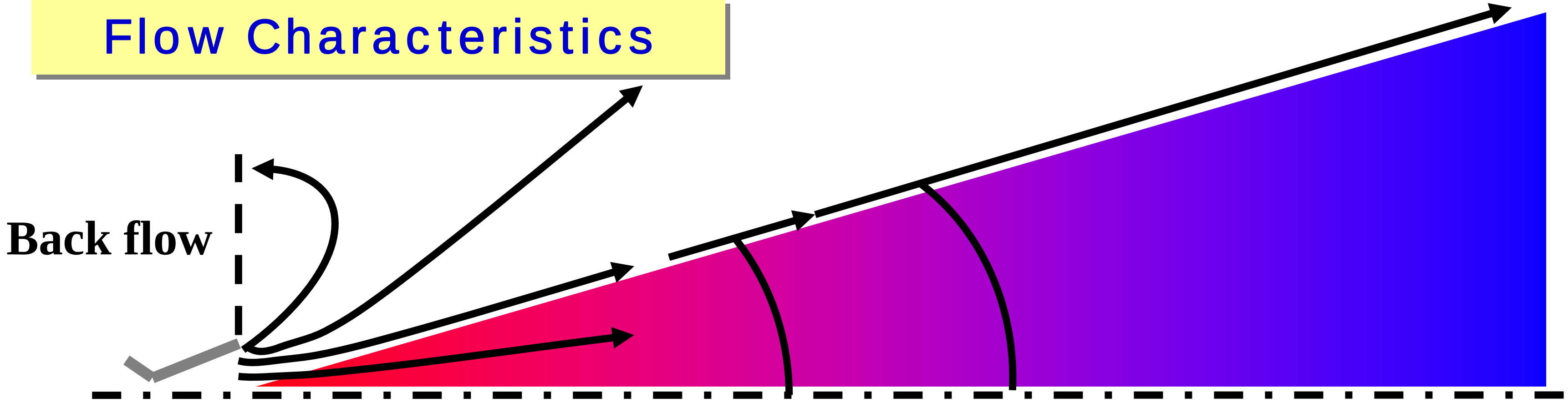
Mariner 10

Lifetime of spacecraft seriously reduced.

Flow Characteristics and Research Difficulties

BUAA

Flow Characteristics



Continuous flow → Transition flow → Free molecular flow

Continuous flow	Transition flow	Free molecular flow
N-S Equations	Complete Boltzmann Equation	No Collisional Boltzmann Equation

Research Difficulties

- □ Boltzmann Equation Solving
- □ Experimental Research

Research Methods

Semi-experiential and analytical methods

- **Simons Method**
- **MOC Method**

Experimental research

- **Ground Experiment**
- **Flight Experiment**

Numerical simulations

- **N-S / DSMC Method**

DLR STG

Combined N-S Equations & DSMC Method

Nozzle flow simulation

- N-S equations (Difference solving)

Plume outside nozzle

- Boltzmann equation (DSMC)

Typical Numerical Simulation

Main research work

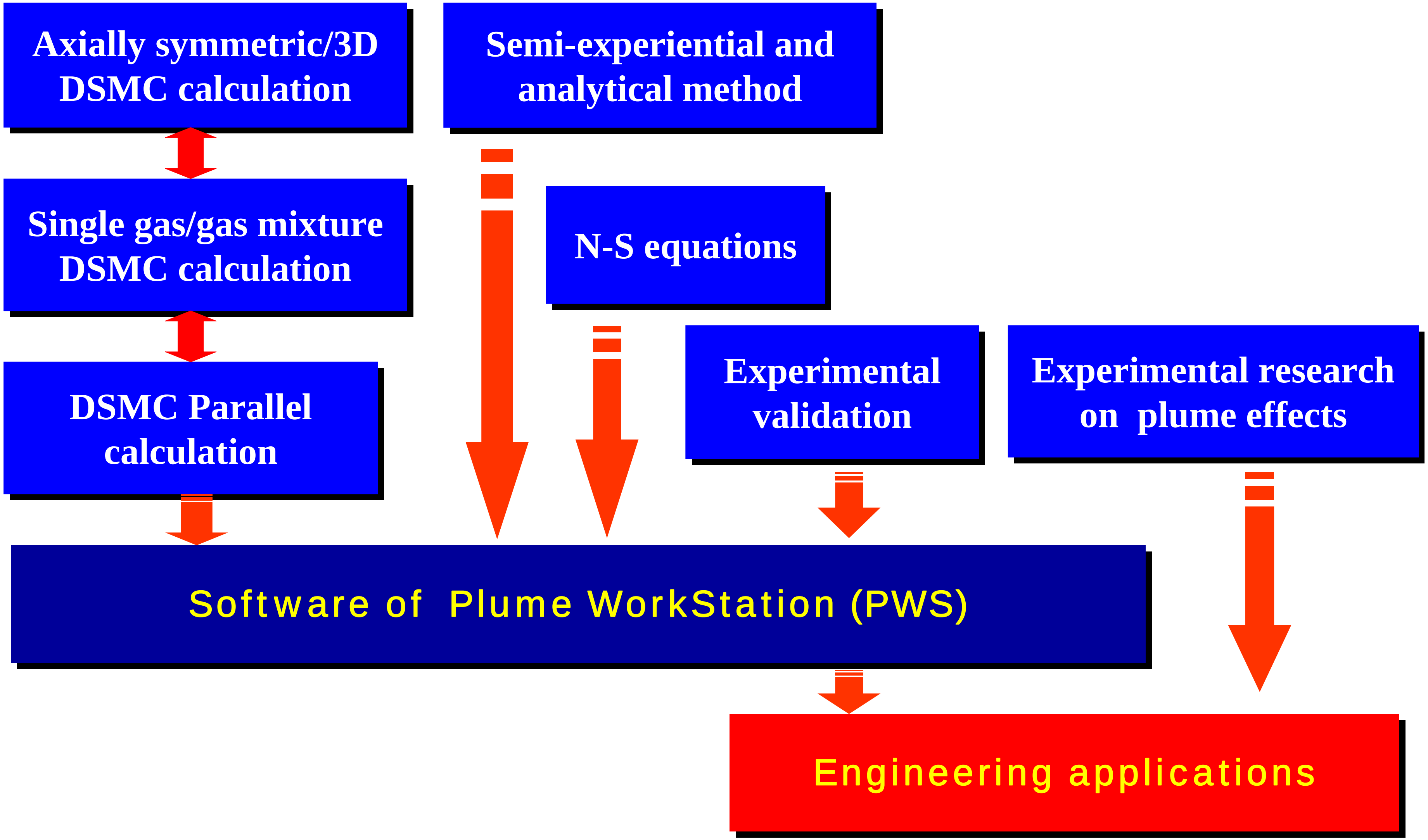
- **1989, S.Parvez et al. , The impact of vacuum plume to solar array.**
- **1991, I.D.Boyd and P.F.Penko, Test and simulation on low density vacuum plume of small thruster.**
- **1992 and 1993, R.I. Samanta Roy, et al. Test and simulation on ion rocket motor vacuum plume contamination.**
- **1993, John J. Scialdone et al, Plume contamination controlling.**
- **2000, M.S.Ivanov et al, Simulation of thruster nozzle plume.**
- **2002, J.H.Park et al, Analysis of the interaction between thruster plume and satellite components.**
- **2004, Henry A. Carlson et al, Hybrid CFD-DSMC method to model continuum-rarefied flows.**

Typical Numerical Simulation

Typical software

Software Name	Country/Company
CONTAM III	USA/Science Application International Corporation
SMILE	Russia /ITAM
DS2V/DS3V/DSWT	Australia/ GAB Consulting Pty Ltd

Research Focus of BUAA



Numerical Simulation

Numerical Simulation

- Nozzle Flow Simulation
- Plume Simulation
- Flow Chart of DSMC Method
- Typical Axially Symmetric Calculation
- Typical 3-D Calculation
- DSMC Parallel Calculation

Nozzle Flow Simulation

Governing equations

Axially-symmetric N-S equations

Turbulent model

The Baldwin-Lomax model

Difference method for solving N-S equations

MacCormack scheme

Mesh treatment

TTM method

Boundary condition

Inlet, exit, the symmetric-axis and solid wall surface boundary condition.

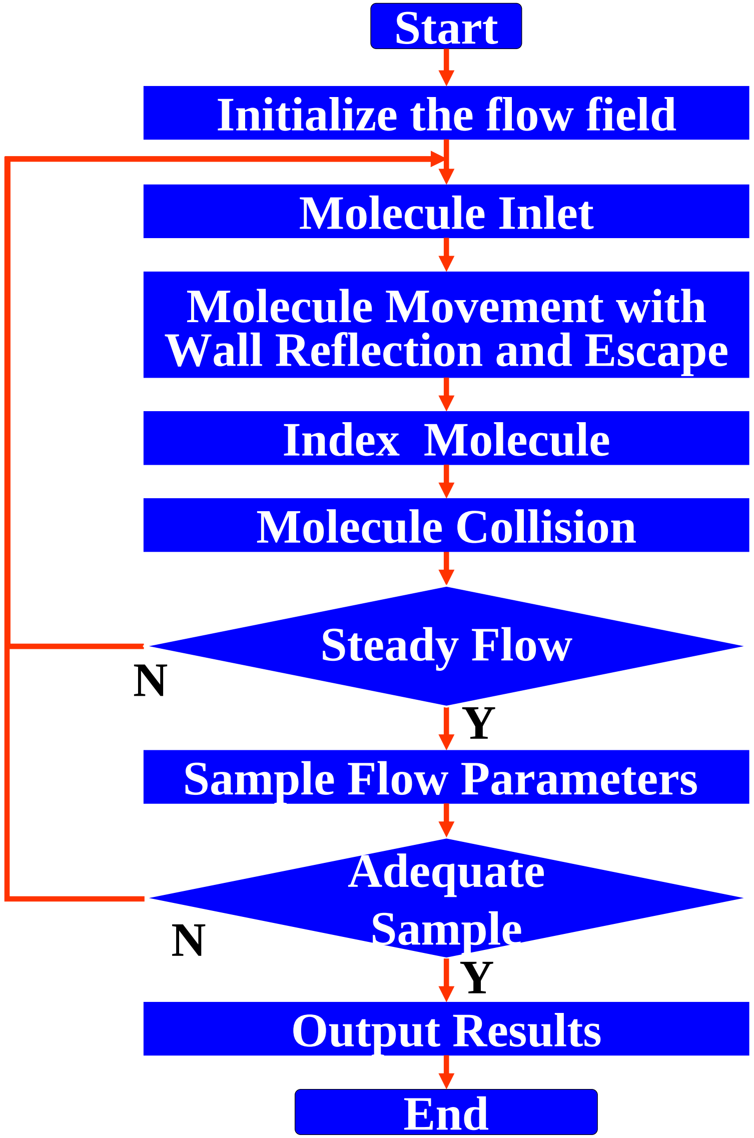
Plume Simulation

The pressure and density at the nozzle exit of the attitude control thruster are relatively low. The DSMC method is adopted to simulate vacuum plume entirely outside the nozzle.

Basic assumption

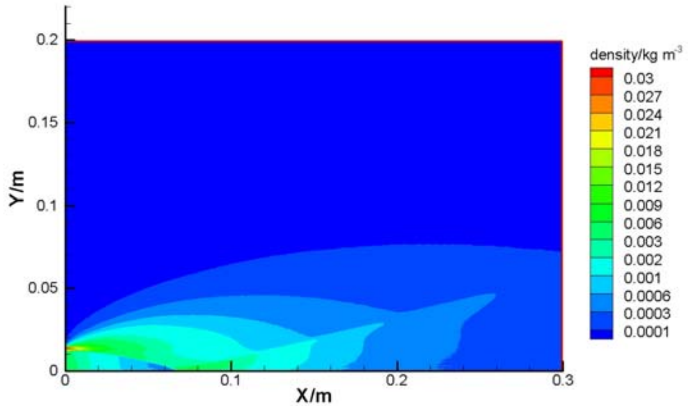
- **Only binary collisions are considered.**
- **Neglect internal degree of freedom and chemical non-equilibrium effect.**
- **The entire gas flow is steady.**
- **The interaction force between molecules is neglected.**

Flow Chart of DSMC Method

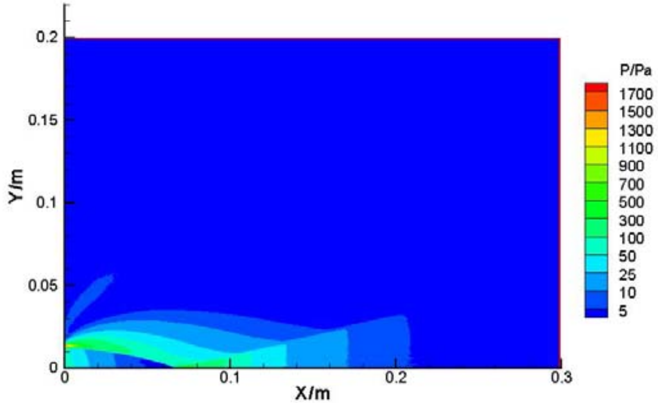


Typical Axially Symmetric Calculation

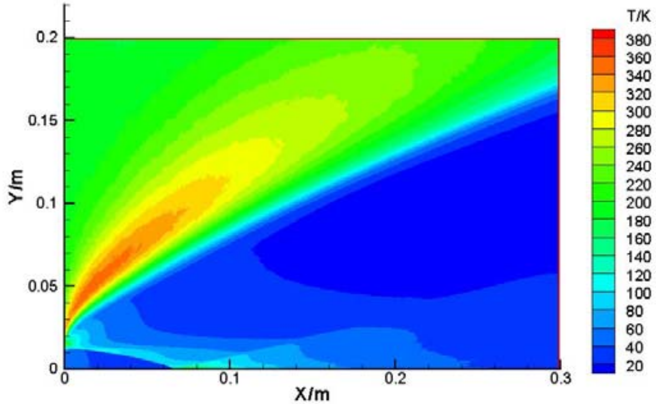
P_0=0.8MPa, T_0=773K DFH-3 Nozzle



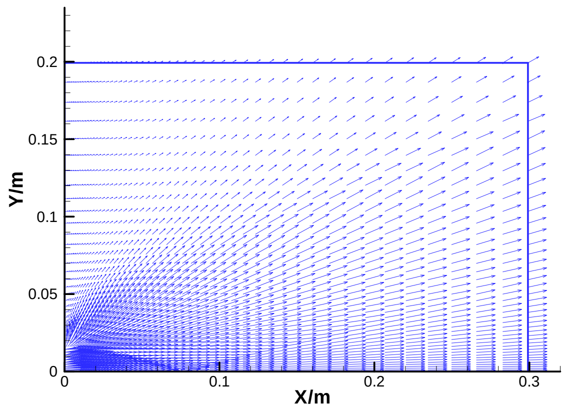
Density contour of plume



Pressure contour of plume



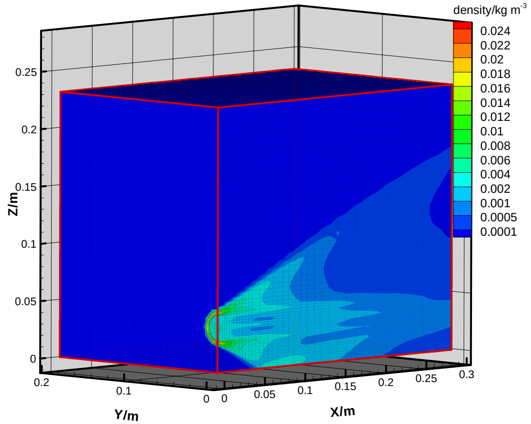
Temperature contour of plume



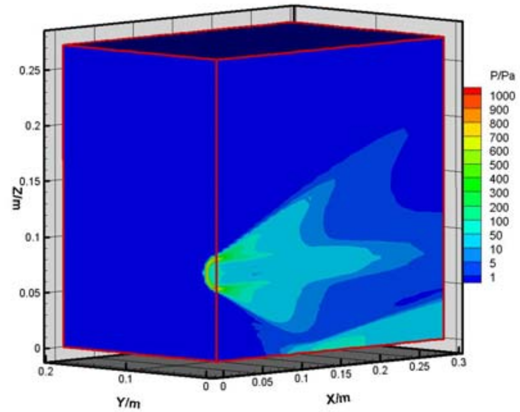
Velocity vector of plume

Typical 3-D Calculation

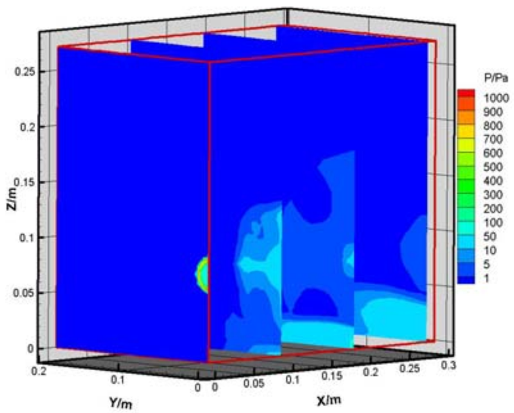
P_0=0.8MPa, T_0=773K DFH-3 Nozzle



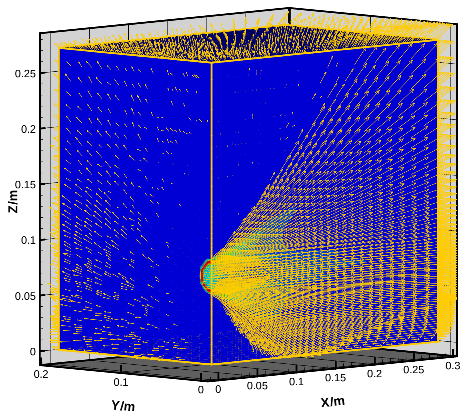
Density contour of plume



Pressure contour of plume



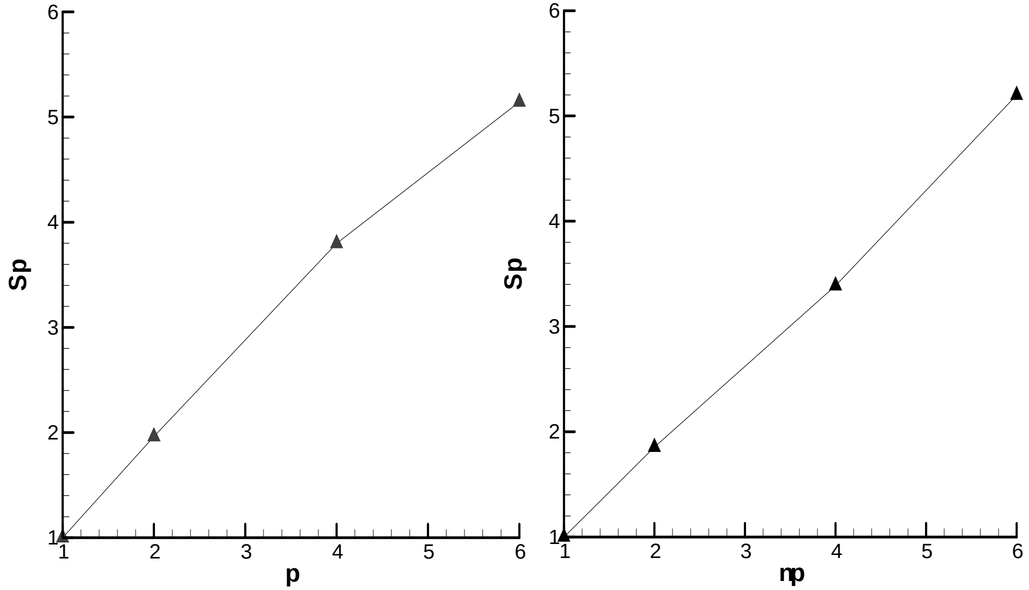
Slice of plume pressure contour



Velocity vector of plume

DSMC Parallel Calculation

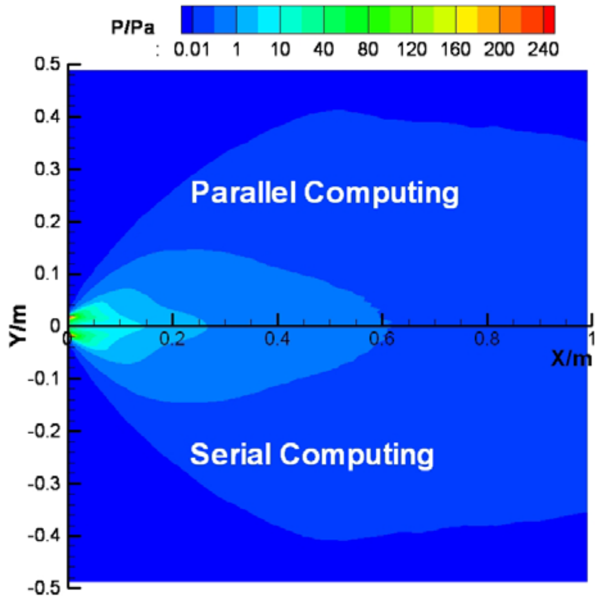
In the DSMC method, parallel calculation is needed for large scale and high speed computation.



(a) (b)

Parallel Computation Acceleration Ratio

(a) Axially Symmetric (b) 3-D



Pressure Contrast Between Serial and Parallel Calculation

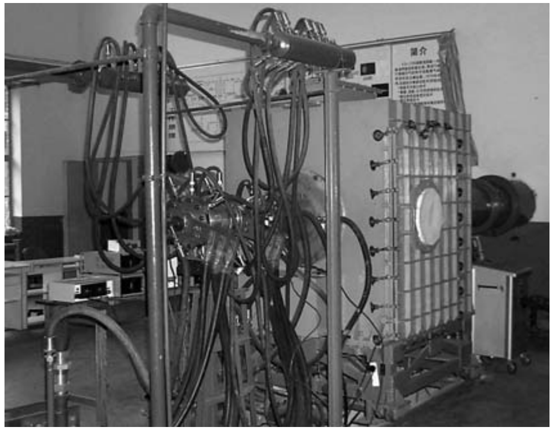
Experimental Validation and Research

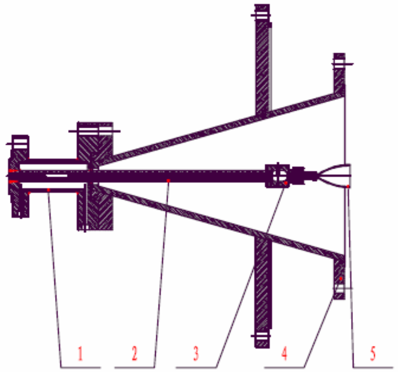
Experimental Validation and Research

- Experimental Validation of PWS
- Experimental Study—Plume Aerodynamic Force
- Experimental Study—Plume Aerodynamic Thermal Effects

Experimental Validation of Numerical Simulation Software

China Aerodynamic Research and Development Center (CARDC) has a supersonic low density wind tunnel, which can simulate high-altitude environment from 60km to 90km.





1: link segment 2: supplying gas pipeline 3: front chamber
4: nozzle of wind tunnel 5: thruster

Plume Validation

- **Model thruster nozzle**
- **Satellite attitude control thruster nozzle**

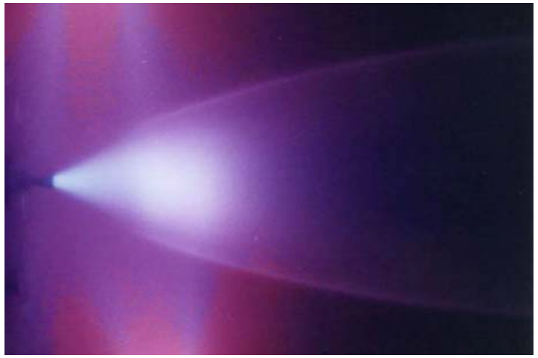
Experimental Validation of Numerical Simulation Software

Model Thruster Nozzle

BUAA

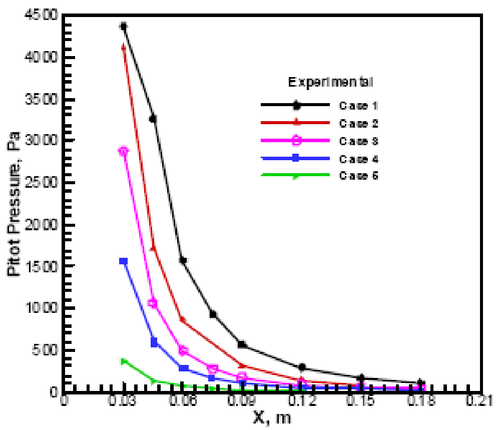
	Nozzle 1	Nozzle 2	Nozzle 3
Thrust *F/N*	2.	2.	0.5
Scared	/	45º	/

Case	Nozzle	P_0/MPa	T_0/K
1	1	1.0	300
2	1	0.5	300
3	2	1.0	300
4	2	0.5	300
5	3	0.11	300

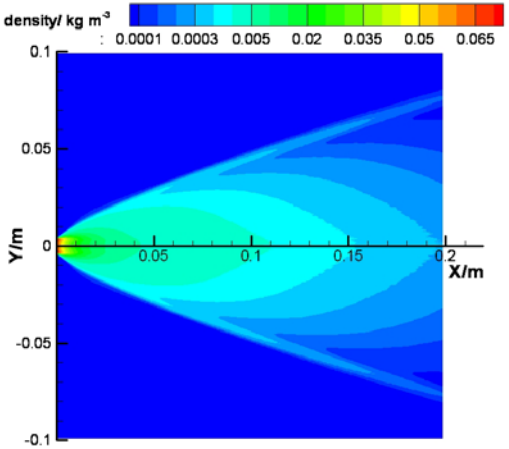


Plume structure (Case1 and glow discharge image)

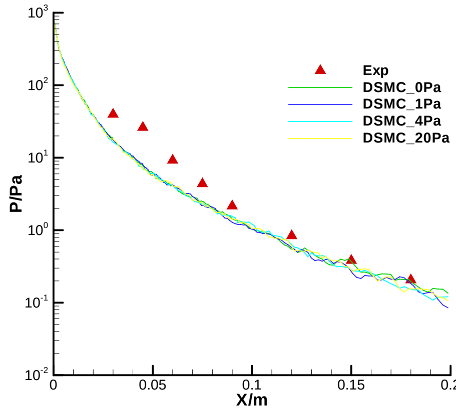
Plume structure (Case3 and glow discharge image)



Pressure along axis



Density contour (Case1)



Contrast between DSMC result and Exp. (Case1)

Experimental Validation of Numerical Simulation Software

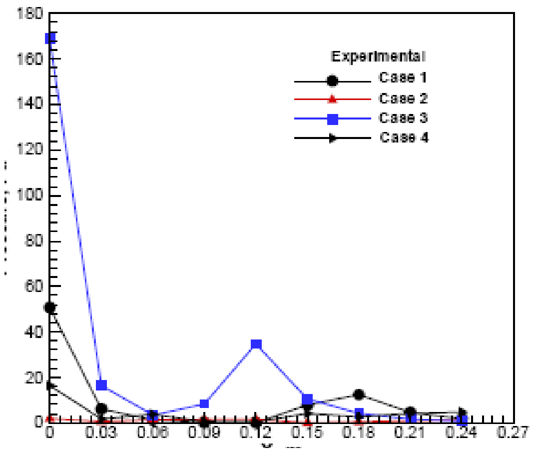
Satellite Attitude Control Thruster Nozzle

BUAA

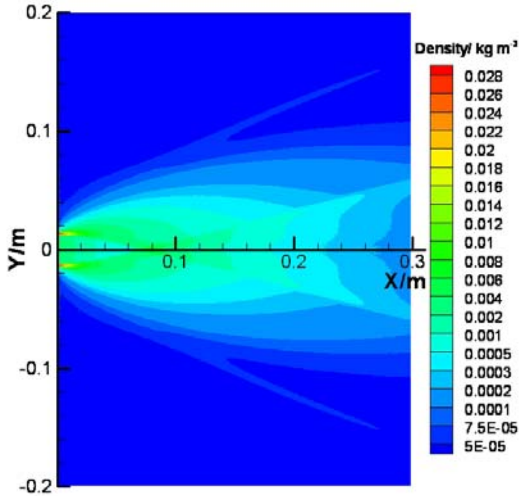
	Nozzle1	Nozzle2
Thrust *N/F*	10.	10.
Aero ratio $(D_e/D_t)^2$	199.7511	96.04
Diameter D_e/mm	42.6	29.4

Case	Nozzle	P_0/MPa	T_0/K
1	1	0.8	773
2	1	0.1	773
3	2	0.8	773
4	2	0.1	773

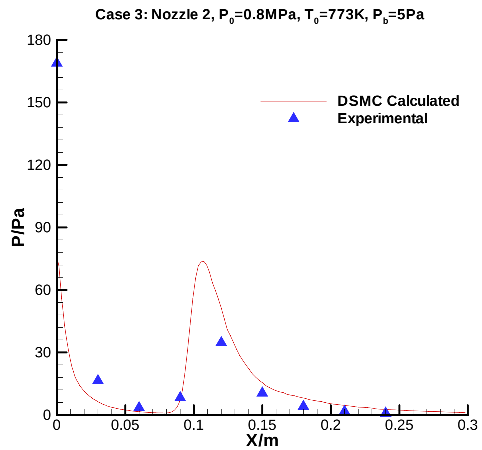
Plume structure (Glow discharge image of Case1)



Pressure along axis



Plume pressure (Case3)

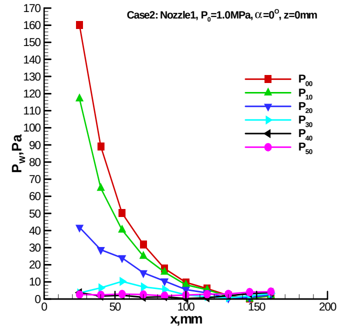


Contrast between DSMC result and Exp. (Case3)

Experimental Study—Plume Aerodynamic Force

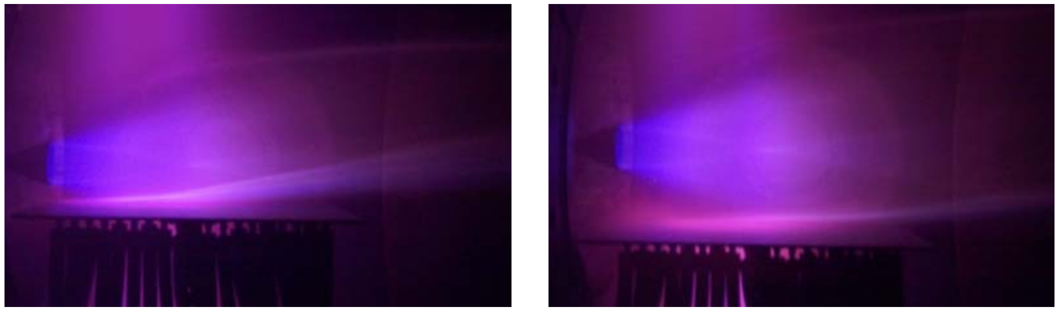
Model Thruster Nozzle

Plume structure (F=2N nozzle and F=2N scarred)

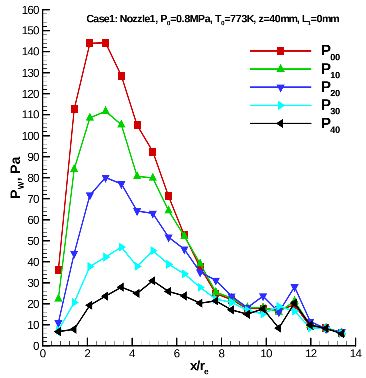


Pressure distribution on plate (Case2)

Satellite Attitude Control Thruster Nozzle



Plume structure (F=10 N nozzle2)



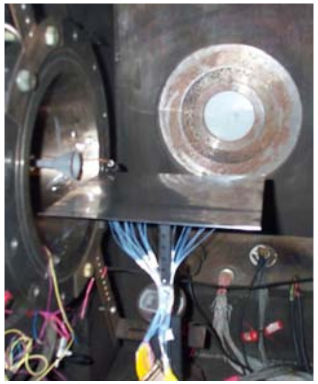
Pressure distribution on plate (Case1)

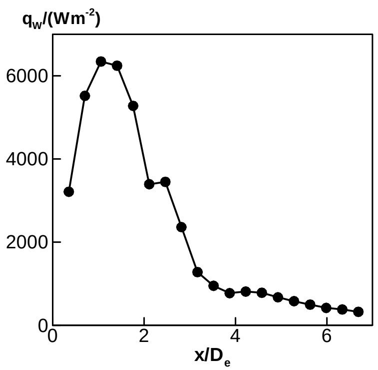
Experimental Study—Plume Aerodynamic Thermal

Aerodynamic Thermal Effects Measurement

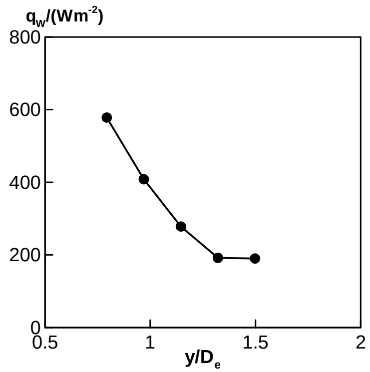
$$q_W = \rho \cdot c \cdot b \cdot \frac{dT}{dt}$$

Results





Result on Horizontal Plate Surface

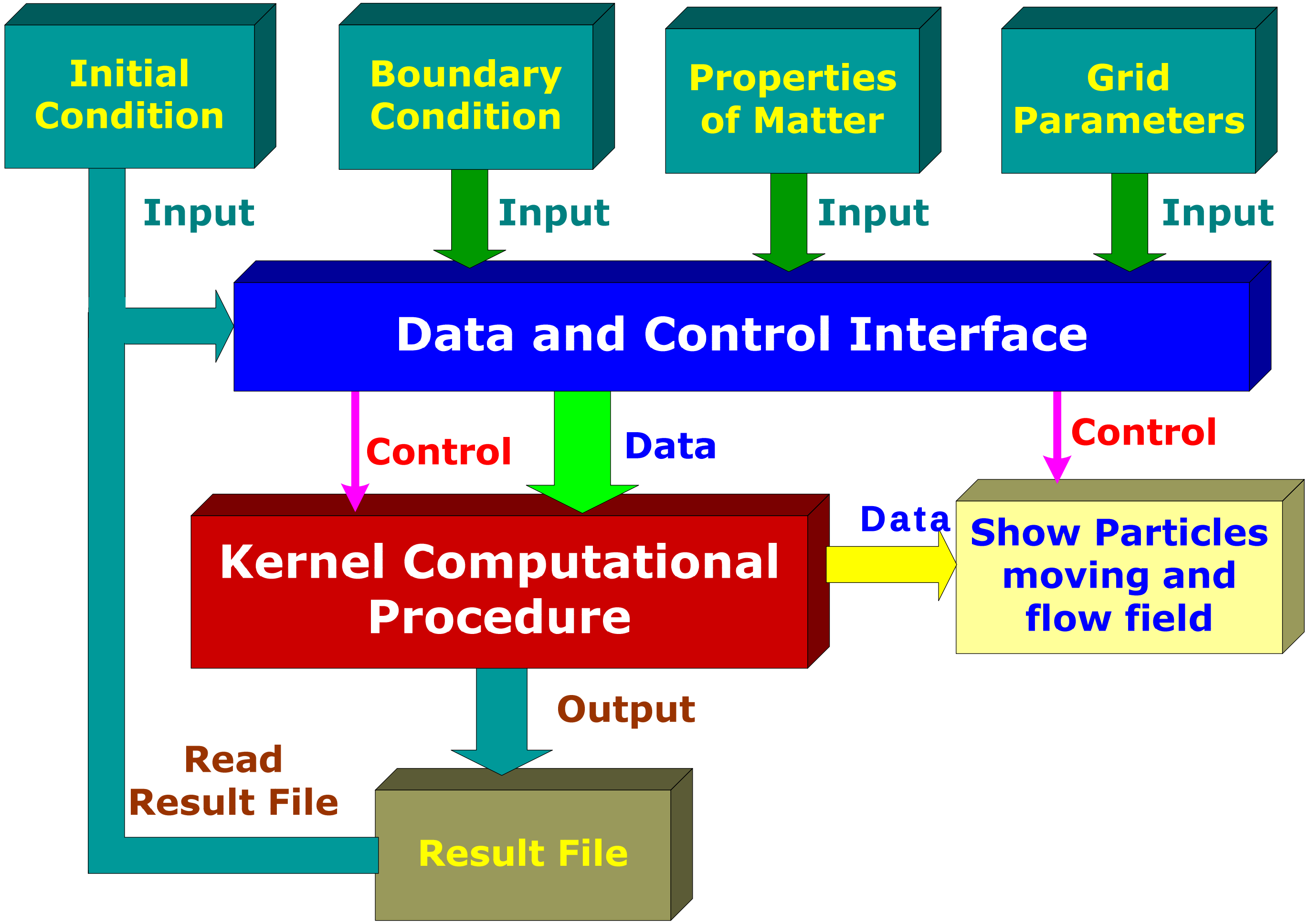


Result on Backflow

Plume WorkStation (PWS)

Numerical Simulation Software—*Plume WorkStation*

BUAA



Input Initial Parameters

Interactive control Interface

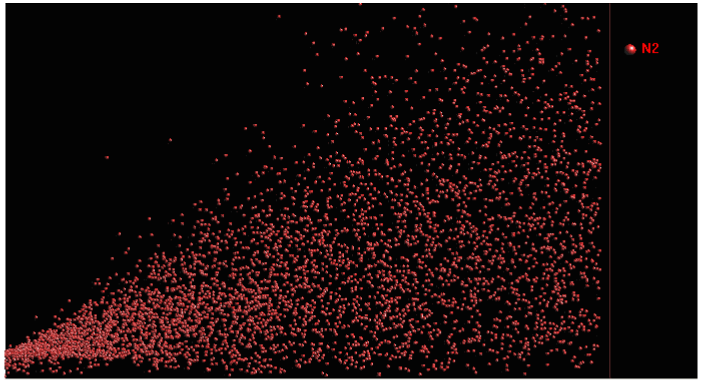
Flow field Real-time display

Kernel computational Procedure

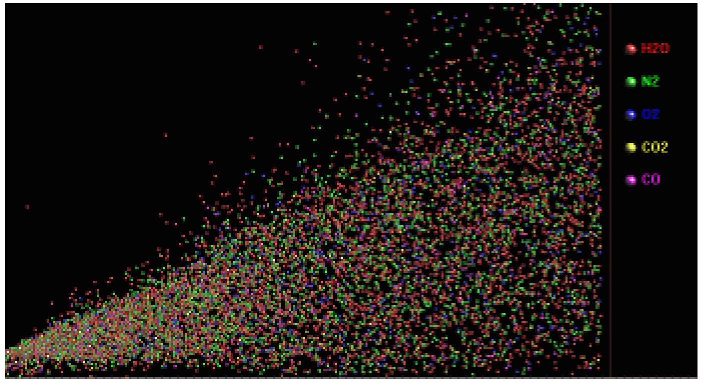
Results Output

Numerical Simulation Software—*Plume WorkStation*

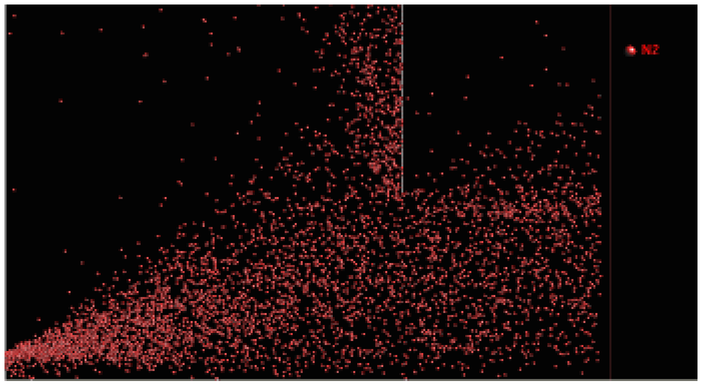
BUAA



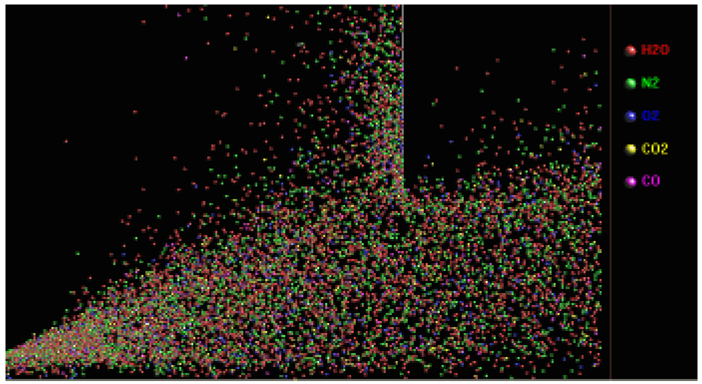
Particle movement simulation
（single species）



Particle movement simulation
（multi-species ）



Particle movement simulation
（single species with baffle）



Particle movement simulation
（multi-species with baffle）

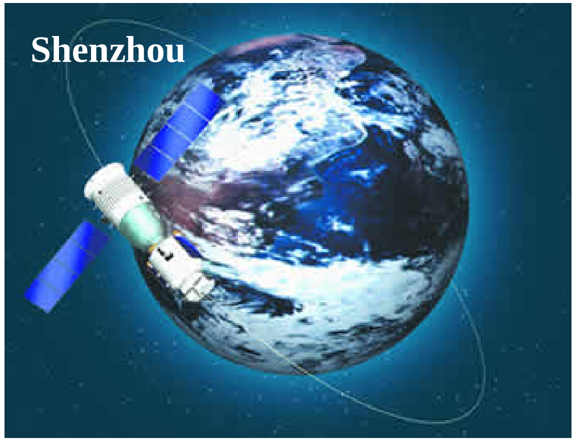
Application

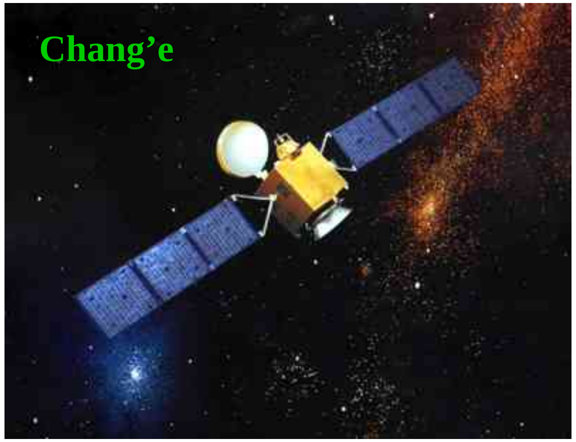
Applications

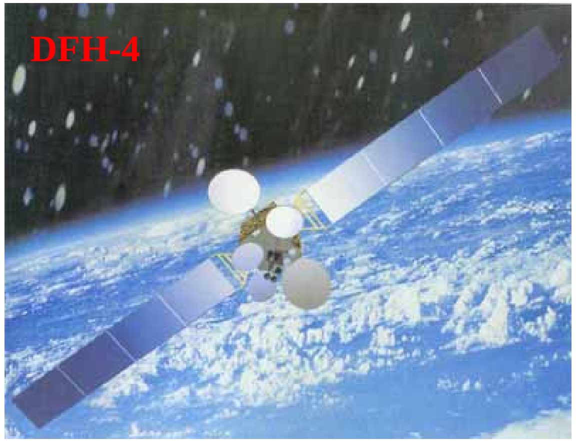
☆ "Shenzhou" Spaceship

☆ "Chang'e" Lunar Orbiter

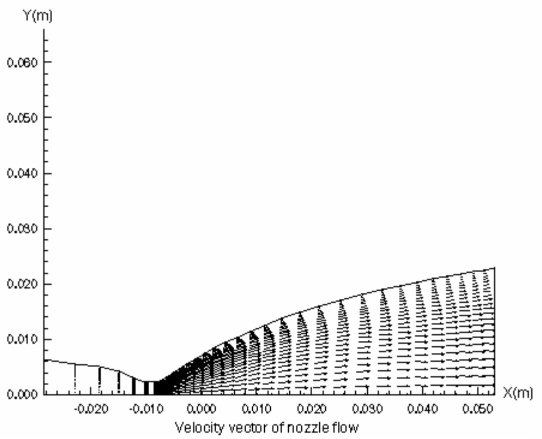
☆ "DFH-4" Communication Satellite



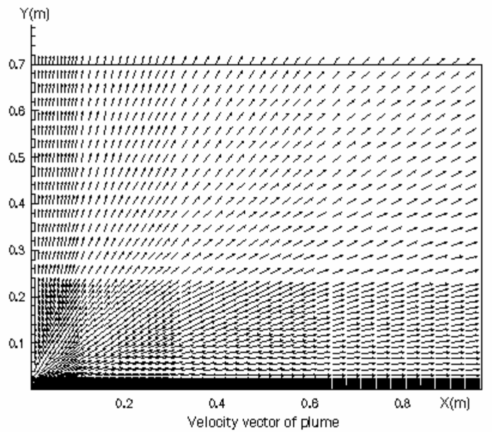




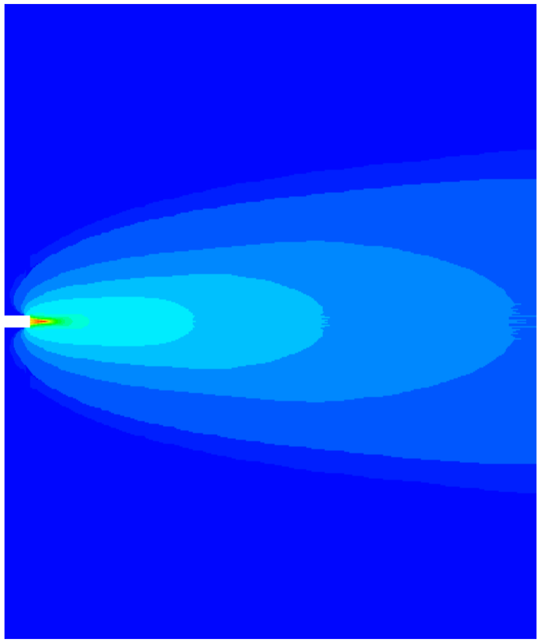
Applications---- “Shenzhou” Spaceship



Velocity vector in nozzle



Velocity vector of plume



Density contour of plume

Shenzhou

Applications---"Chang'e" Satellite

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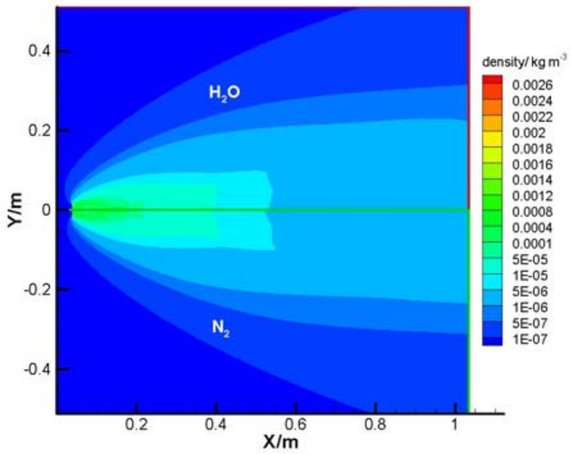
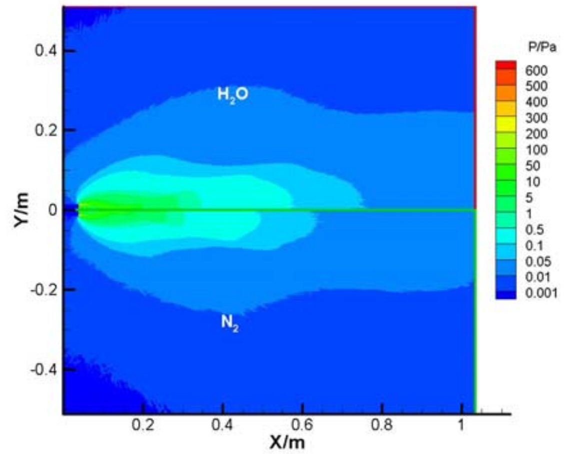
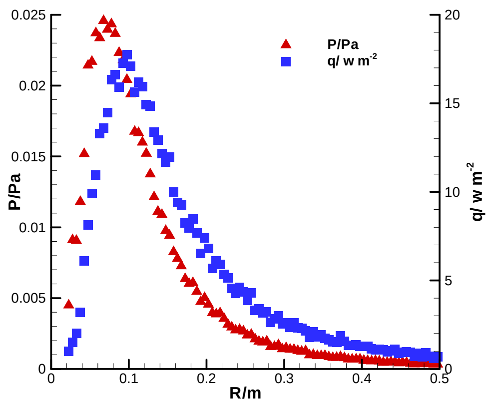


Density contour contrast between H_2O and N_2



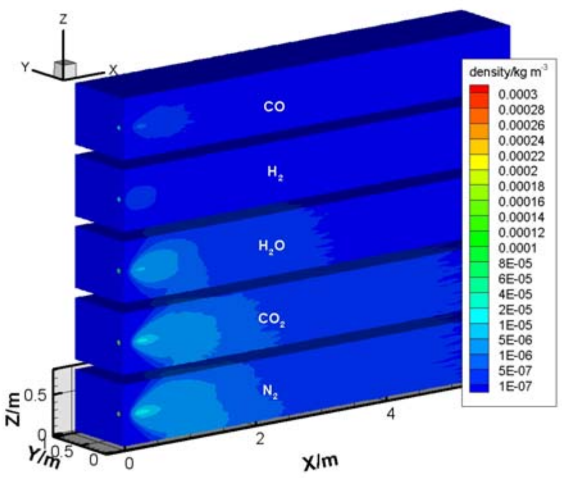
Pressure contour contrast between H_2O and N_2

Chang'e

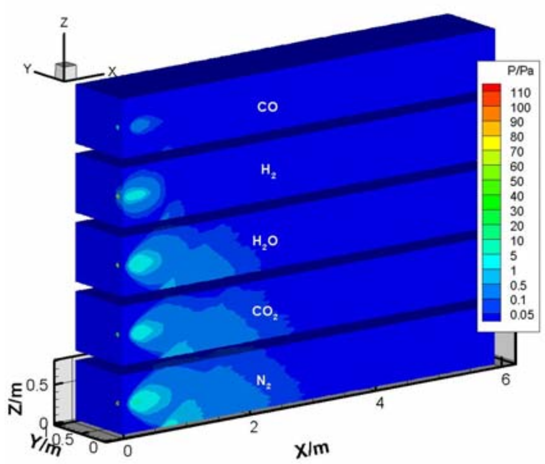


Pressure and heat flux distribution on satellite surface

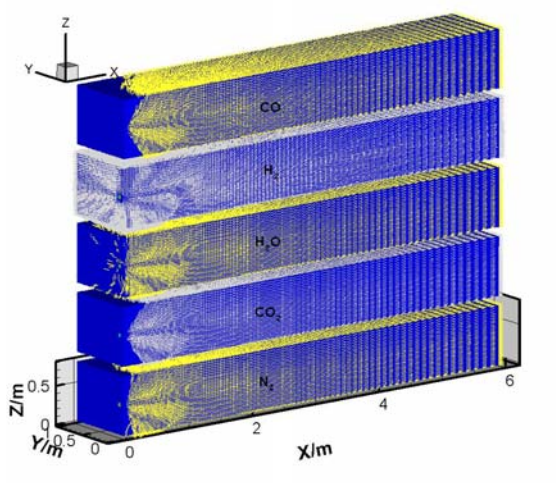
Applications--- “DFH-4” telecommunication satellite



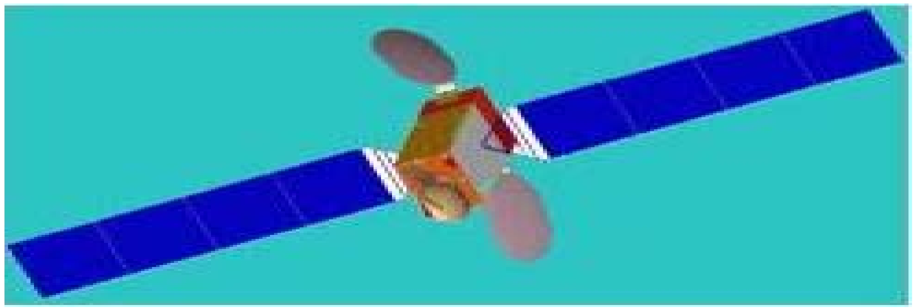
Each species
density contour



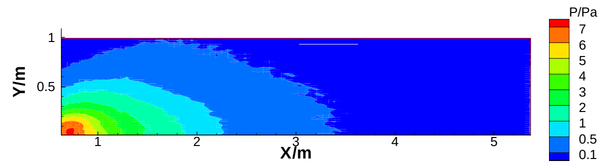
Each species
pressure contour



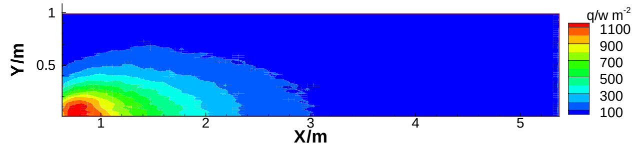
Each species
velocity vector



DFH-4



Pressure distribution on solar cell panel



Heat flux distribution on solar cell panel

Conclusion

- A new software PWS developed at BUAA can simulate the vacuum plume.
- The experimental validation of PWS shows that PWS works effectively.
- Research on vacuum plume is conducted for typical engineering applications.
- Further work concerning plume effects will be conducted based on more advanced experimental systems.

Thank You!