JAPAN-RUSSIA WORKSHOP ON SUPERCOMPUTER MODELING, INSTABILITY AND TURBULENCE IN FLUID DYNAMICS (JR SMIT2015)
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Session I

MHD Heat Shield in Argon Arcjet Plasma Flow

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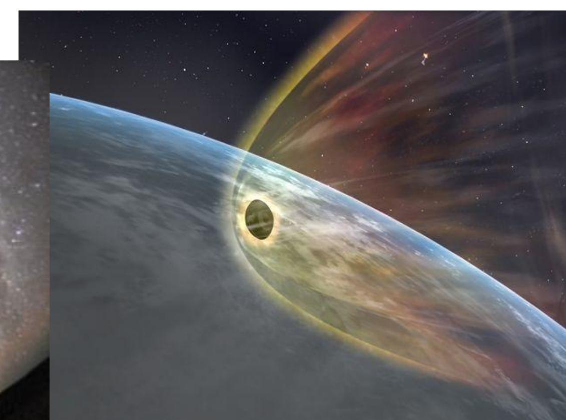
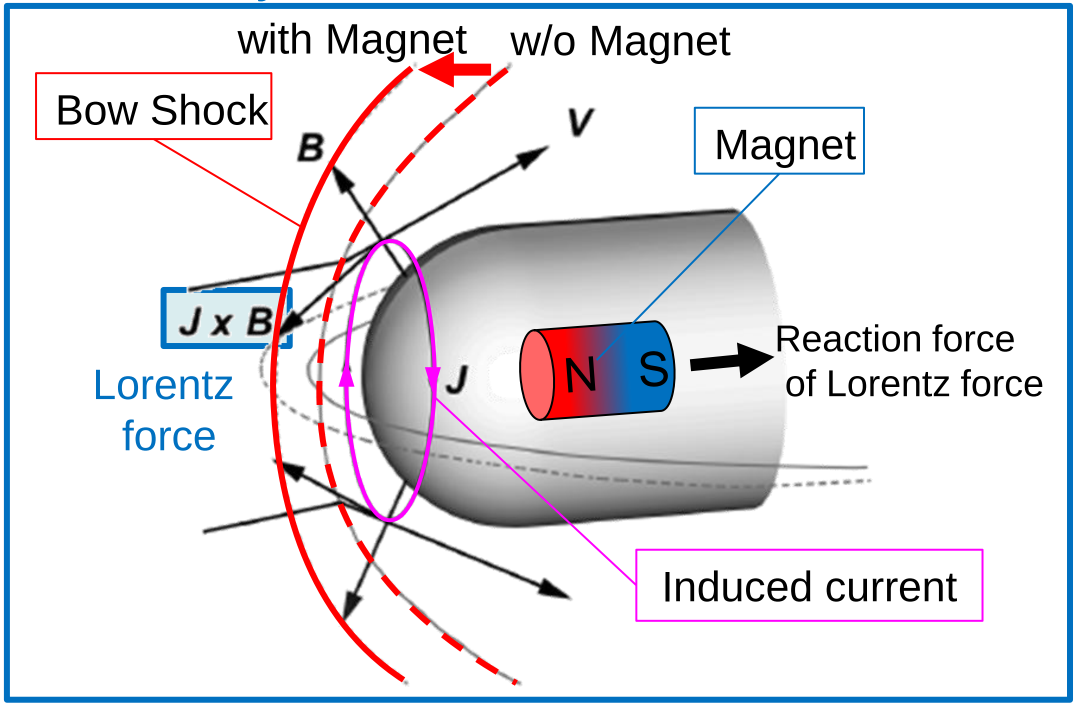
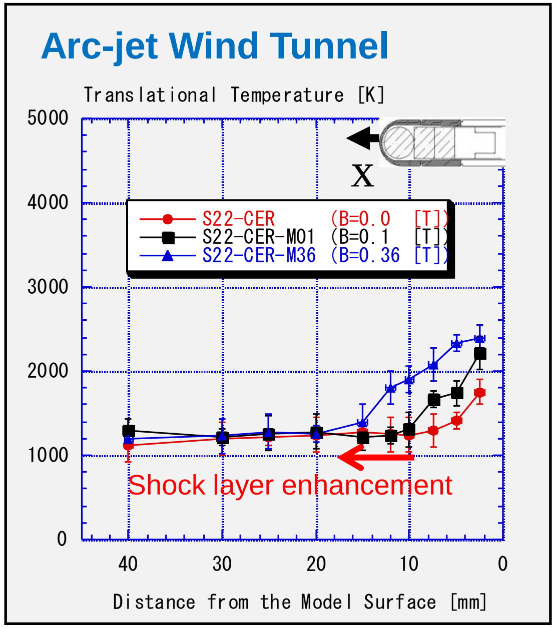
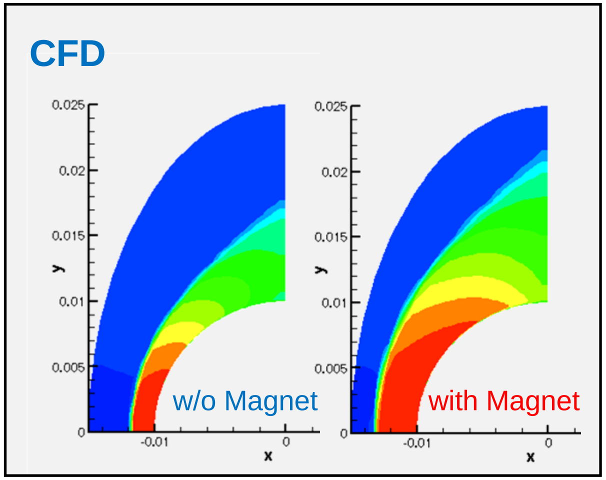


MHD Heat Shield

- Applied magnetic field interacts with the weakly ionized plasma behind the strong shock wave.
- The flow field is affected by Lorentz force.
  - Enhancement of shock layer
  - Reduction of aerodynamic heating
  - Enhancement of drag force
- New type of heat protection system for re-entry vehicle

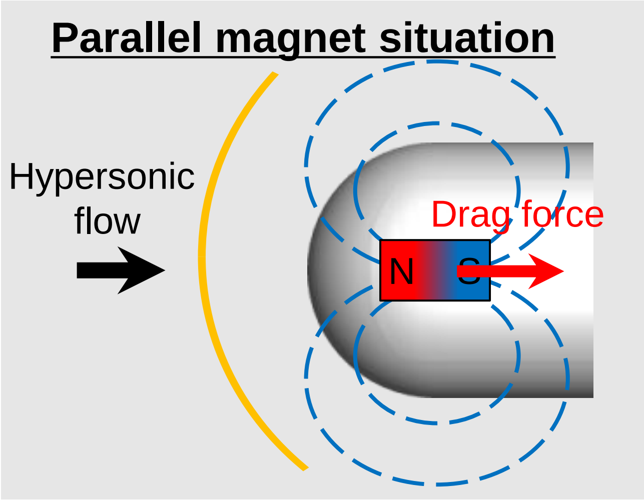


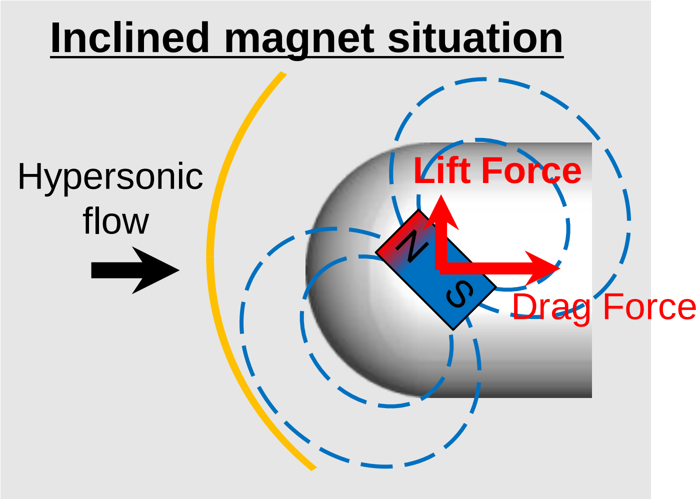




Electrodynamic Effect for Force Control

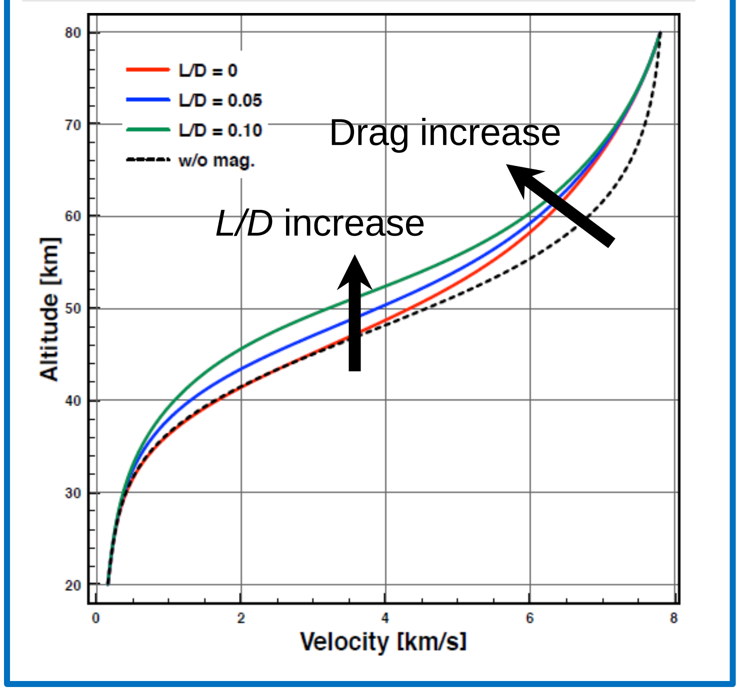
For application, the magnetic orientation such as a magnetic inclination angle could be a controllable parameter.





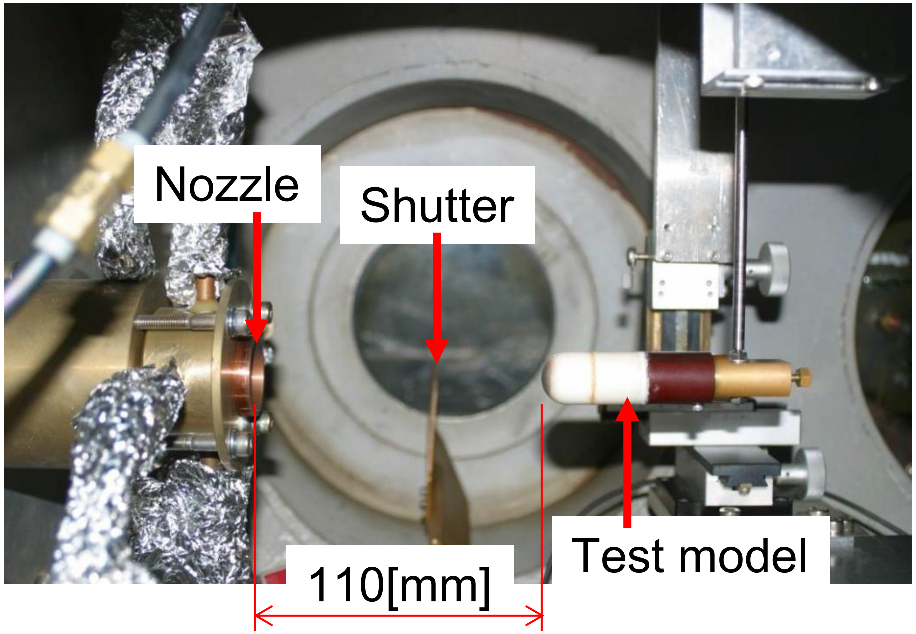
The re-entry flight path could be controlled without moving parts by changing the aerodynamic force.

H. Otsu, et al, AIAA-Paper 2011-3466.

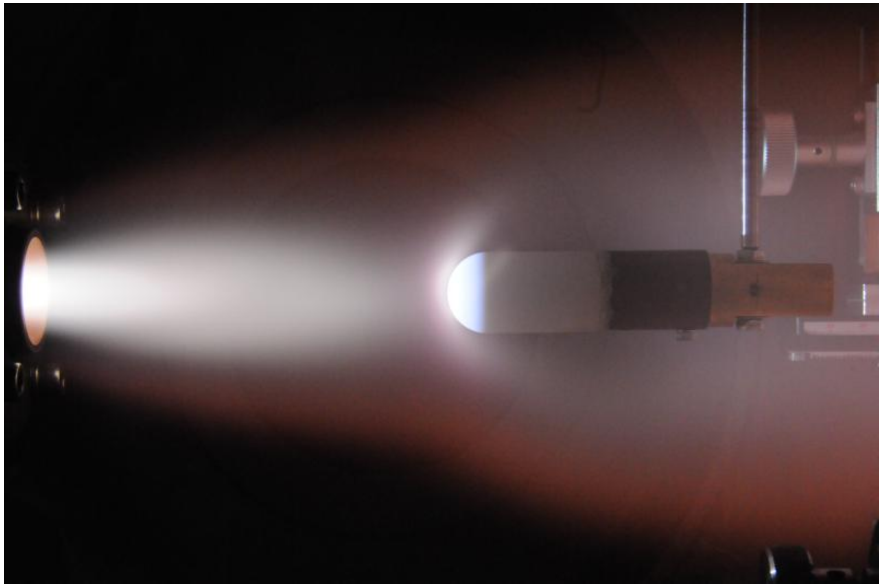


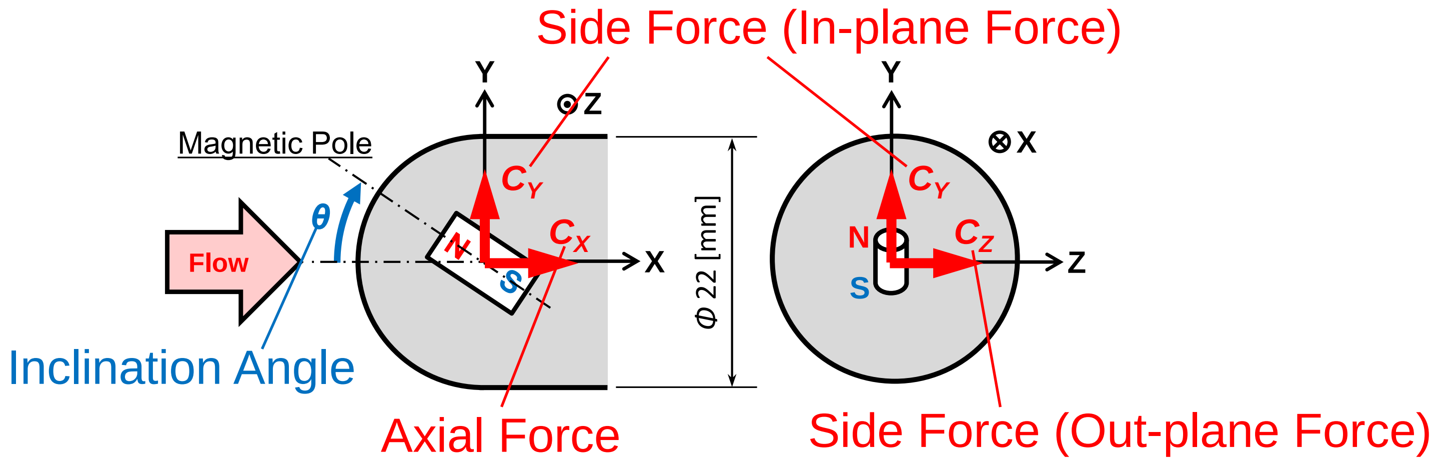
Argon Arcjet Wind Tunnel Experiment

Experimental Setup



After the Shutter Opening

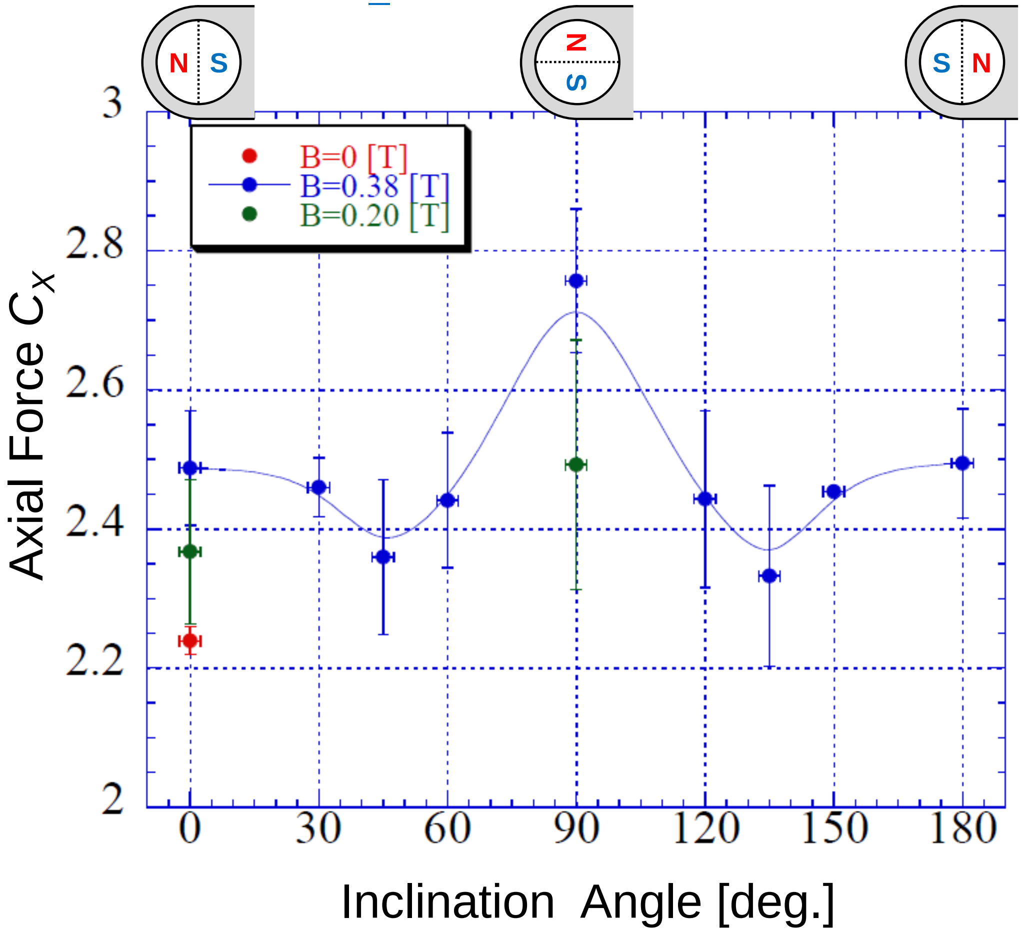




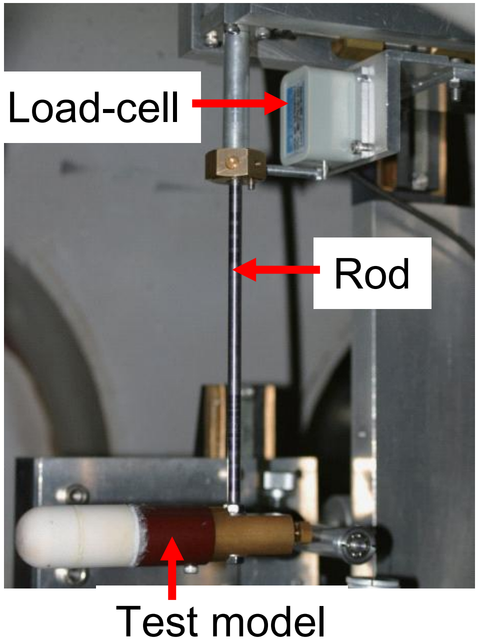
Experimental Result (C_X)

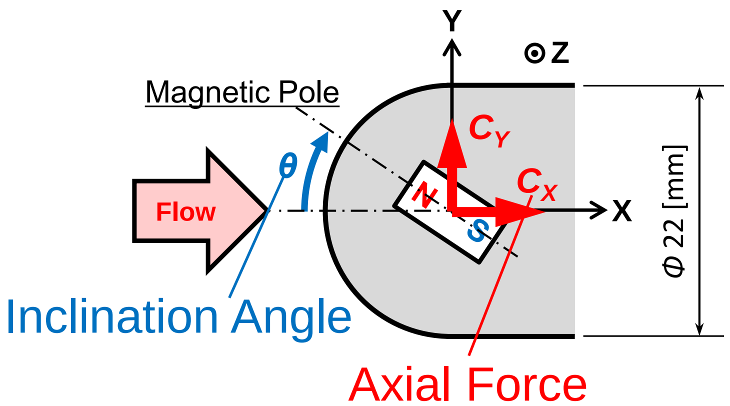
M. Kawamura et al., JRS, Vol. 50, No. 2, 2013.

Axial Force C_X



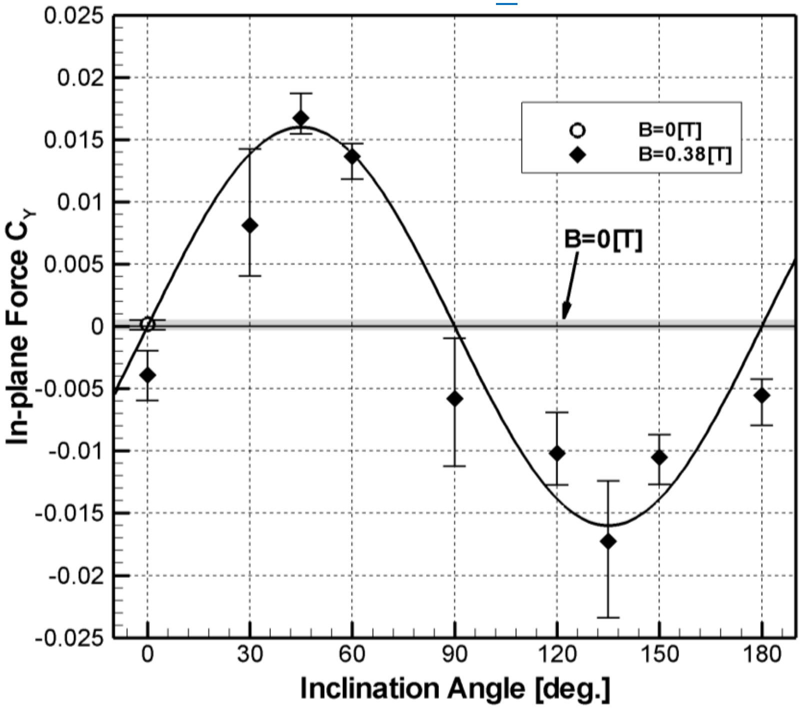
Force Measurement



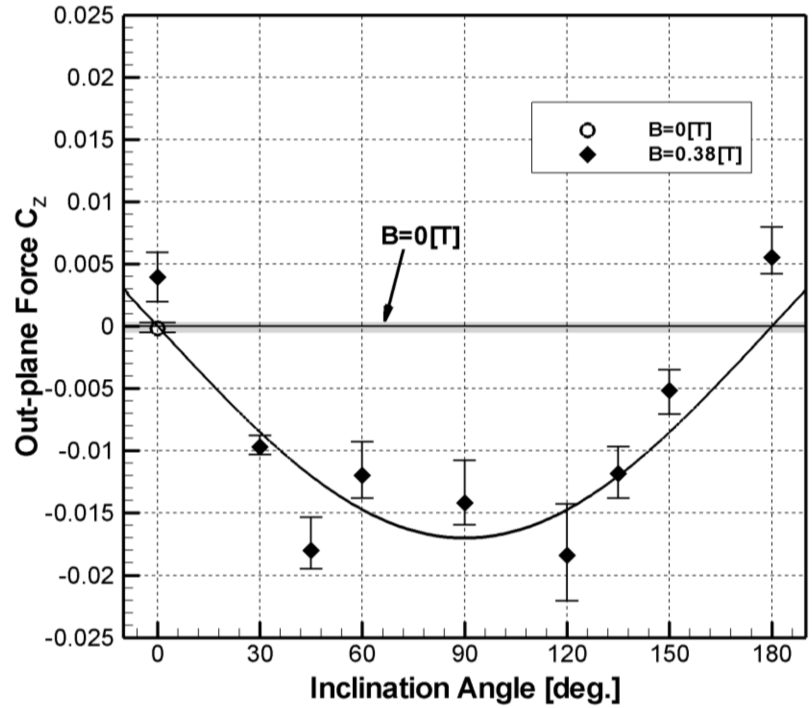


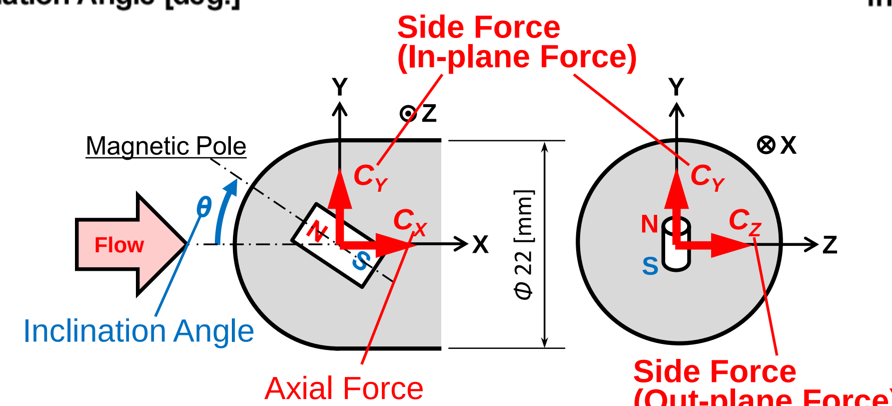
Experimental Result (C_Y and C_Z)

In-plane Force C_Y



Out-plane Force C_Z





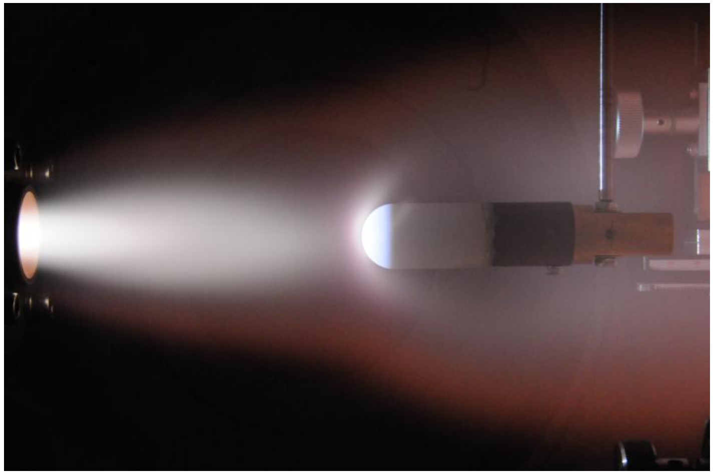
Objective

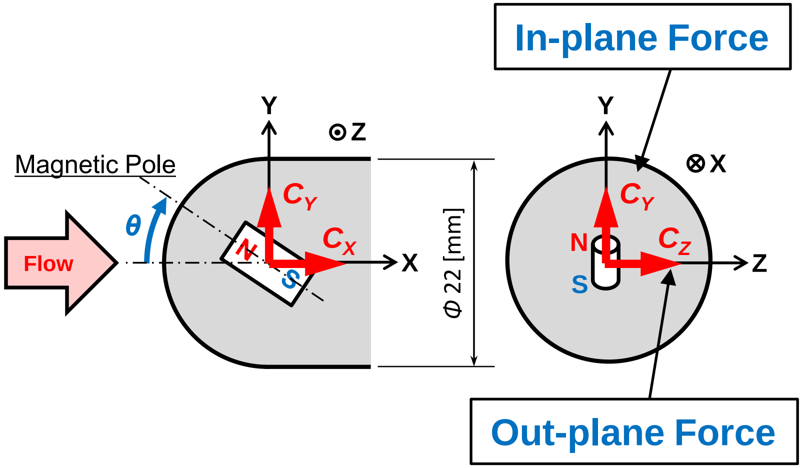
Final Target:

Available system configuration using MHD heat shield

To estimate the electrodynamic effect in the REAL flight, the measured force data is good example for the variation.

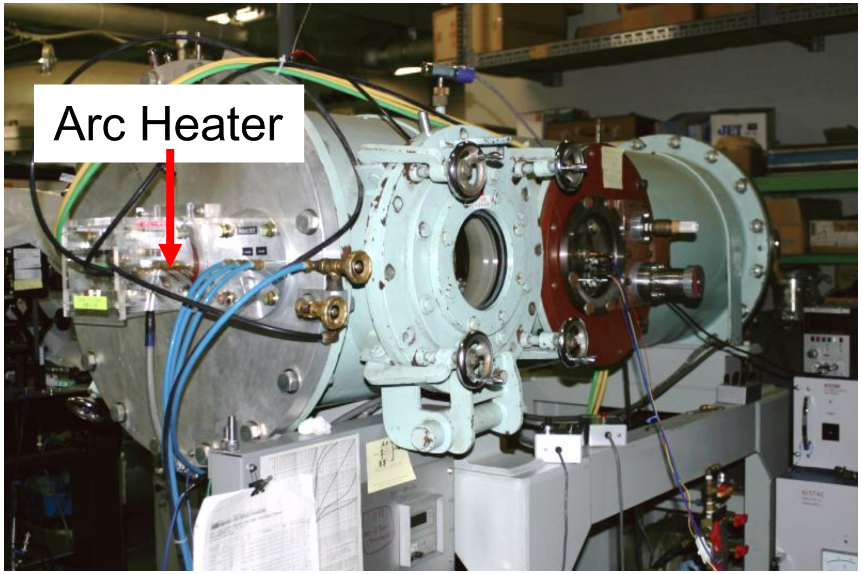
We try to simulate the arc-jet wind tunnel experiment.





1.5kW Arcjet Wind Tunnel

- Half angle of conical nozzle : 25°
- Nozzle exit diameter : 30[mm]
- Mass flow rate : 8[l/sec]
- Input power : 1.5[kW]

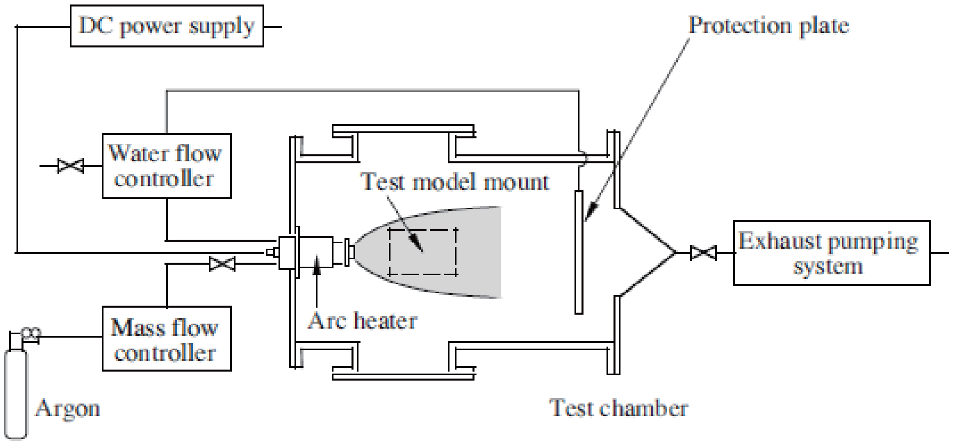


Test Flow Condition

Test gas	Argon
Mach number	1.7
Max total enthalpy, MJ/kg	1.1 *
Pitot pressure, Pa	160 *
Static pressure, Pa	34 *
Flow velocity, m/s	1097 *
Heavy particle temperature, K	1200 *
Electron temperature, K	≈ 6100 *
Neutral particle number density, m^{-3}	2.05×10^{21}
Electron number density, m^{-3}	$\approx 1 \times 10^{19}$ *
Ionization degree	≈ 0.5 %
Electric conductivity, S/m	731

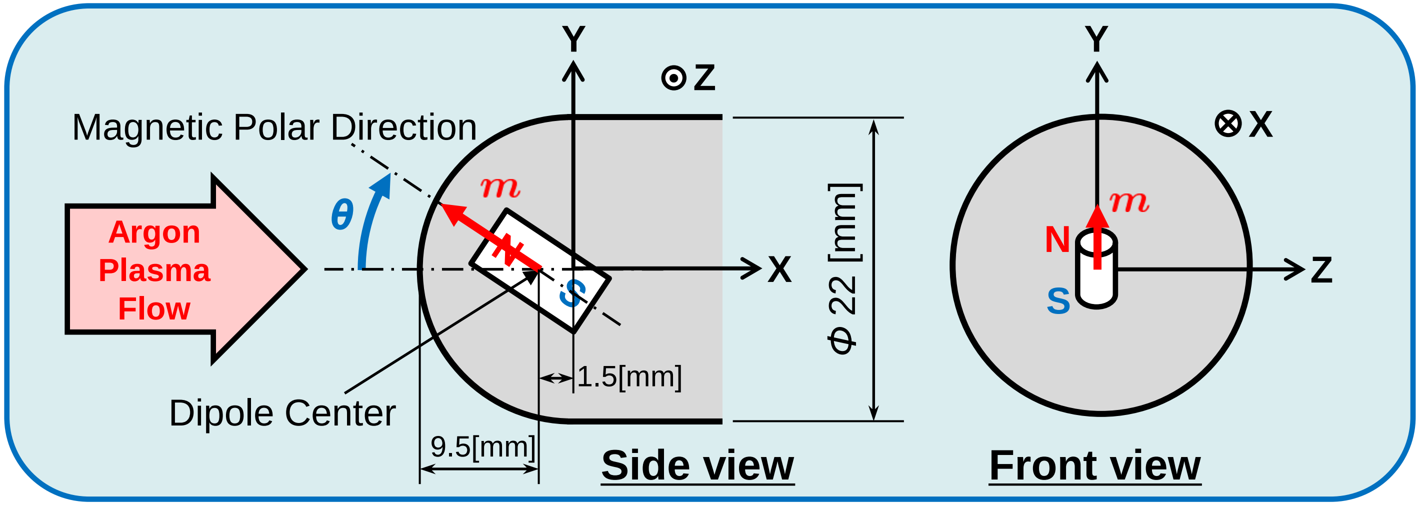
* Measured.

Schematic of Arcjet Wind Tunnel



Configuration and Flow Condition

- Body Geometry & Coordinate System
  - A cylinder with a spherical head



- Flow Condition
  - 1.5[kW] argon arcjet wind tunnel
  - Uniform flow

◆Knudsen number :0.1
◆Magnetic Reynolds number :0.022
◆Interaction parameter :15
◆Hall parameter :173
※ B_{ref} = 0.38[T]

Magnetic Reynolds number

$$R_m = \mu_0 \sigma V L$$

Interaction parameter

$$Q = \frac{Lorentz\ force}{Inertial\ force} = \frac{\sigma B^2 L}{\rho V}$$

Flow Field

- 3D Navier-Stokes equations

  Effect of the Lorentz force and Joule heating are included.

$$\frac{\partial}{\partial t}\begin{bmatrix}\rho \\ \rho_s \\ \rho \boldsymbol{V} \\ E_t\end{bmatrix} + \nabla \cdot (\boldsymbol{F} + \boldsymbol{F}_v) = \boldsymbol{S} + \begin{bmatrix} 0 \\ 0 \\ \boldsymbol{J} \times \boldsymbol{B} \\ \boldsymbol{J} \cdot \boldsymbol{E}\end{bmatrix}$$

ρ : Density
ρ_s : Density of species *s*
$\boldsymbol{V}$: Flow velocity
E_t : Total Energy
$\boldsymbol{F}$: Inviscid term
$\boldsymbol{F_v}$: Viscous term
$\boldsymbol{S}$: Source term
$\boldsymbol{J}$: Current density
$\boldsymbol{E}$: Electric field
$\boldsymbol{B}$: Magnetic flux density
t : Time

- Laminar flow

Electromagnetic Field

- Maxwell equations
  - Magnetohydrodynamic (MHD) approximation
  - Low magnetic Reynolds number approximation

    Induced magnetic field could be negligible and not considered. $\frac{\partial \boldsymbol{B}}{\partial t} \approx 0$

  Simplified to,

$$\boldsymbol{E} = -\nabla \phi$$
$$\nabla \cdot \boldsymbol{J} = 0$$

- Ohm's law

  Hall and ion-slip effects are considered.

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{V} \times \boldsymbol{B}) - C_H(\boldsymbol{J} \times \boldsymbol{b}) + C_i(\boldsymbol{J} \times \boldsymbol{b} \times \boldsymbol{b})$$

- Poisson equation for the electric potential

  Given by the combining the above equations,

$$\nabla \cdot \tilde{\boldsymbol{\sigma}} [\nabla \phi] = \nabla \cdot \tilde{\boldsymbol{\sigma}} [\boldsymbol{V} \times \boldsymbol{B}]$$

$\boldsymbol{J}$: Current density
$\boldsymbol{E}$: Electric field
$\boldsymbol{B}$: Magnetic flux density
ϕ : Electric potential
σ : Conductivity
C_H : Hall parameter
C_i : Ion-slip parameter
$\boldsymbol{V}$: Flow velocity
μ_0 : Permeability of vacuum
R_m : Magnetic Reynolds number
L_{ref} : Reference length
t : Time

Thermo-Chemical Model

Thermodynamic property

Real gas effect for argon plasma.

Local electrical neutrality is assumed.

Chemically non-equilibrium

3 species (Ar, Ar^+, e^-) are considered. $\mathrm{Ar} + \mathrm{M} \rightleftharpoons \mathrm{Ar}^+ + \mathrm{e}^- + \mathrm{M}$

Thermal model

The electron temperature is solved by the Poisson equation.

Electrical conductivity and parameters

Evaluated using the collision integral,

$$\sigma = \frac{e^2 n_e}{k_B T_e \sum_{j \neq e} n_j \Delta_{e,j}^{(1,1)}} \qquad C_H = \frac{e|\boldsymbol{B}|}{k_B T_e \sum_{j \neq e} n_j \Delta_{e,j}^{(1,1)}}$$

$$C_i = C_H \left(\frac{n_{Ar}}{n_{Ar} + n_{Ar+}} \right)^2 \frac{e|\boldsymbol{B}|}{k_B T n_{Ar} \Delta_{Ar+,Ar}^{(1,1)}}$$

σ : Conductivity

C_H : Hall parameter

C_i : Ion-slip parameter

e : Elementary charge

k_B : Boltzmann constant

n_s : Number density of species *s*

T_e : Electron temperature

$\boldsymbol{B}$: Magnetic flux density

$\Delta_{i,j}^{(1,1)}$: Collision integral

Database and Models

- Chemical Reaction Model
  - Hoffert’s model
- Thermodynamic Property
  - NASA Glenn’s database
- Transport Coefficient
  - Gupta’s mixing rule
- Collision Integral
  - Laricchiuta’s database
    (for combination of neutral particle and others)
  - Coulomb collision theory
    (for combination of ionized particles or electron)

Computational Method

- Discretization : Finite volume method
- Inviscid term : AUSM-DV scheme + 2nd-order MUSCL
- Viscous term : 2nd-order central difference
- Time integration : Matrix Free Gauss Seidel (MFGS) implicit method

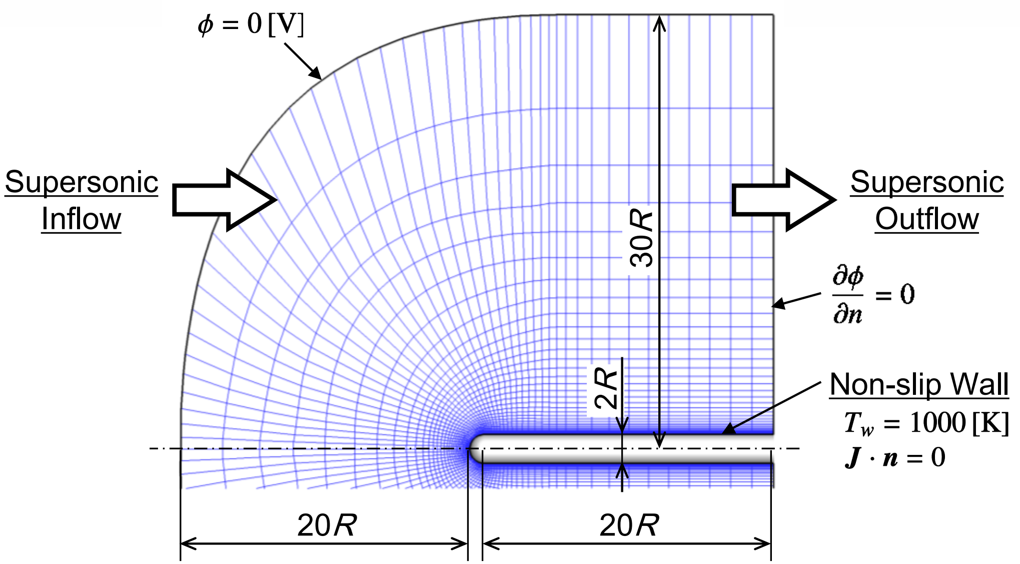
+ Local time stepping

↕ **Weakly coupled**

- Electric field : ILU(0)-BiCGstab
- Electron temperature : BiCGstab

Computational Domain and Grid

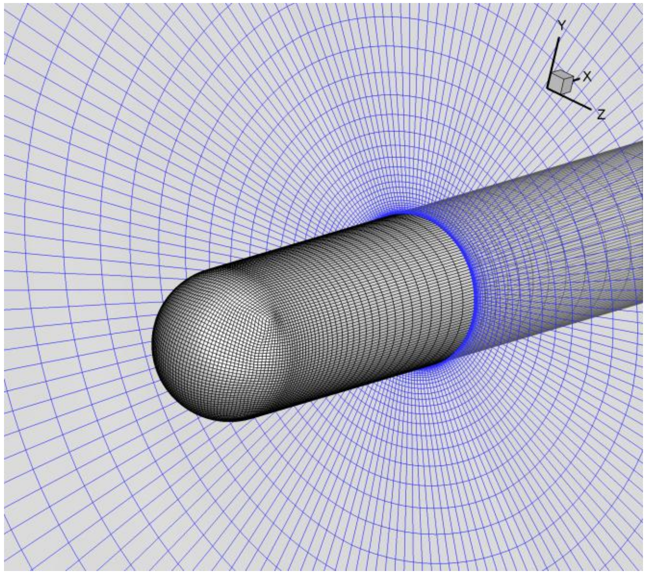
- Computational domain & boundary conditions



- Computational grid

<u>Grid points</u>

On wall : 12,000 points
Normal to wall : 49 points
Total : 600,000 points

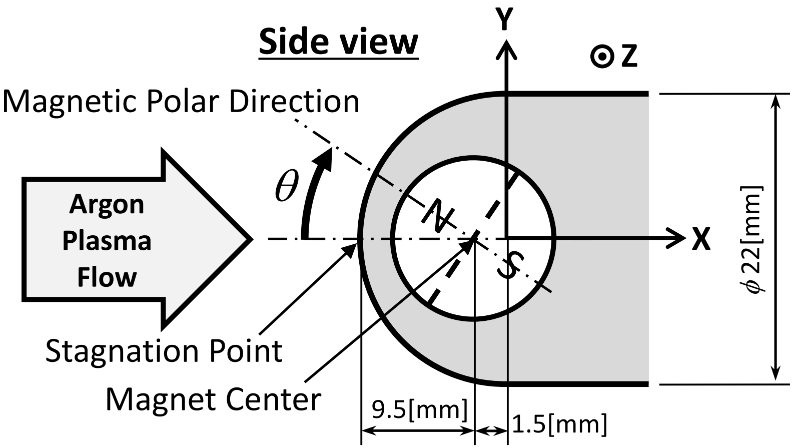


After some calculations,
It was confirmed that this grid is reasonable for this study.

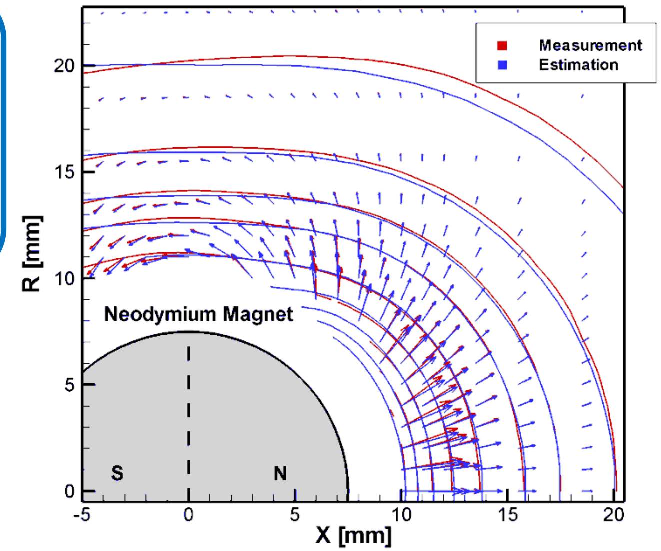
Magnetic Field Modeling

Parameters

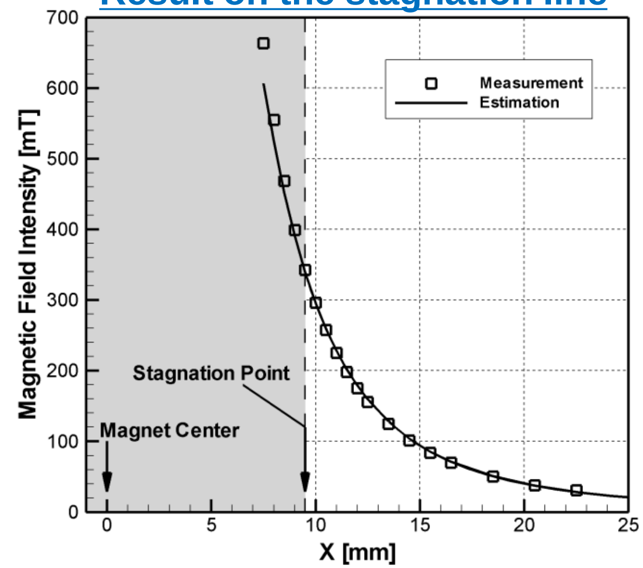
- Maximum strength : 0.38 [Tesla]
- Inclination angle θ : from 0 [deg.] to 180 [deg.]
- Magnetic configuration : reconstructed



Result of fitting



Result on the stagnation line



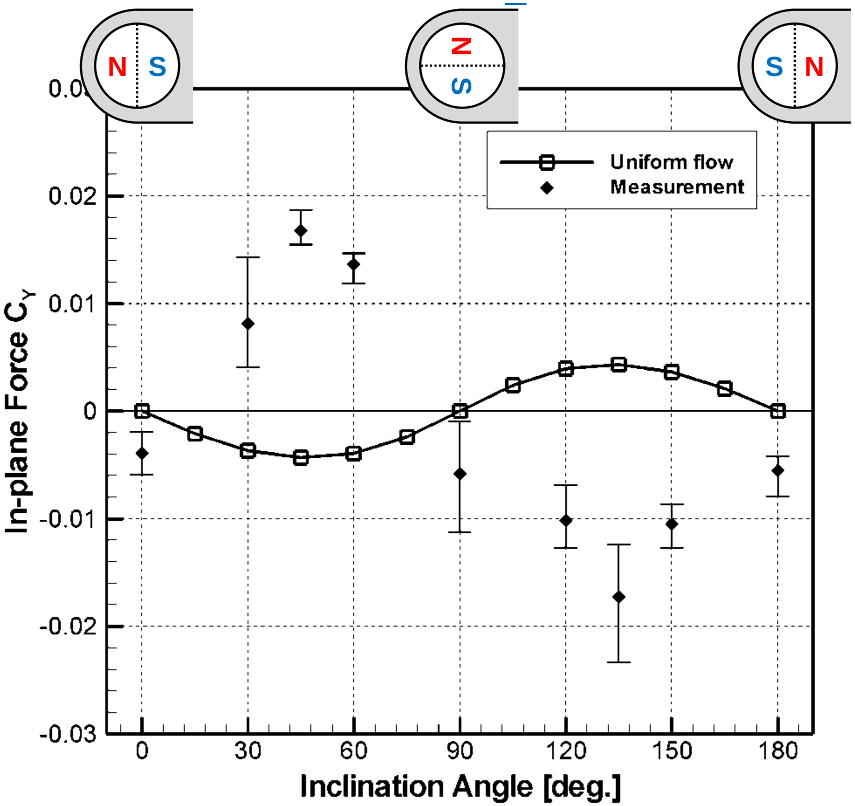
- Generated by combination of ring current C_i as,

$$\boldsymbol{B}(\boldsymbol{x}) = \frac{\mu_0}{4\pi} \sum_i^n \oint_{C_i} I_i \frac{d\boldsymbol{s} \times (\boldsymbol{x} - \boldsymbol{s})}{|\boldsymbol{x} - \boldsymbol{s}|^3}$$

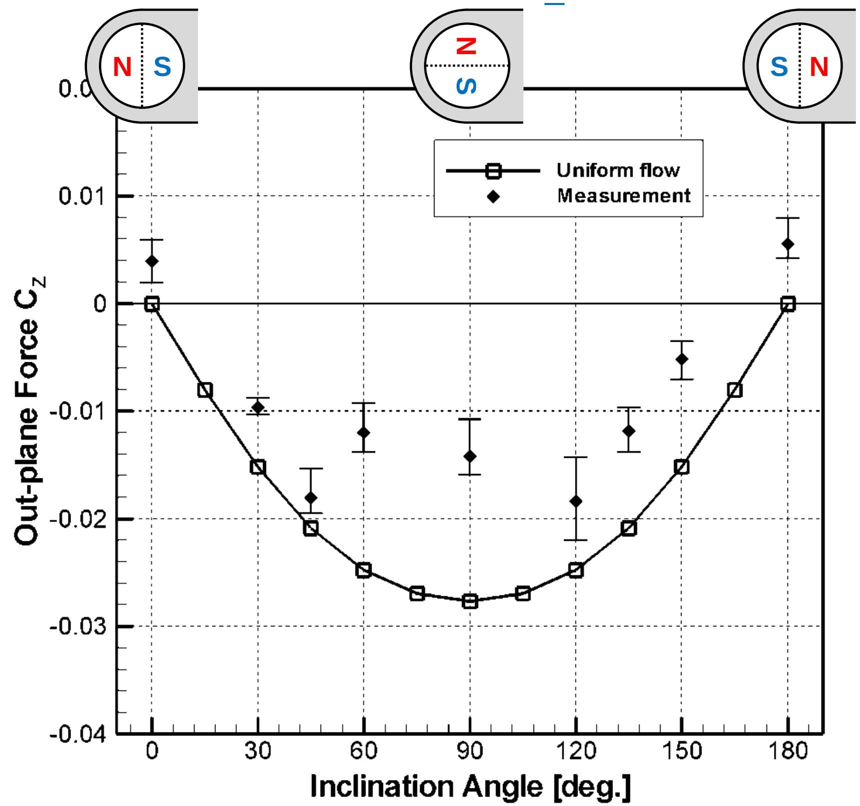
- Current strength I_i are given by fitting to actual magnetic field using the Genetic Algorithm.

Side Force C_Y, C_Z (Uniform flow case)

In-plane Force C_Y



Out-plane Force C_Z

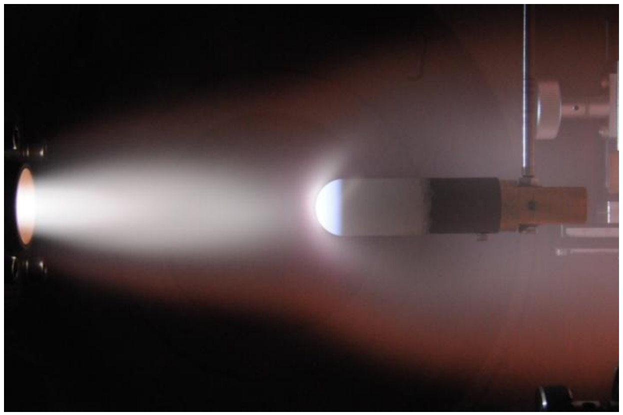


In the uniform flow cases,

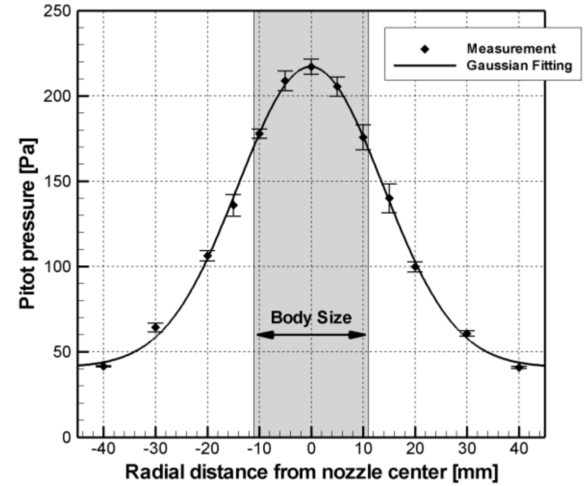
- In-plane force C_Y: Qualitatively different
- Out-plane force C_Z: In qualitatively agreement

Influence of Plume Size

Photograph of Arc-jet Plume

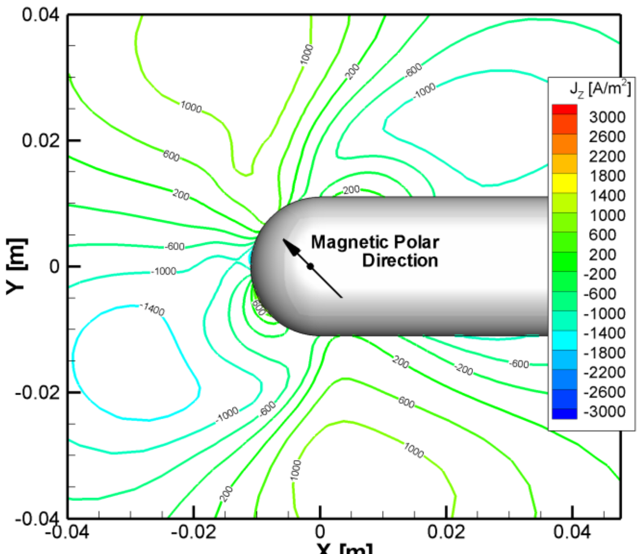


Radial Distribution of Pitot Pressure



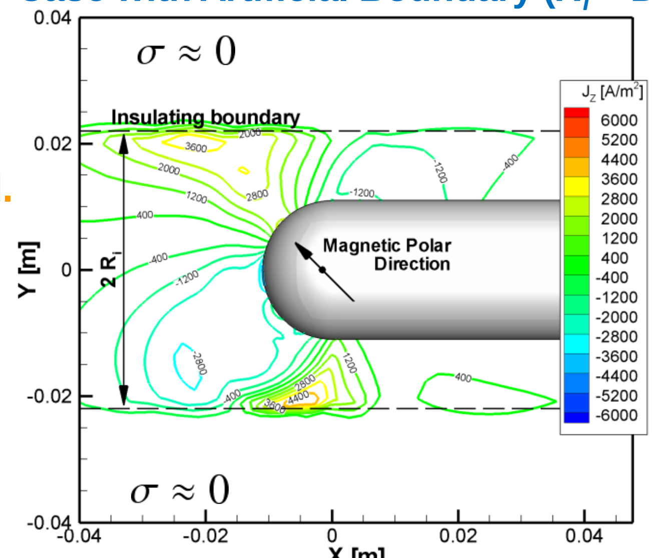
Electric Current Contour

Case of Uniform flow



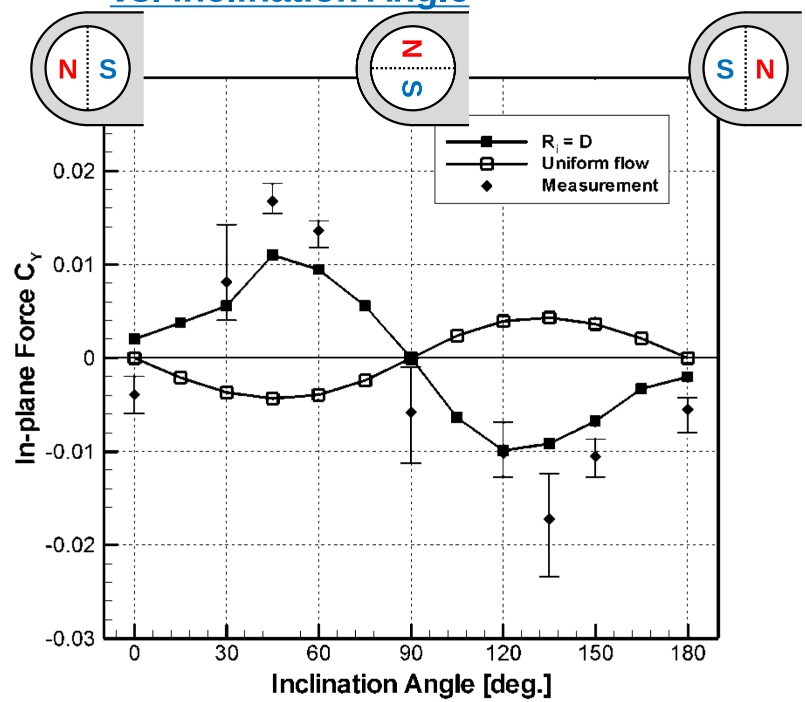
Plume size is briefly considered.

Case with Artificial Boundary ($R_i = D$)

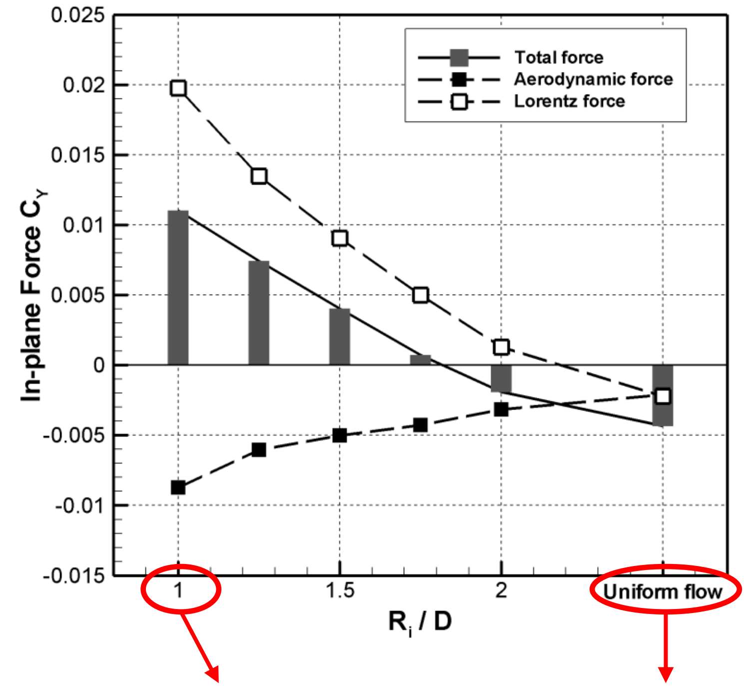


Influence on In-plane Force C_Y

vs. Inclination Angle

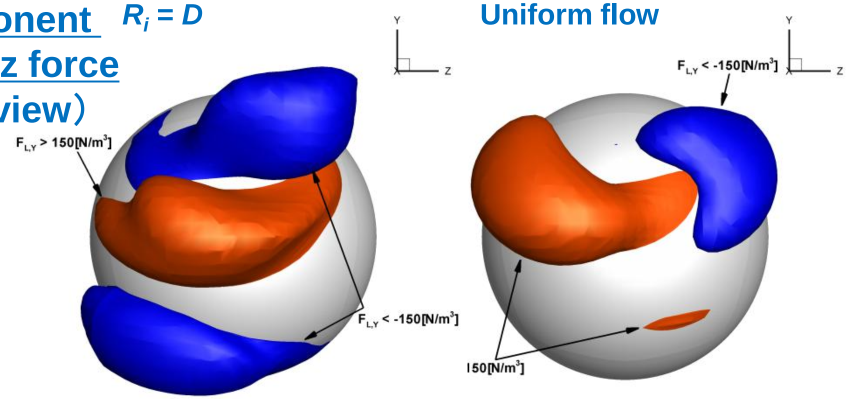


vs. Artificial Boundary Radius
(θ = 45[deg.])



Y component of Lorentz force (Front view)

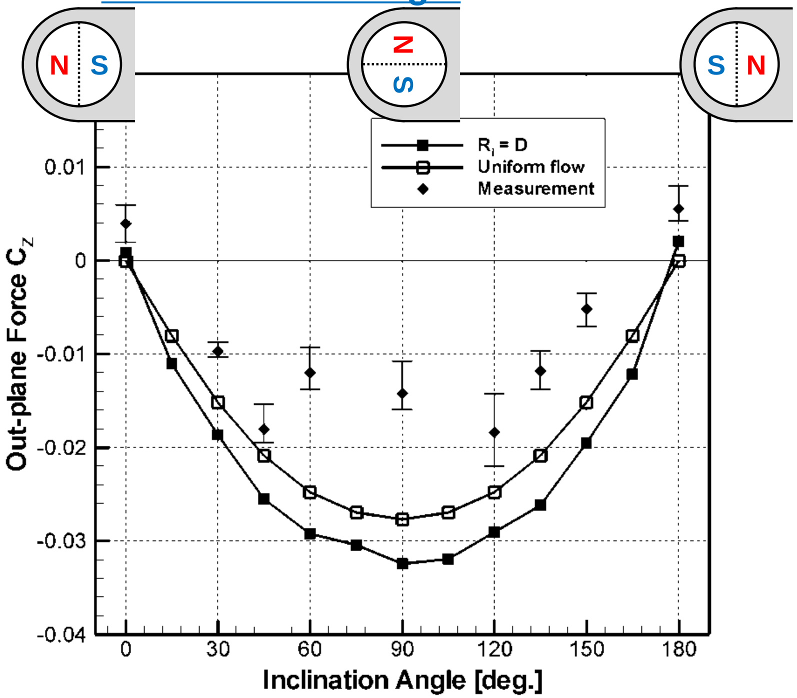
$R_i = D$ **Uniform flow**



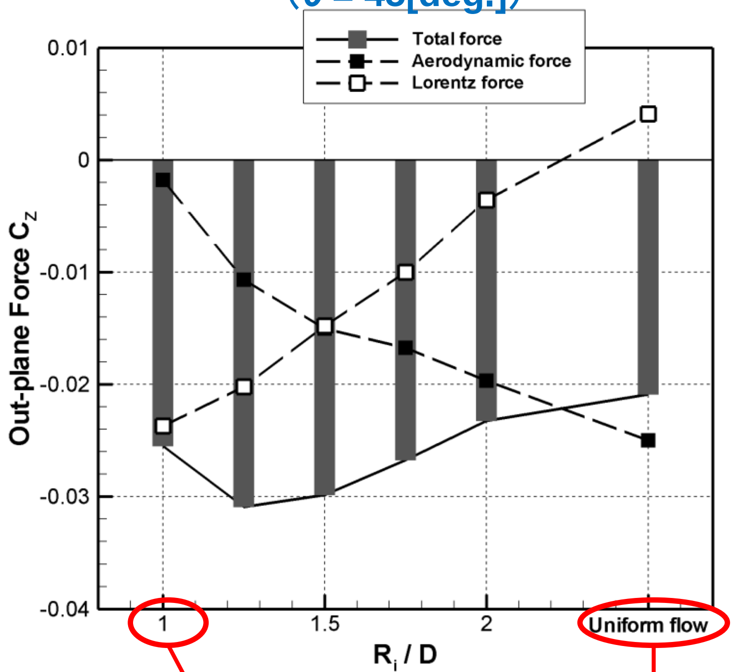
- Large impact on C_Y due to the Lorentz force part.
- The results become to be close to experiment.

Influence on Out-plane Force C_Z

vs. Inclination Angle

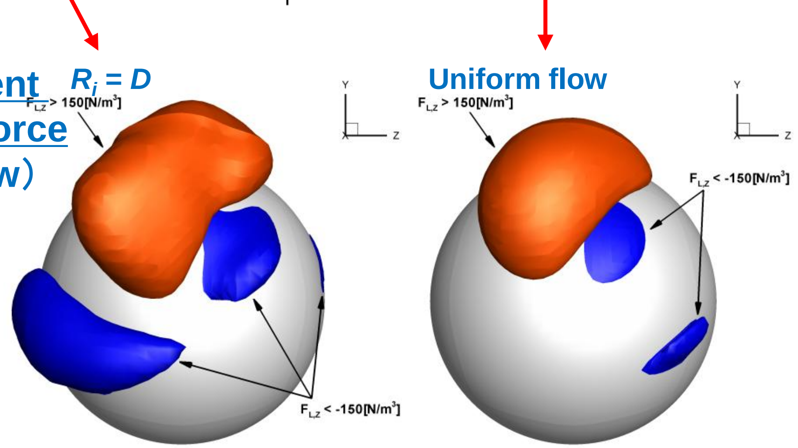


vs. Artificial Boundary Radius
（θ = 45[deg.]）



- Small impact on C_Z.
- Both Lorentz and pressure part are clearly affected and they cancel each other out.
- The results also qualitatively agree with the experiment.

Z component of Lorentz force
（Front view）



Summary

We try to simulate the arc-jet wind tunnel experiment and compare the numerical and experimental results of the in-plane and out-plane forces.

- Under the uniform flow condition, the in-plane force is qualitatively different.
- The plume size is briefly considered by using the artificial insulating boundary.
- The plumes size significantly affects on the in-plane force.
- The numerical results are close to the experimental one if the plume size is small.

⇒ Future work: we should simulate with the reproduction process of the arc-jet plasma flow.

Thank you for your attention.