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Kinetic Energy Measurement of a 1kW Arcjet by Pitot Probe and Laser Absorption Spectroscopy

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Background

Diagnostics of the high enthalpy flow

- Laser Absorption Spectroscopy (LAS)

Estimation of specific enthalpy

$$h_0 = \int_{T_{\mathrm{ref}}}^{T} C_{\mathrm{p}} dT + h_{\mathrm{chem}} + \frac{1}{2} V^2$$

Thermochemical equilibrium calculation

Assumption;

Frozen flow at nozzle expansion

Arcjet

Recombination is not considered

→ **Validation by experiment**

Estimation of γ

γ is also estimated on the assumption of the frozen flow

① $$\int_{T_{\mathrm{ref}}}^{T_0} C_{\mathrm{p}} dT + h_{\mathrm{chem}} = \int_{T_{\mathrm{ref}}}^{T} C_{\mathrm{p}} dT + \frac{1}{2}V^2 + h_{\mathrm{chem}}$$

at the plenum — at the plume

chemical potential is canceled

② $$\int_{T_{\mathrm{ref}}}^{T_0} C_{\mathrm{p}} dT = \int_{T_{\mathrm{ref}}}^{T} C_{\mathrm{p}} dT + \frac{1}{2}V^2$$

measured (T, V)

total temperature is obtained

③ $$T_0 \rightarrow R, \gamma$$

frozen flow

Specific heat ratio

For example…

Ar:O_2 = 4:1

Plenum pressure; 0.55atm

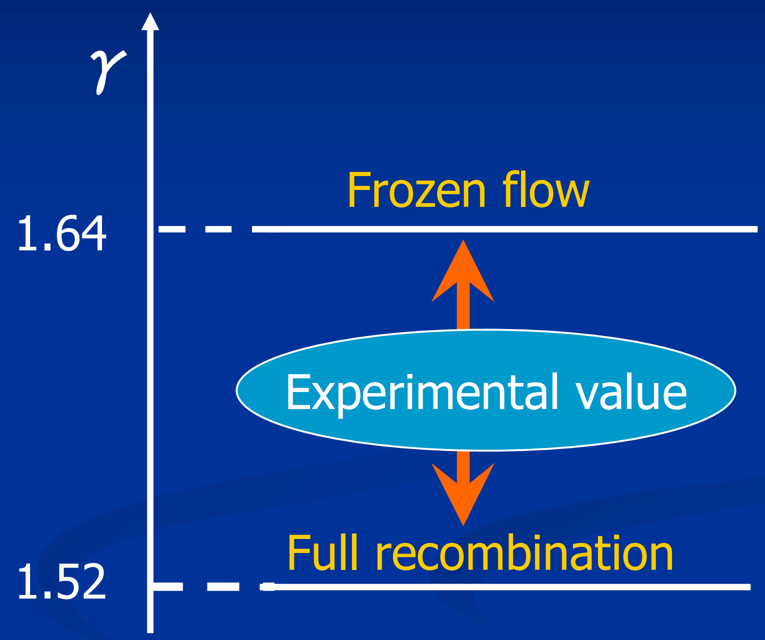
Total temperature; 4000K

- Frozen flow

  γ = 1.64

- Full recombination

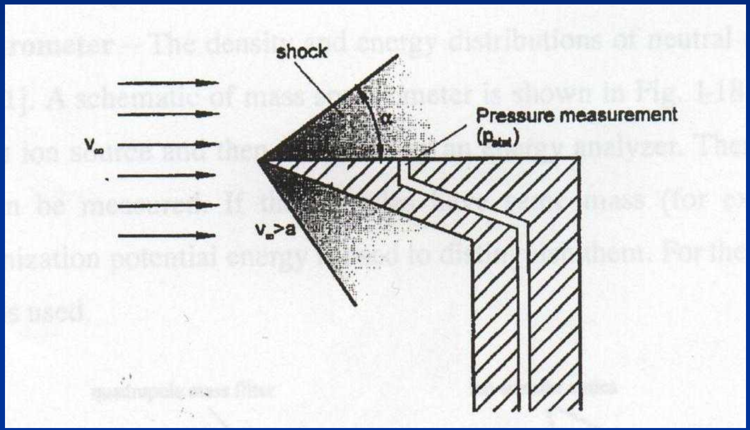
  γ = 1.52



To validate γ estimated by equilibrium calculation, it is necessary to estimate γ at the precision of less than ±0.01 by experiments.

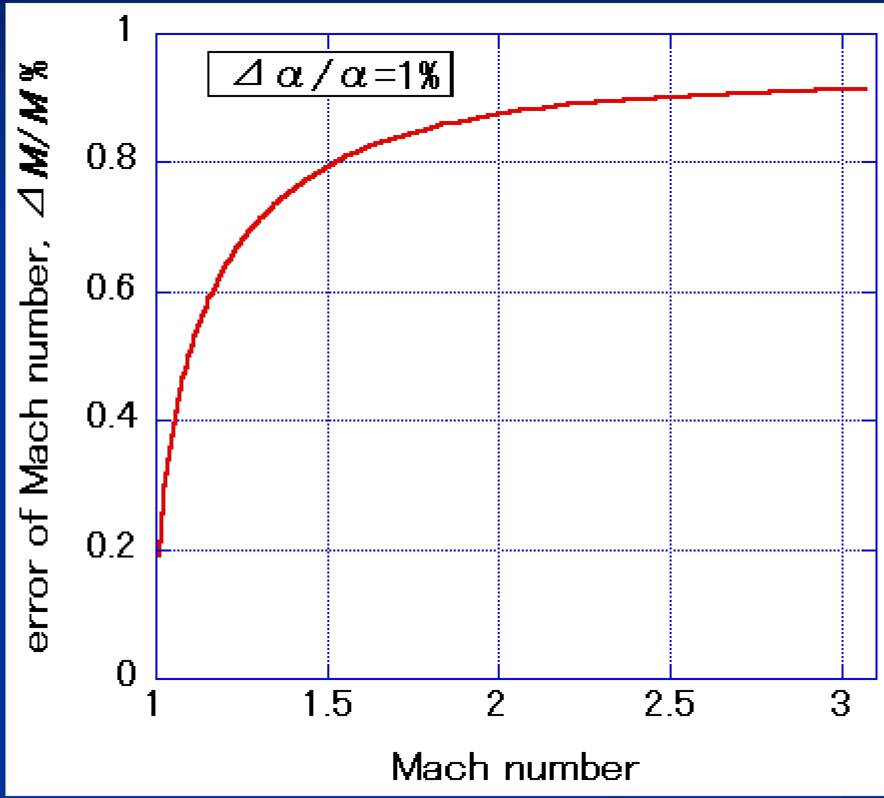
→ Mach number measurement

Mach Probe



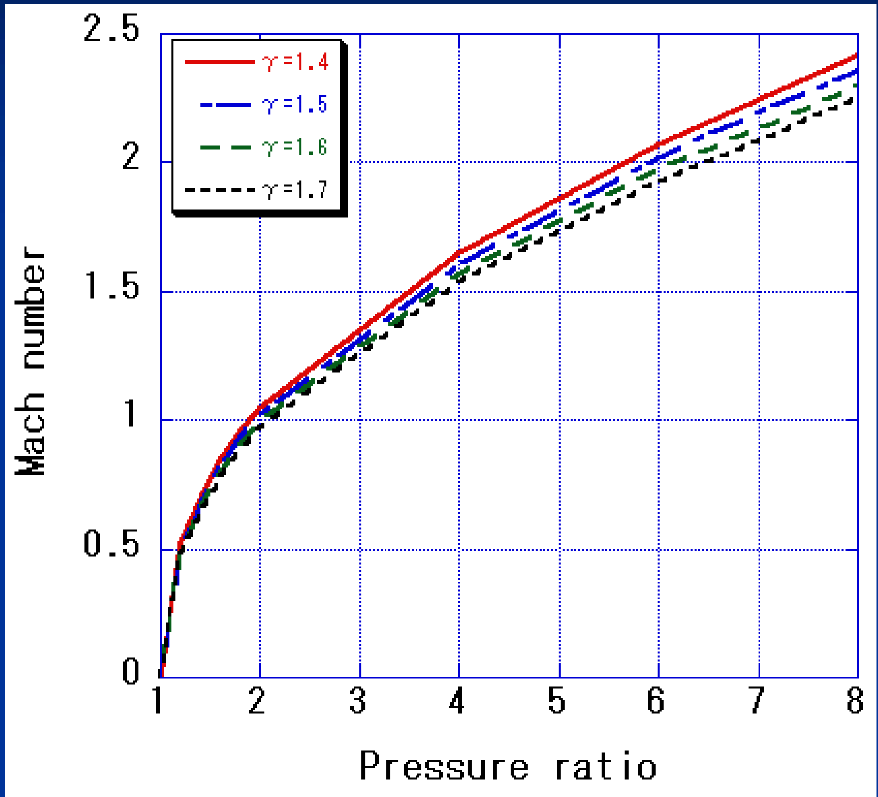
Mach Probe

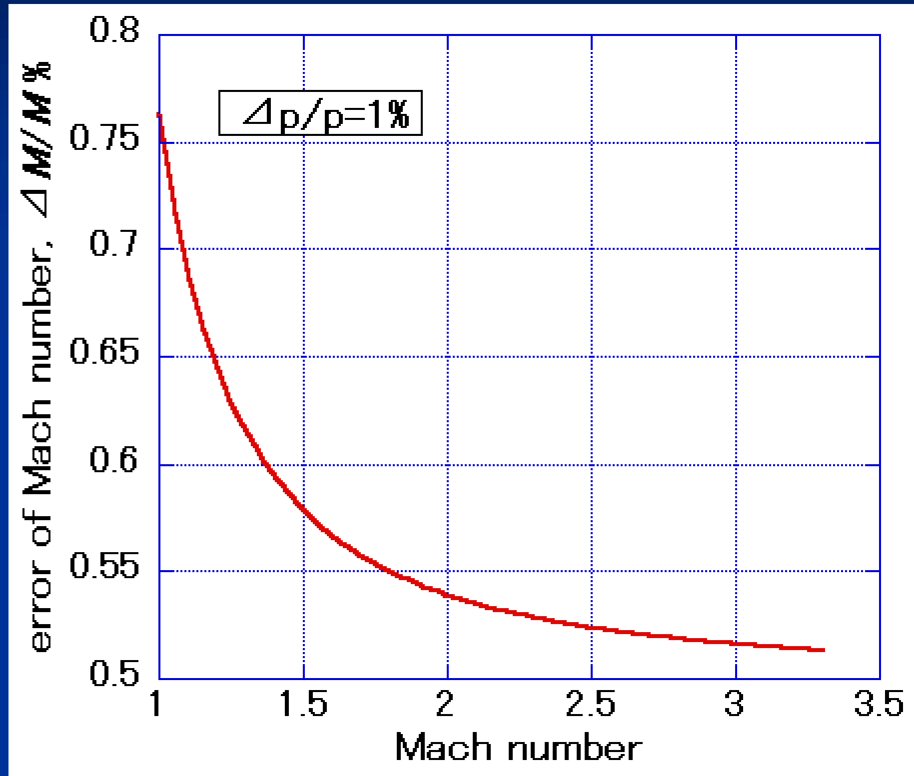
$$M = \frac{1}{\sin \alpha}$$



Estimated error of Mach number

Pitot Probe





Mach number over p_{pitot}/p_{static} for various γ

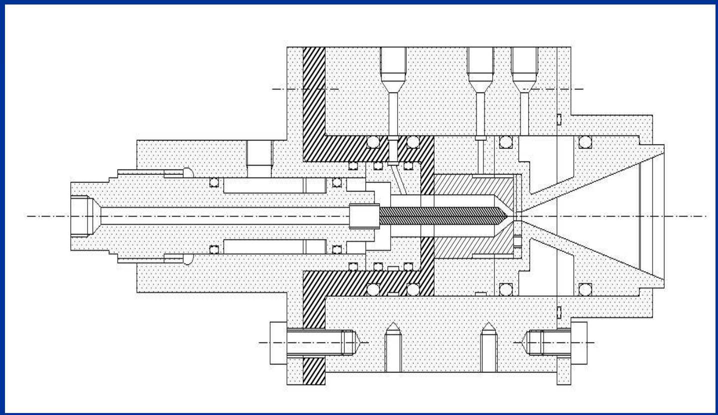
Estimated error of Mach number (γ =5/3)

- Pitot probe is more feasible for the measurement of Mach number than Mach Probe

Objectives

- Estimation of γ by comparison of Pitot probe measurement and LAS measurement
- Experimental validation of γ estimated by equilibrium calculation
- Validation of the assumption of frozen flow at the nozzle expansion

Arcjet

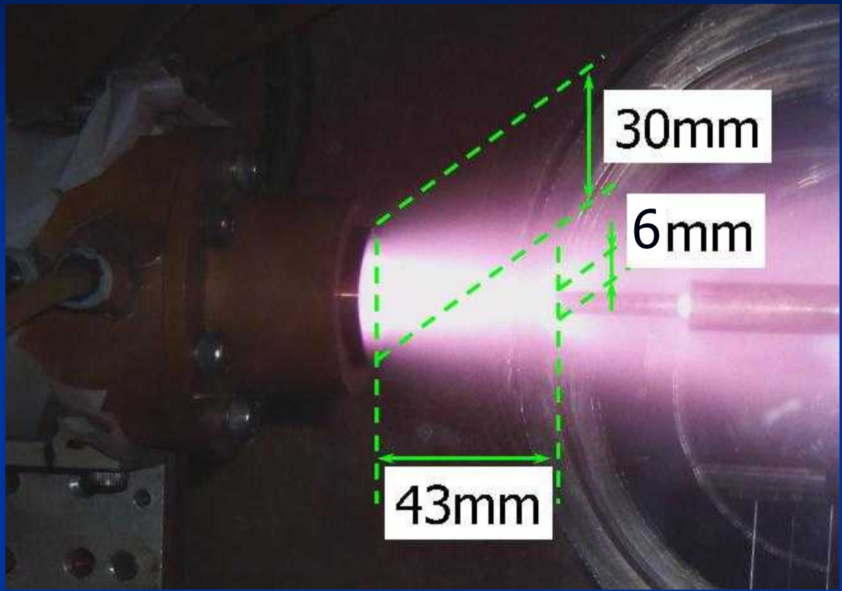


Schematic of Arcjet

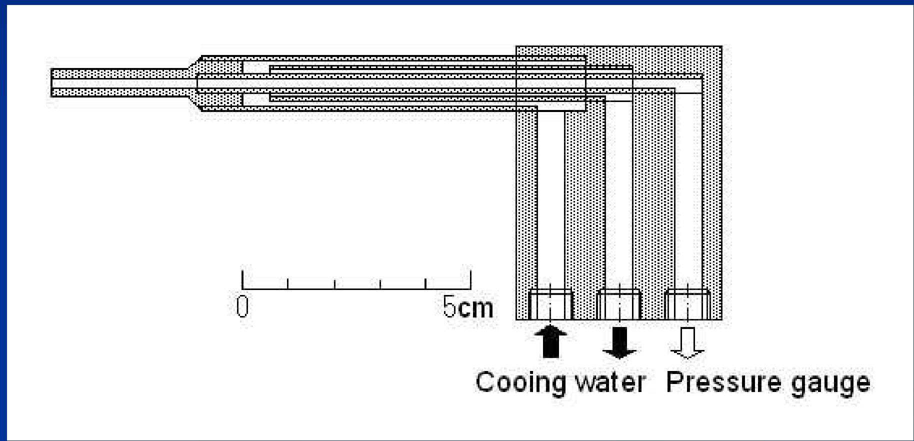
Parameters	Values
Throat diameter, mm	2
Nozzle diameter, mm	30
input power, kW	1.2(35A)
thermal efficiency	0.39
argon flow rate, slm	4

Working gas is pure argon.
Specific heat ratio should be 5/3.

Pitot probe measurement



Appearance of pitot probe measurement



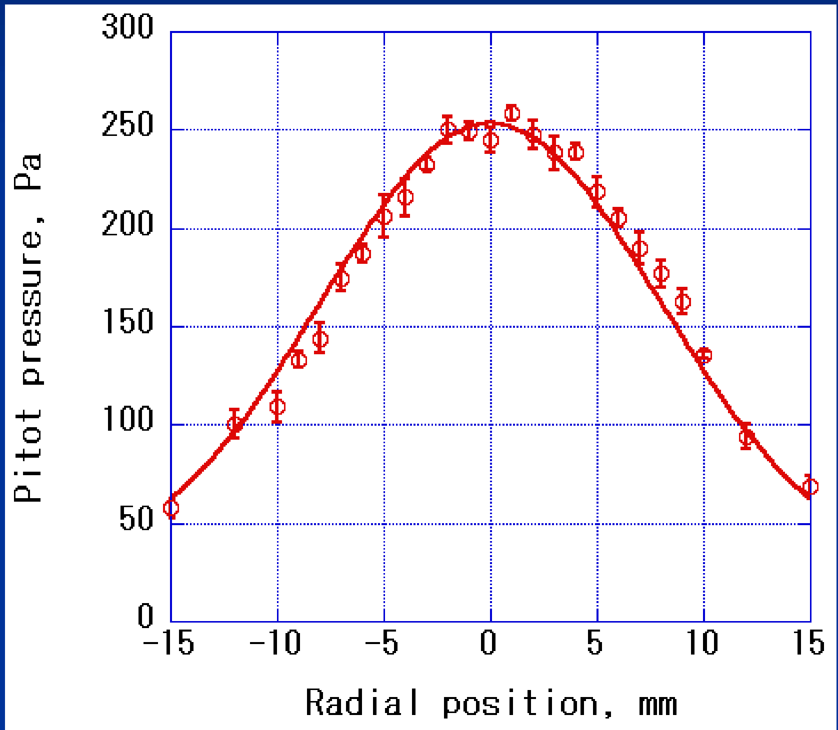
Schematic of pitot probe

Miniature pitot probe;
Bore diameter 2mm

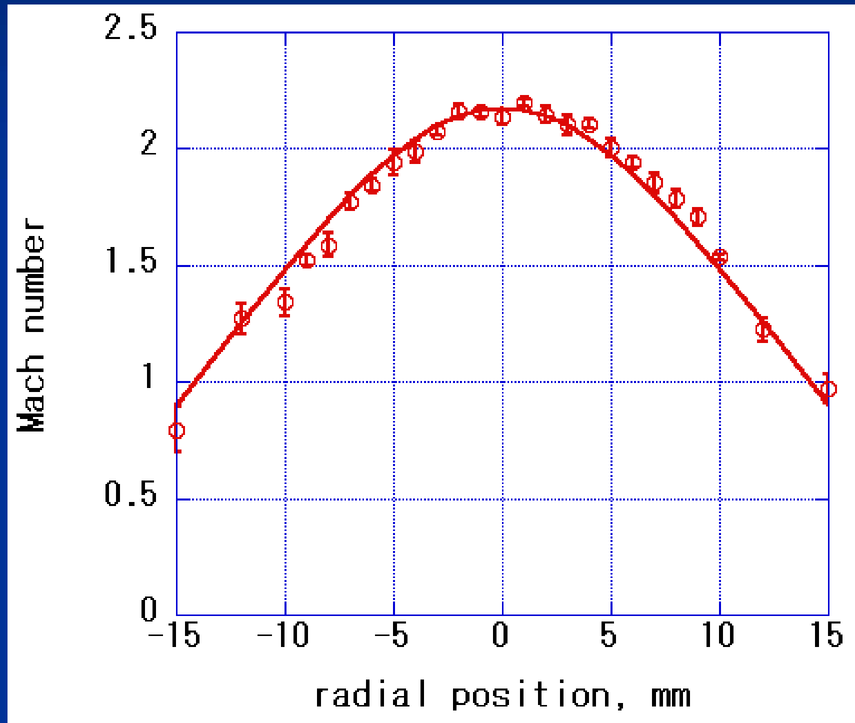
- Assumption

$p_{static} = p_{ambient} = 34\text{Pa}$

Pitot probe results



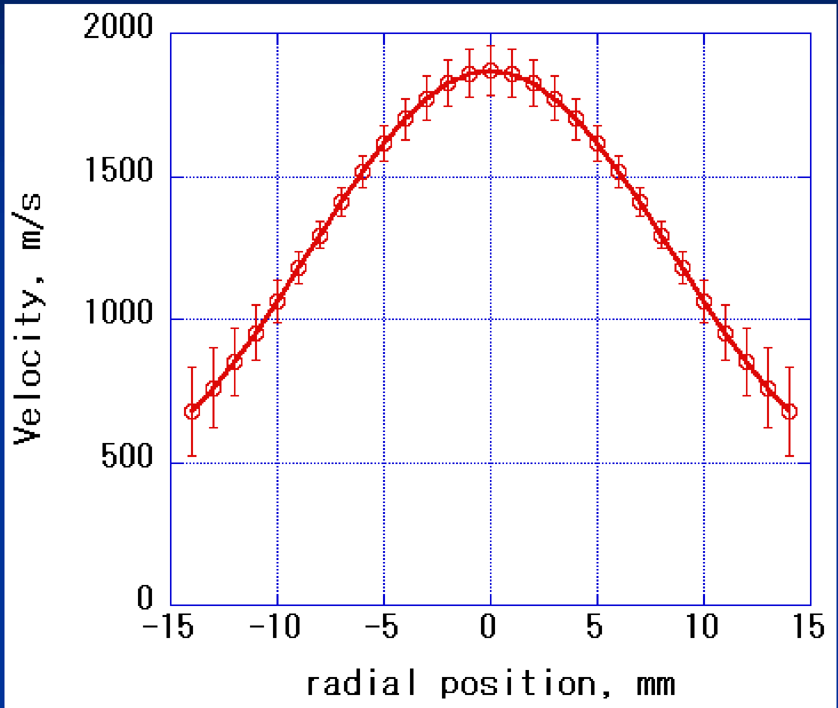
Radial distribution of pressure ratio(x=43mm)



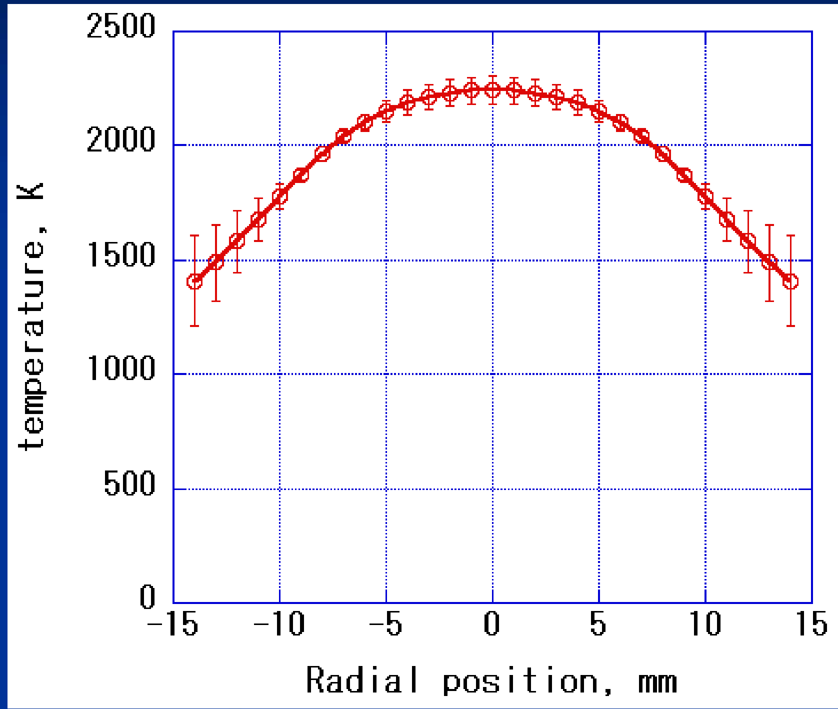
Radial distribution of Mach number(x=43mm, γ =5/3)

At the center of the plume, M =2.17 ±0.03

LAS Results



Velocity distribution (x=43mm)



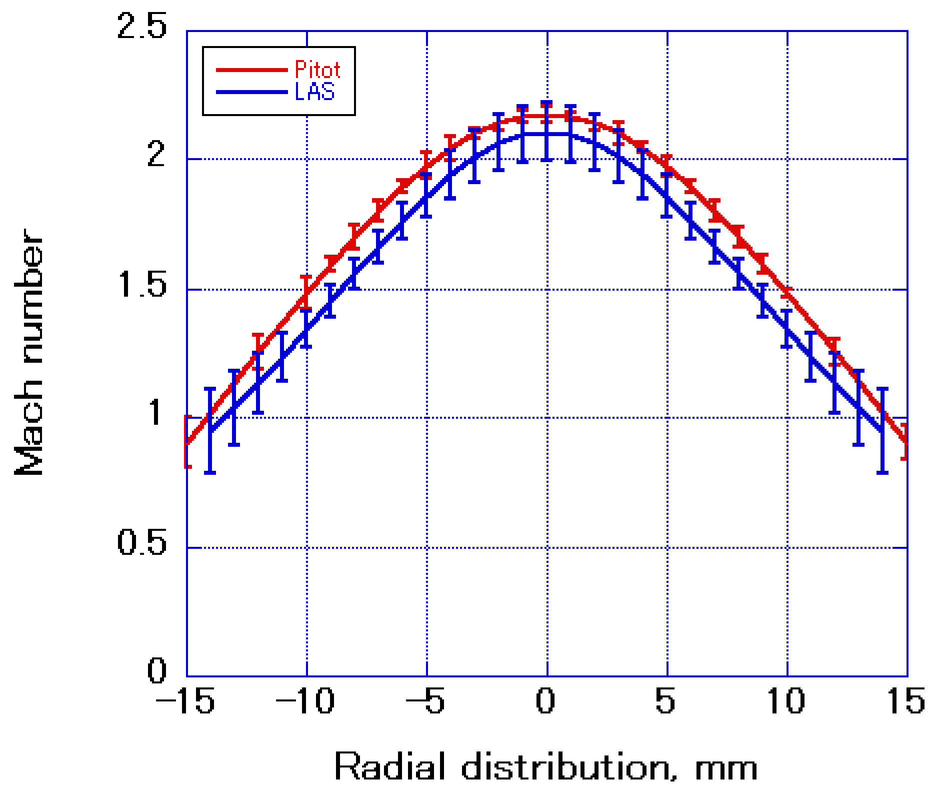
Temperature distribution (x=43mm)

Target line;
Argon 772.42nm
($4s^2[1/2] \rightarrow 4p^2[1/2]$)

At the center

	Velocity	Temperature
value	1870±90 m/s	2244±60 K
error	5%	3%

Mach Number



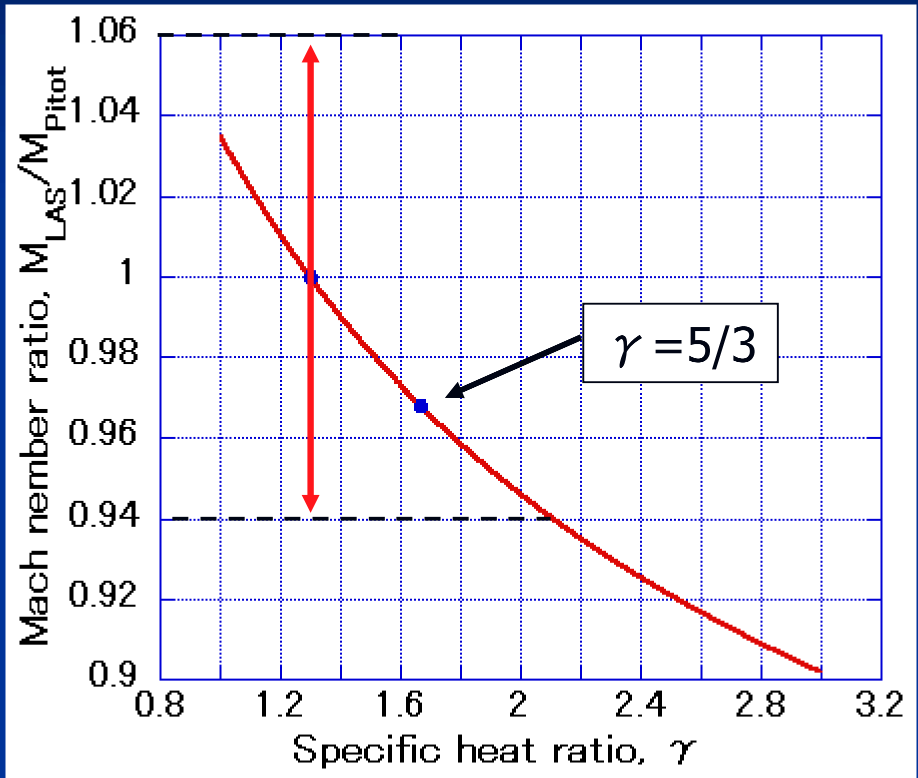
At the center

	M_{pitot}	M_{LAS}
value	2.17±0.03	2.11±0.1
error	1%	5%

- Good agreement between Pitot probe and LAS

  Mach number by the probe is averagely 7% higher than Mach number by LAS.

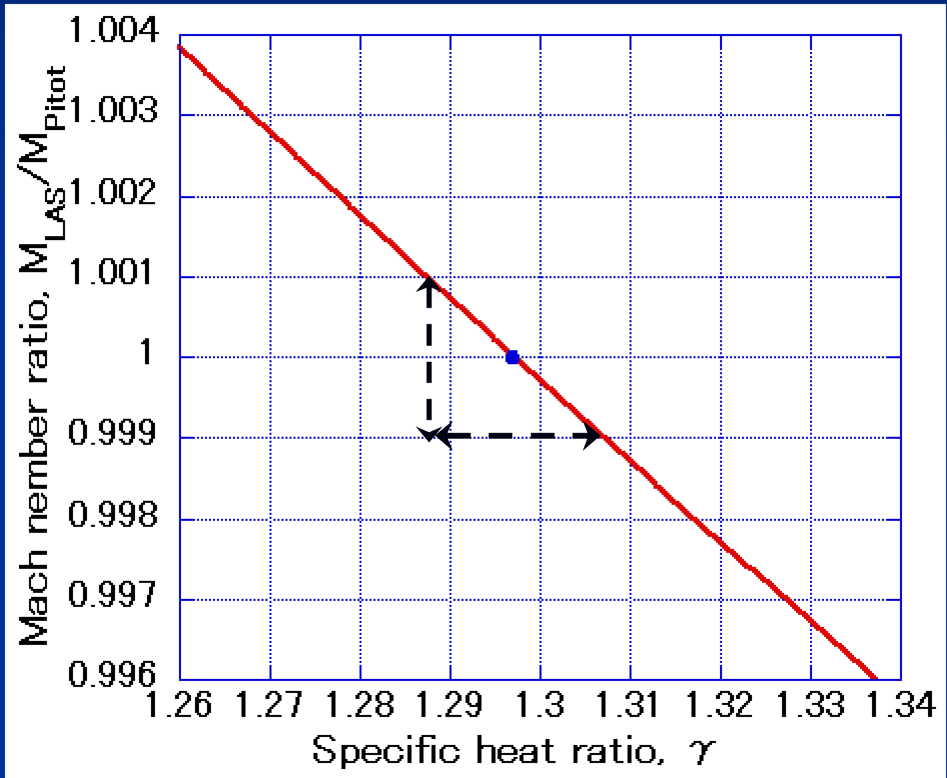
Estimation of γ



At the center of the plume,
γ =1.30,
M_{LAS}/M_{Pitot} =1±0.06.

The deviation is too large to estimate γ .

Precision improvement of the γ estimation



In order to estimate γ at the precision of 2 decimal digits, the deviation of M_{LAS}/M_{pitot} should be less than ±0.001. (Now ±0.06)

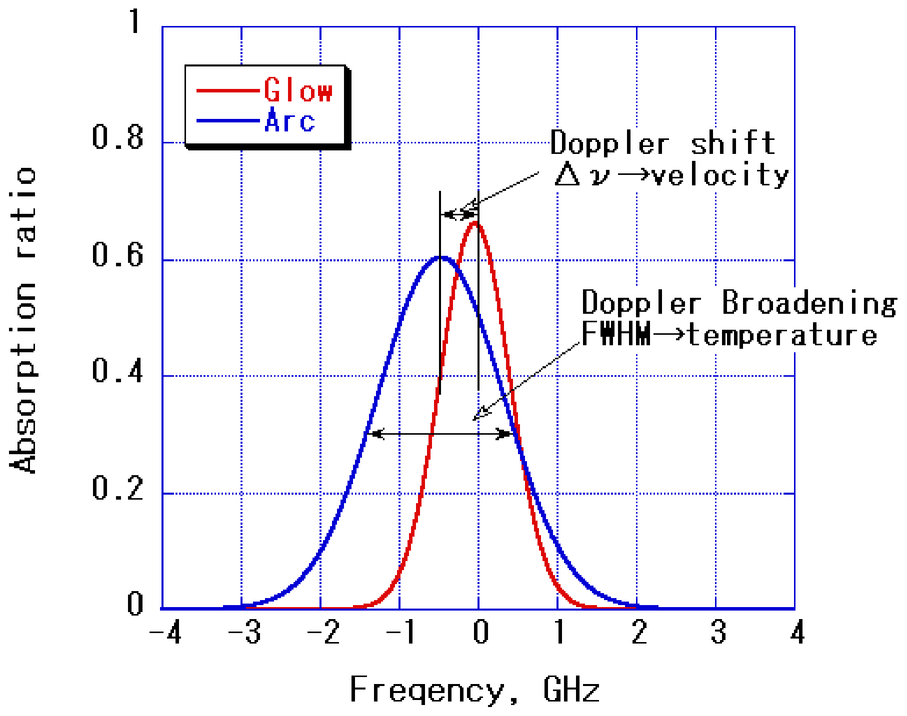
More accurate measurement is needed.

6% → 0.1%

	M_{pitot}	M_{LAS}
error	1%	5%

•Improvement of LAS measurement accuracy

Accuracy of LAS

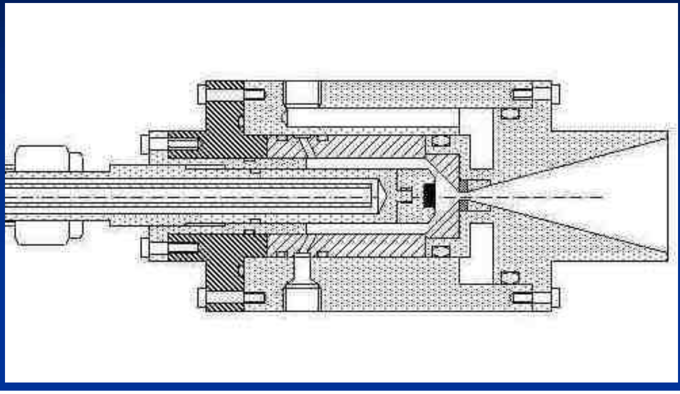


- Error of temperature

$$\frac{\Delta T}{T} = 2\frac{\Delta(\Delta\nu_D)}{\Delta\nu_D} \approx 2\left\{\frac{\Delta k}{k} + \frac{\Delta FSP}{\Delta\nu_D}\right\}$$

$$\frac{\Delta k}{k} = \frac{\Delta(I/I_0)}{(I/I_0)\ln(I/I_0)}$$

Ar-O_2 Flow



Parameters	Values
Throat diameter, mm	2
Nozzle diameter, mm	30
input power, kW	0.70(35A)
gas flow rate, slm	Ar;4 O_2;1

γ =1.54

LAS

M=4.03±0.03

Pitot probe

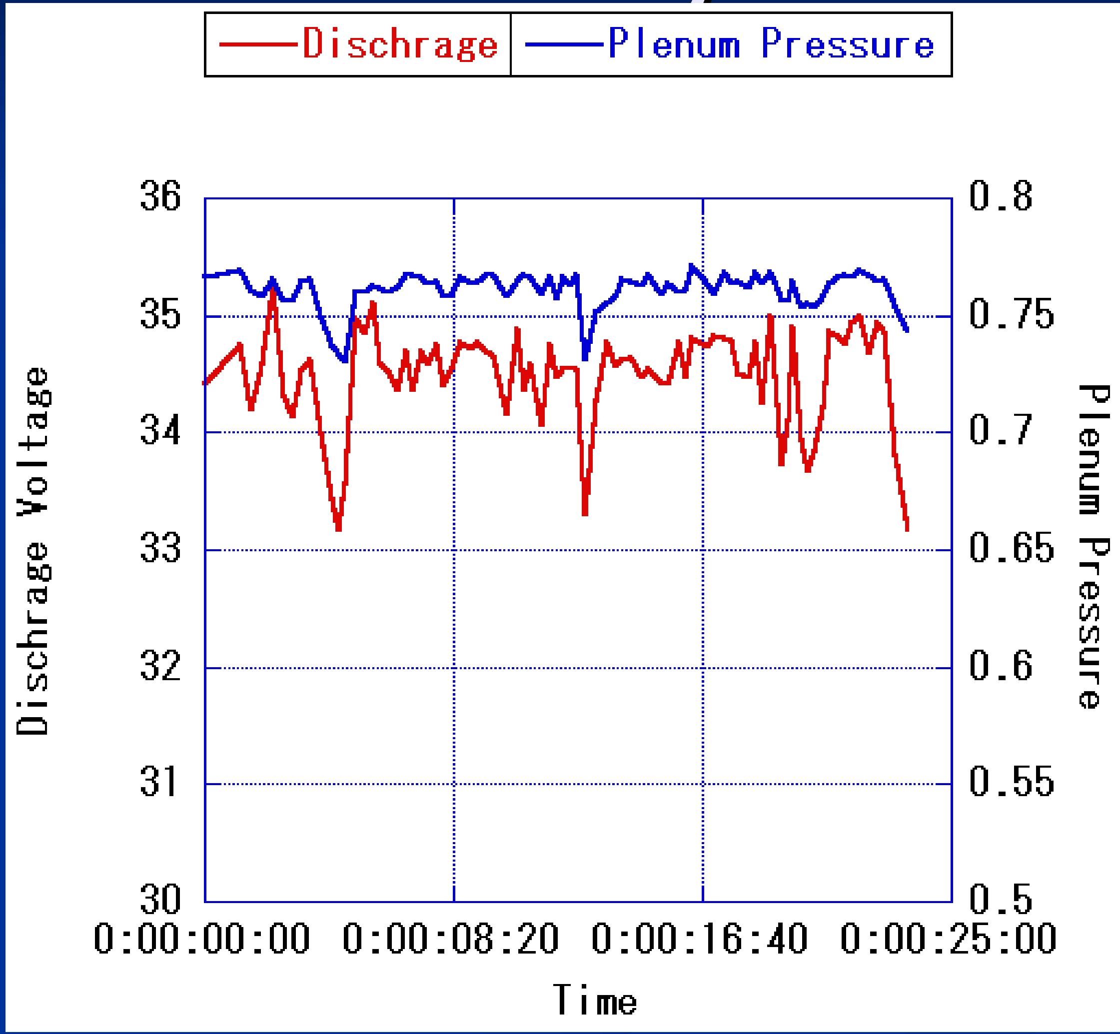
M=3.27±0.002

γ ; Can't be estimated

Conclusion

- Good agreement between Pitot probe and LAS on the condition of pure argon.
  M_{LAS} is averagely 7% higher than M_{pitot}.
- The measurement error should be one order of magnitude smaller than now.
- It is not able to estimate γ on the condition of argon and oxygen.
- In order to estimate γ, to correct the pitot pressure would be necessary.

Stability



Dischrage
Plenum Pressure
36
35
34
33
32
31
30
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0:00:00:00
0:00:08:20
0:00:16:40
0:00:25:00
Time
Dischrage Voltage
Plenum Pressure

(Background)

Aerodynamic heating at the planetary entry

- ◆Earth (N_2, O_2)
  - •Space plane
  - •Sample return mission

Re-entry image of HOPE-X

Development of Thermal Protection System (TPS)

Simulation of the entry condition on the ground

- ◆High enthalpy wind tunnel
  - •Arc-heater wind tunnel

γ-T

Plenum pressure	$Ar:O_2$
0.55atm	4:1