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Fri. Jul 19, 2024 10:45 AM - 12:45 PM Room D

[13-D-02] Numerical Investigation of Disturbance Growth on a Blunt Body in High Enthalpy Hypersonic Flow

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Keywords: Boundary layer transition, Blunt body, High Enthalpy Hypersonic Flow

Numerical Investigation of Disturbance Growth on a Blunt Body in High Enthalpy Hypersonic Flow

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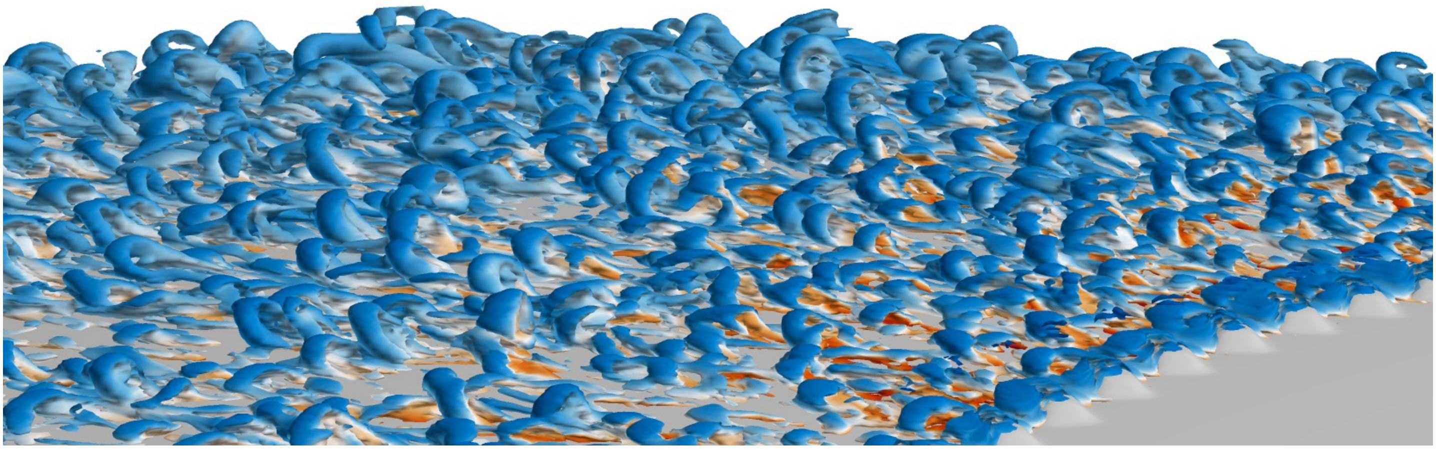
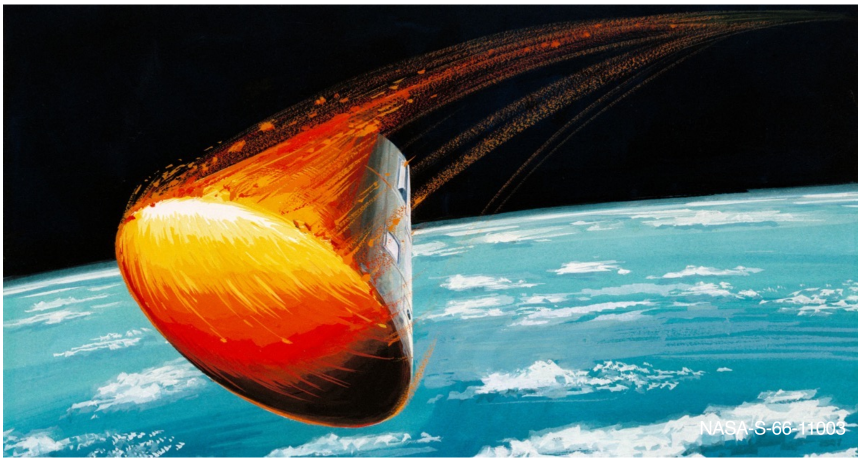


Contents

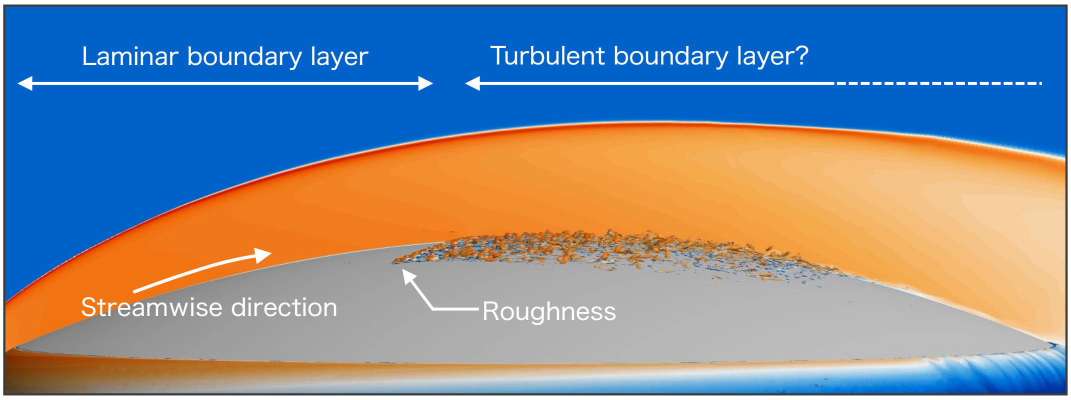
- Boundary Layer Transition (BLT) in re-entry capsules
- Blunt-body paradox
- Direct numerical simulation of disturbance growth
- Measurement of disturbance growth by FLDI

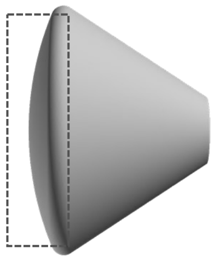
Thermal protection of re-entry capsules



- Re-entry from Lunar orbit exceeds 11 km/s
- Evaluation of aerodynamic heating is necessary for TPS design

BLT on front heat shield

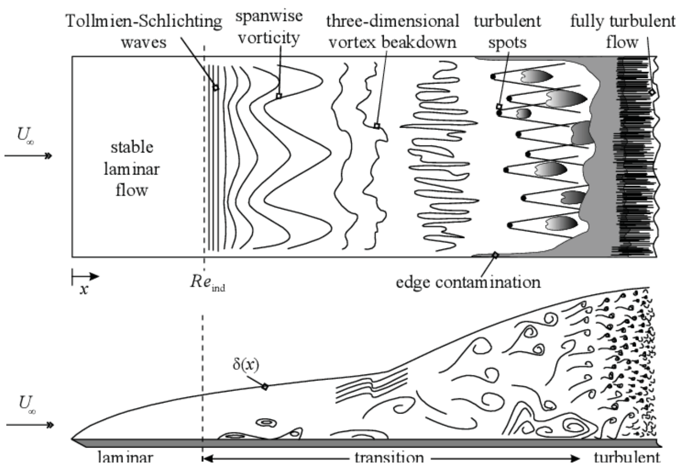


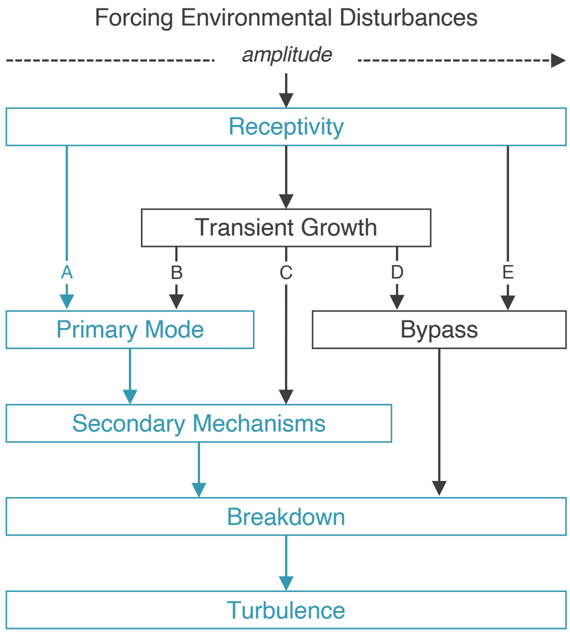


- Turbulent heat flux is several times larger than laminar heat flux
- Prediction of BLT and turbulent heat flux is required for TPS design

BLT due to modal disturbances

T-S wave → destabilization
→ breakdown → turbulence





[1] Reshotko and Tumin, (2000)
[2] Farano et al., JFM, (2015)

Blunt-body paradox

Why is early transition even though modal disturbance is stable?

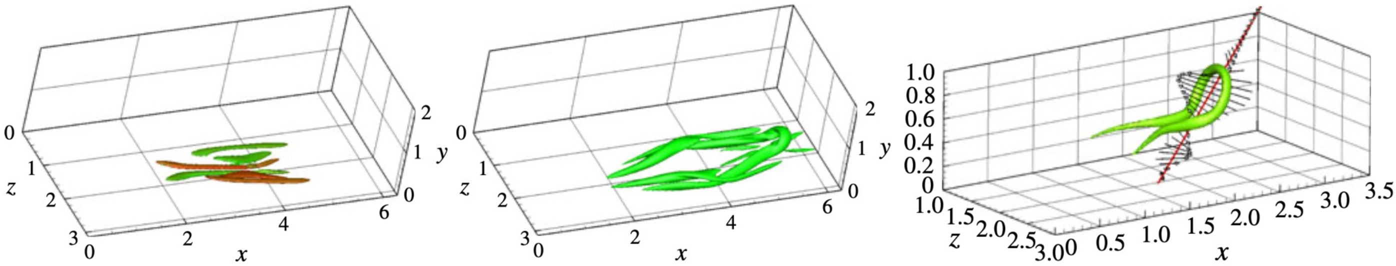
- Tollmien–Schlichting (TS) stable
- Görtler stable
- Cross-flow is negligible

- Transient growth[1] : Candidate mechanisms of transition
  - Lift-up effect of streamwise vorticity creates streaks[2]
- Transition triggers: wall roughness, freestream disturbances

Blunt-body paradox

[1] Reshotko and Tumin, (2000)
[2] Farano et al., JFM, (2015)

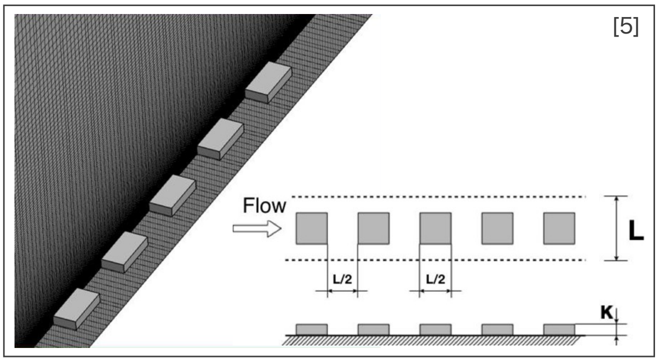
Streamwise vorticity → Lift-up mechanism → Formation and collapse of hairpin vortices

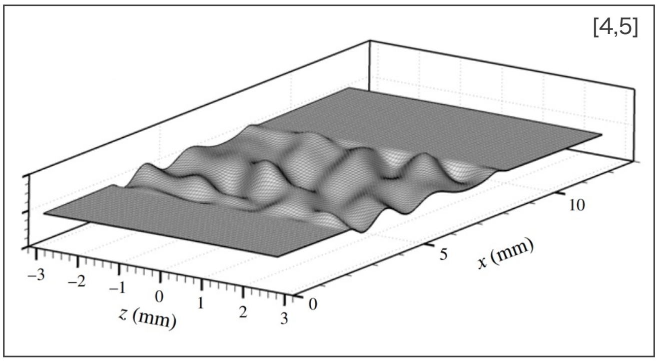


- Transient growth[1] : Candidate mechanisms of transition
  - Lift-up effect of streamwise vorticity creates streaks[2]
- Transition triggers: wall roughness, freestream disturbances

Effect of roughness on BLT

[3] Hein et al., AIAA, (2018)
[4] Giovanni and Stemmer, JSR, (2018)
[5] Giovanni and Stemmer, JSR, (2019)





Isolated roughness

- No growth of mode disturbances
- No transient growth was observed (roughness was too low)

Distributed roughness

- Hairpin vortex grows
- Chemical non-equilibrium amplifies disturbances

Important for high enthalpy flows!

Objective

To clarify the transition mechanism and obtain turbulent heat flux in the re-entry capsule, we evaluate the disturbance growth process under high enthalpy conditions using Apollo capsule models with isolated roughness elements

Numerical method

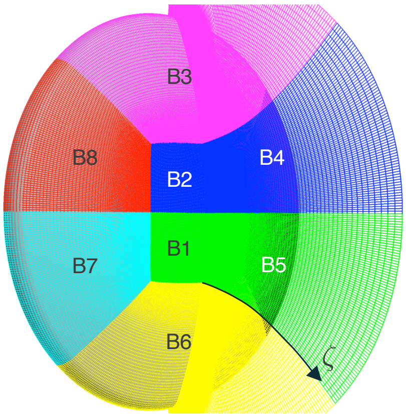
$$\frac{\partial \boldsymbol{Q}}{\partial t}+\frac{\partial \boldsymbol{F}_i}{\partial \xi_i}+\frac{\partial \boldsymbol{F}_{vi}}{\partial \xi_i}+\boldsymbol{S}=0 \quad (i=1,2,3)$$: 3D general curvilinear coordinate system Navier-Stokes equations

$$\boldsymbol{Q}=J\begin{bmatrix}\rho\\ \rho u_1\\ \rho u_2\\ \rho u_3\\ E\\ Y_{n-1}\end{bmatrix},\ \boldsymbol{F}_i=J\begin{bmatrix}\rho U_i\\ \rho u_1 U_i+\dfrac{\partial \xi_i}{\partial x_1}p\\ \rho u_2 U_i+\dfrac{\partial \xi_i}{\partial x_2}p\\ \rho u_3 U_i+\dfrac{\partial \xi_i}{\partial x_3}p\\ (E+p)U_i\\ \rho Y_{n-1}U_i\end{bmatrix},\ \boldsymbol{F}_{vi}=-J\frac{\partial \xi_i}{\partial x_j}\begin{bmatrix}0\\ \tau_{j1}\\ \tau_{j2}\\ \tau_{j3}\\ \tau_{jk}u_k+\kappa\dfrac{\partial T}{\partial x_j}+\sum_s \rho v_{n-1}h_{n-1}\\ \rho v_{n-1}\end{bmatrix},\ \boldsymbol{S}=-J\begin{bmatrix}0\\0\\0\\0\\0\\0\\ s_{Y_{n-1}}\end{bmatrix}.$$

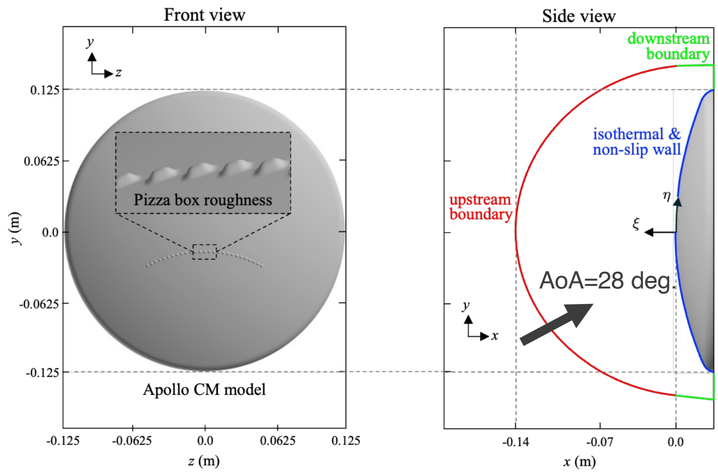
Inviscid terms	SLAU2 & 7th order Weighted Compact Nonlinear Scheme (WCNS)
Viscous terms	6th order compact difference scheme
Time integration	5-stage 4th-order accuracy Runge-Kutta scheme
Reaction model	Dunn & Kang model (5-species & 17-reaction)

Computational conditions

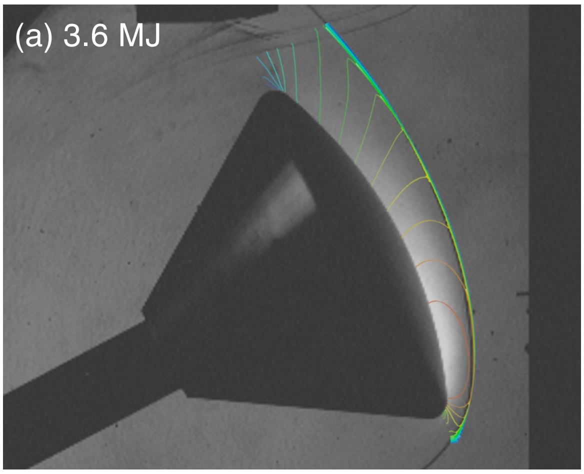
Stagnation conditions			Freestream conditions			
H_0, MJ/kg	p_0, MPa	T_0, K	u_∞, km/s	p_∞, kPa	T_∞, K	Re_∞
3.6	17	2968	2.5	1.5	271	2.7E6
6.5	33	4529	3.4	3.5	660	2.4E6
9.2	53	5739	3.9	7.6	1012	2.5E6

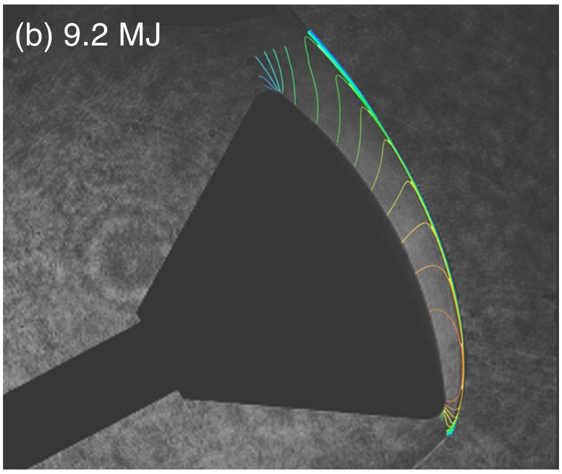


Multi-block mesh (total mesh: 70 million)



Validation: Comparison of bow shock shapes

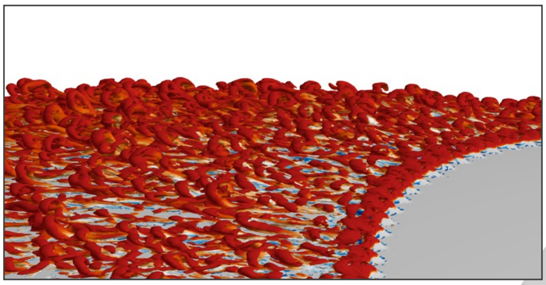




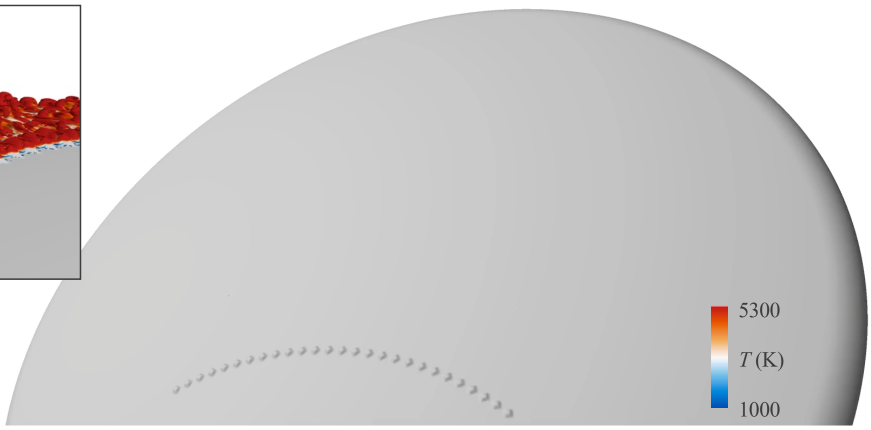
- Shock wave departure distance is consistent with Schlieren images
- No carbuncles were observed, and robust shock capture was achieved

[6] Ma & Mahesh, JFM, (2022)

Forest of hairpin

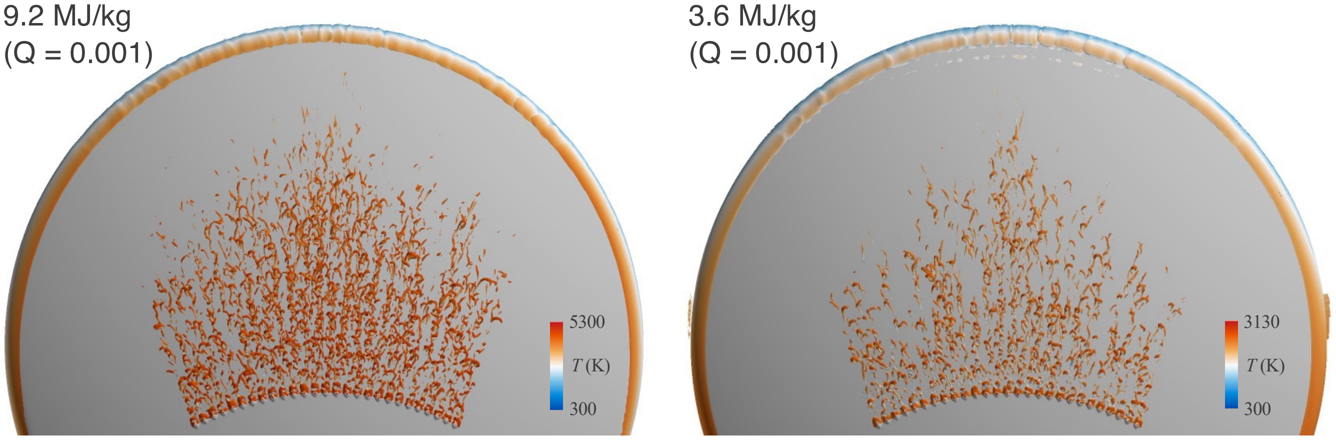


Side view
(9MJ condition, Q=0.001)



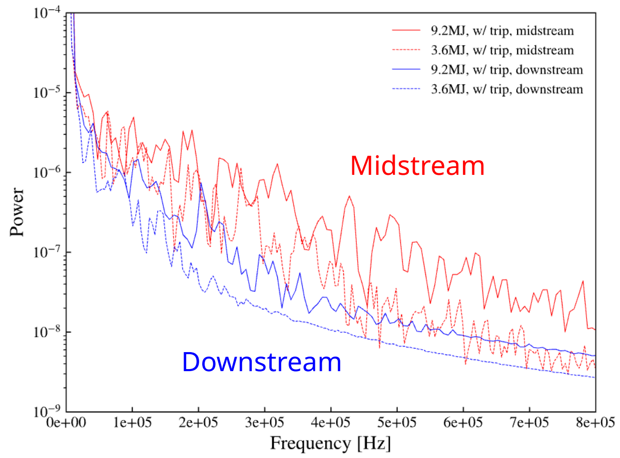
- Numerous hairpin vortices are formed in the wake of roughness[6]
- Hairpin vortex grows once, then starts to decay and disappears

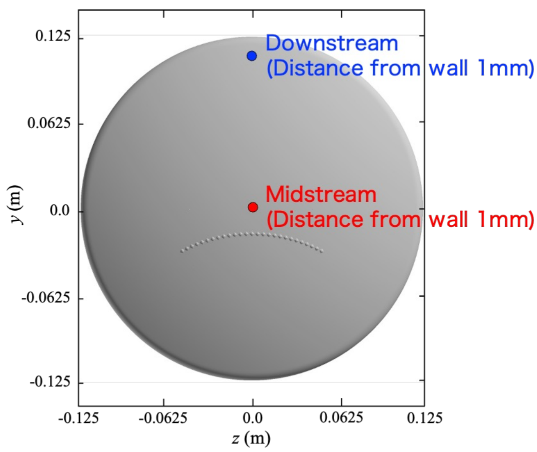
Enthalpy effect on disturbance growth



- Roughness wake hairpin vortices are reduced under low enthalpy condition
- Density disturbance power is also lower under low enthalpy condition

Enthalpy effect on disturbance growth



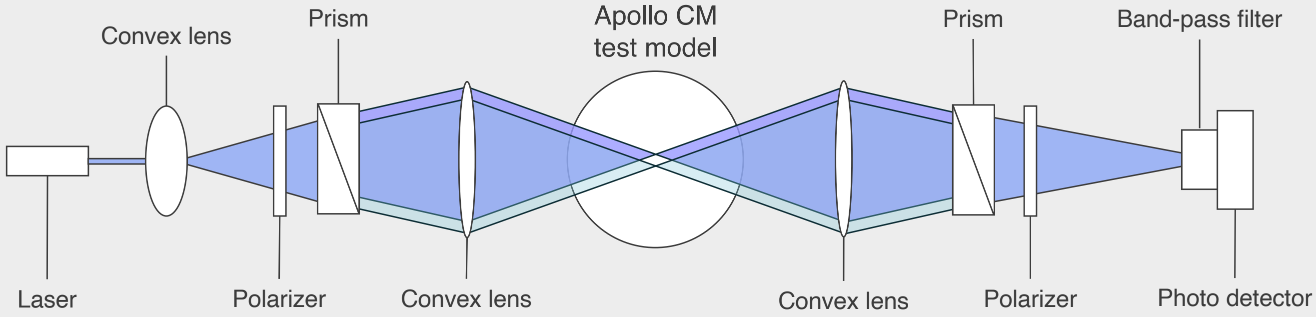


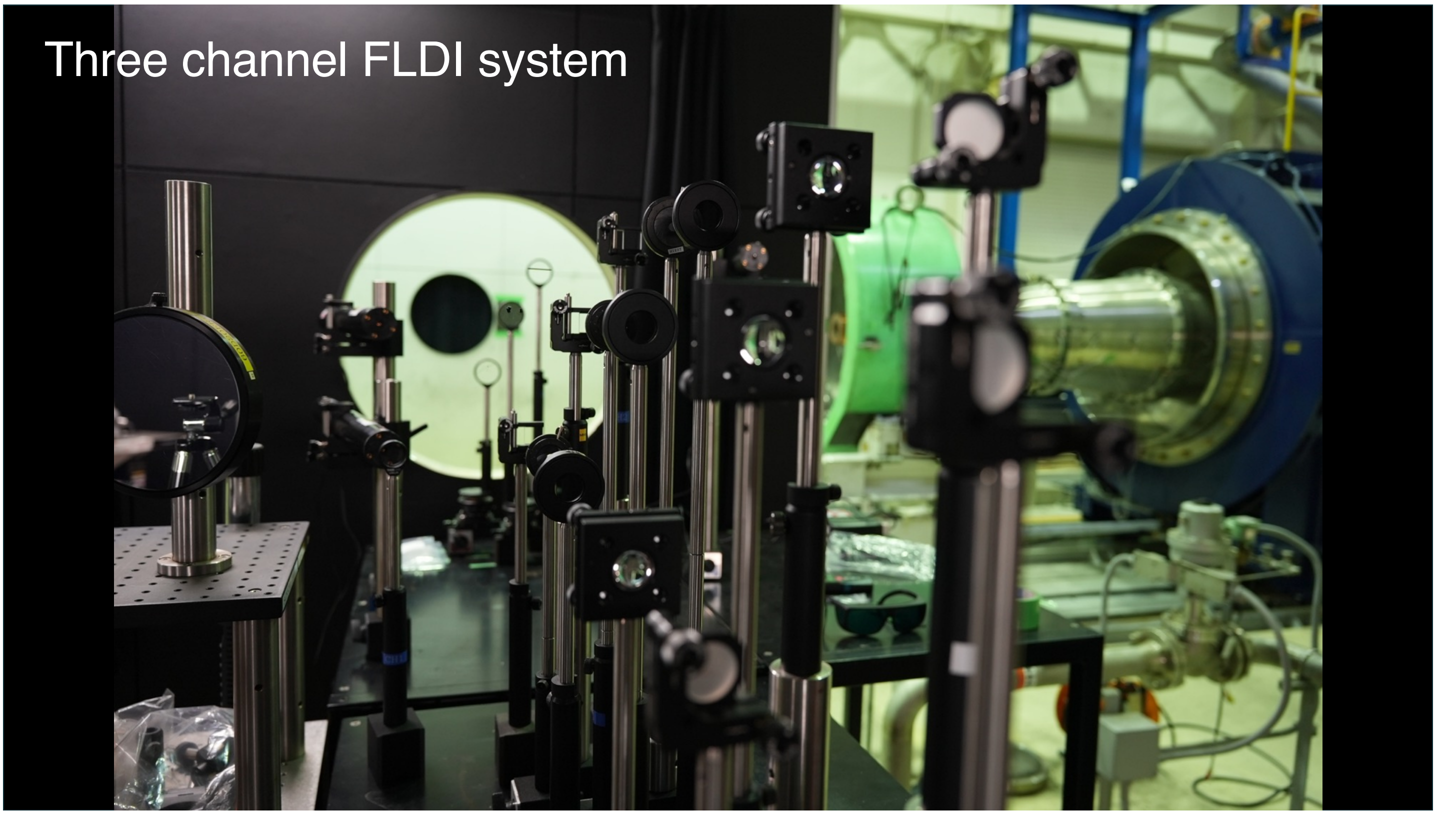
- Roughness wake hairpin vortices are reduced under low enthalpy condition
- Density disturbance power is also lower under low enthalpy condition

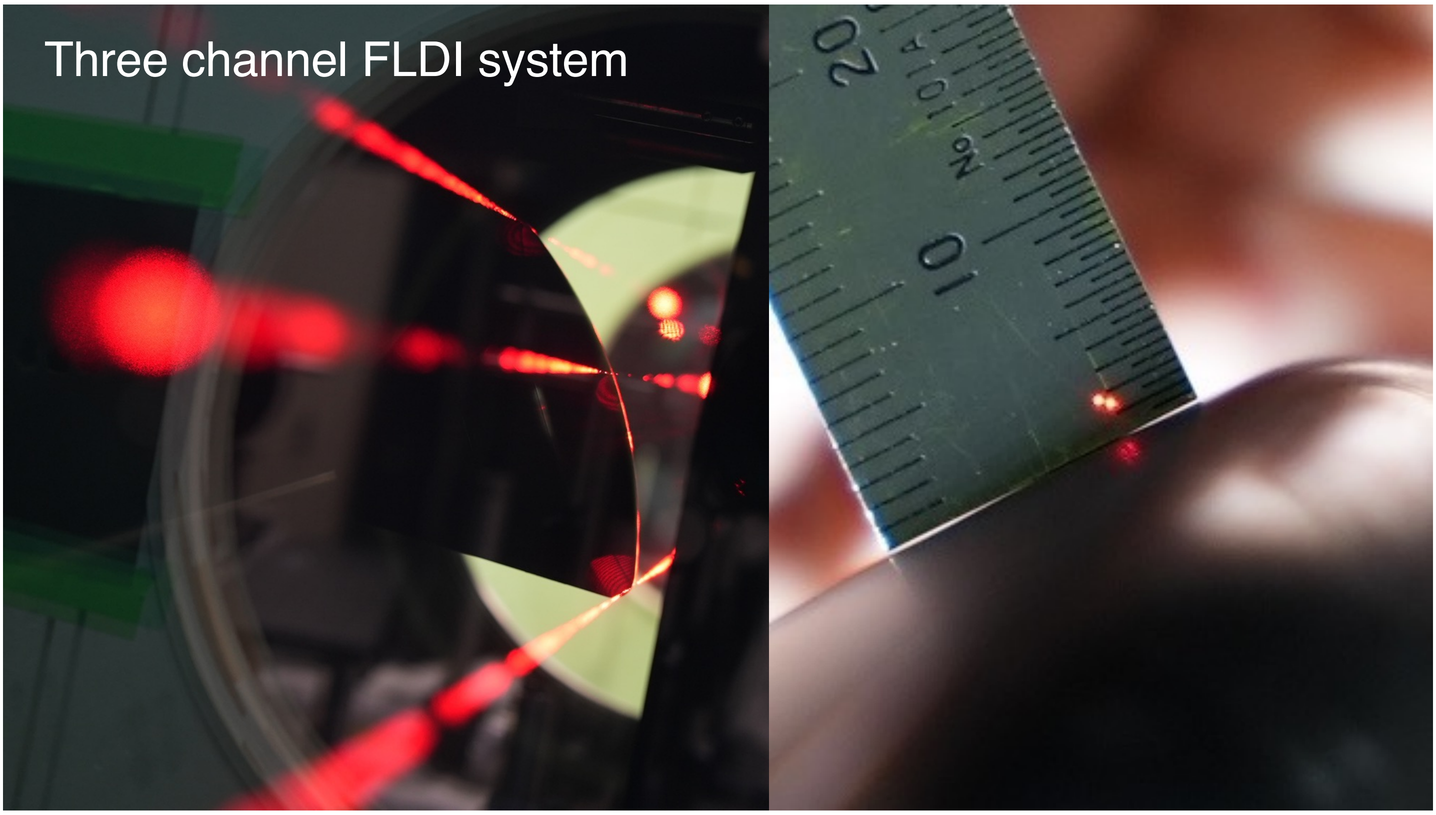
Density disturbance measurement with FLDI

- Measured density disturbance about 1 mm upstream from model surface with three-channel FLDI
- Not affected by mechanical vibrations of the model and achieves multi-MHz bandwidths

Focused Laser Differential Interferometry, FLDI

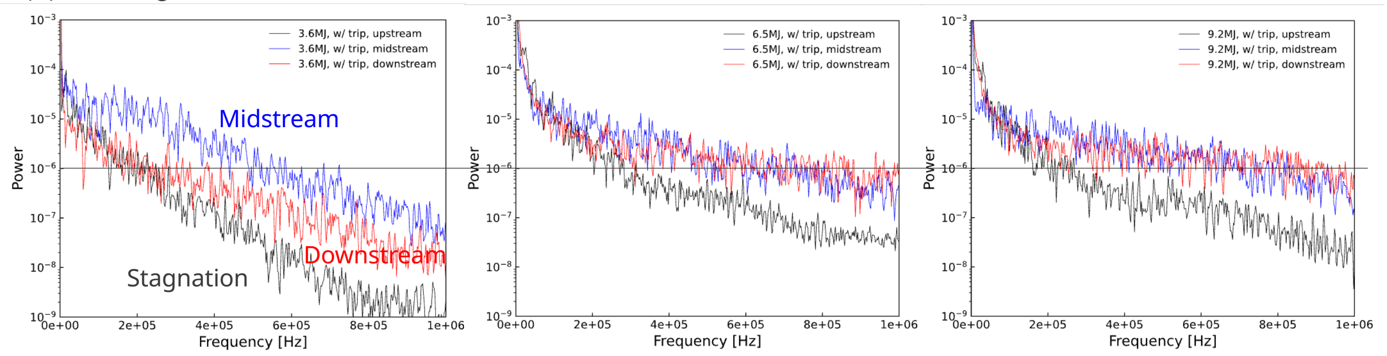



Three channel FLDI system


Three channel FLDI system

Power spectrum of density disturbance

(a) 3 MJ/kg (b) 6 MJ/kg (c) 9 MJ/kg



- 3MJ: Power tends to decay from midstream to downstream
- 6, 9MJ: Power maintained downstream at the same level as midstream

→ Tendency to grow more disturbance under higher enthalpy conditions (qualitatively consistent with DNS)

Conclusion

To clarify the transition mechanism and obtain turbulent heat flux in the re-entry capsule, we evaluated the disturbance growth process under high enthalpy conditions using Apollo capsule models with isolated roughness elements

- Numerous hairpin vortices were formed in the wake of roughness
- Tendency to grow more disturbance under higher enthalpy conditions
  - DNS and experimental results were qualitatively consistent
  - Are high enthalpy conditions more likely to transition?