Numerical Investigation of Flow and Starting Characteristics of Nozzle-Diffuser System for Plasma Wind Tunnel

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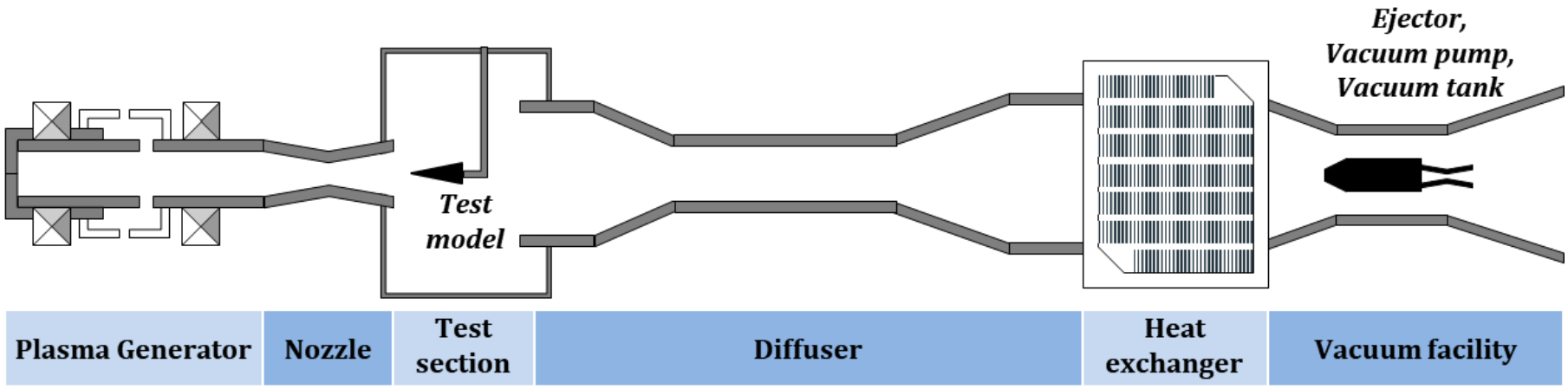
Outline

1. Background
2. Materials and Methods
3. Flow Analysis of Nozzle-Diffuser System
4. Starting Characteristics
5. Conclusion

Background

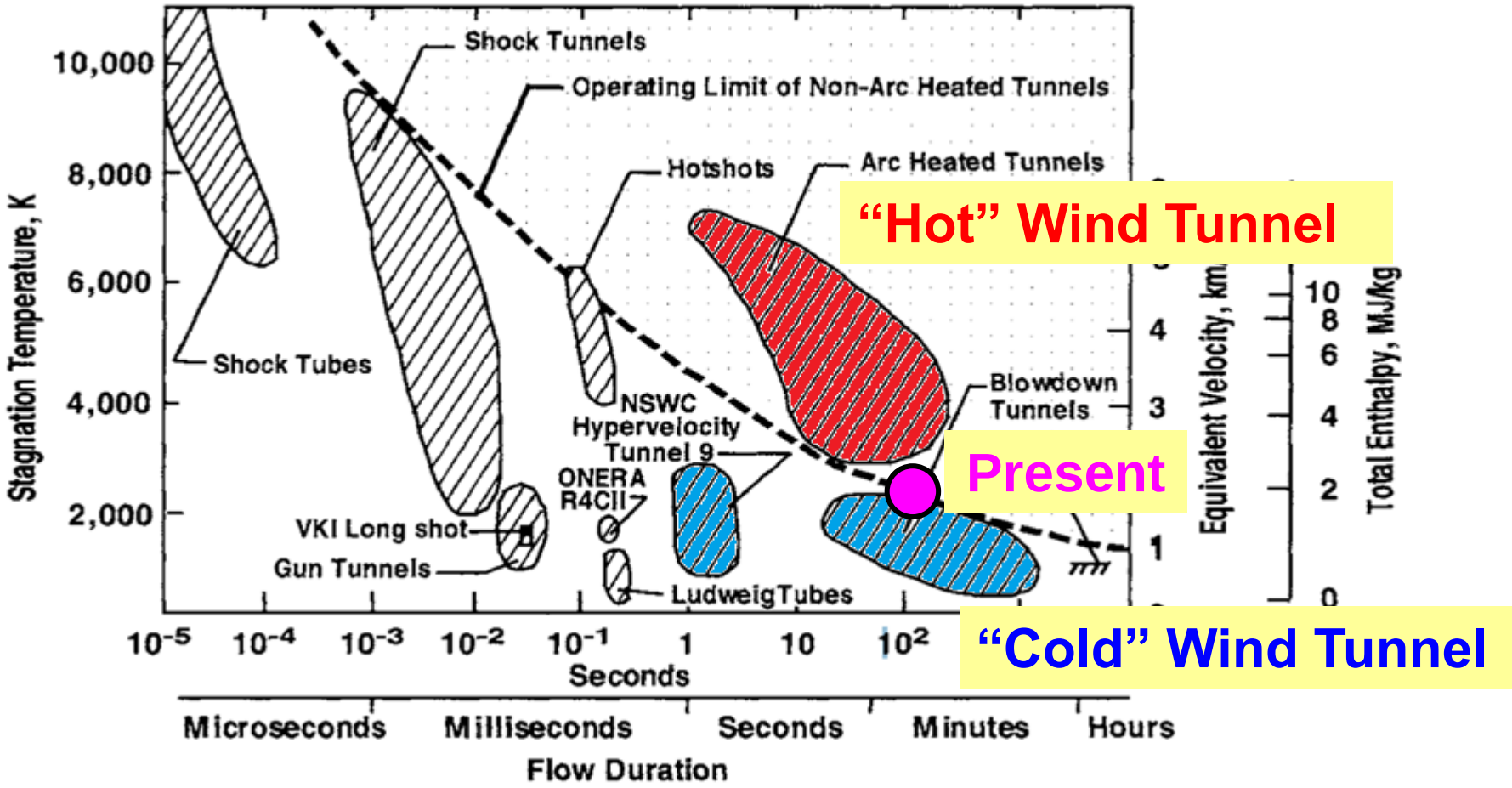
Plasma Wind Tunnel (PWT)

- Simulating hypersonic/high enthalpy flows
- Additional components with high power
  - Plasma generator
  - Cooling system, ejector, vacuum facility



< Schematic of a plasma wind tunnel >

Type of Wind Tunnel



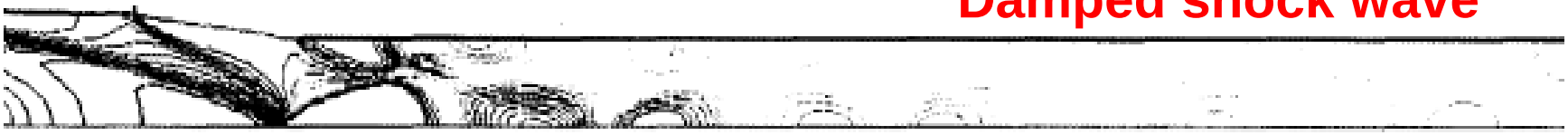
< Capabilities of aerothermal facility [1] >

Characteristics of PWT

- **Low Reynolds number**
  - $Re_D = 10^4 \sim 10^6$ $(vs. 10^5 \sim 10^7$ $in\ SWT)$
  - **Viscous dominant / Damped shock wave**

Re = 3,000

Damped shock wave



Re = 30,000

Sharply defined shock wave

< Pressure contour difference according to Reynolds number [2] >

Characteristics of PWT

- **Far higher pressure ratio required [2, 3]**
  - **Owing to shock wave, dominant viscous effect**
- **May requiring long time test duration [4, 5]**
  - **Ablation, Reentry test**

< Difference between general SWT and PWT >

	Pressure Ratio	Test Duration	Reynolds Number ($Re_D = \frac{\rho_\infty V_\infty D}{\mu_\infty}$)
SWT	$10^0 \sim 10^2$	$10^1 \sim 10^2$ sec.	$10^5 \sim 10^7$
PWT	$10^2 \sim 10^3$	$10^0 \sim 10^3$ $sec.$	$10^2 \sim 10^5$ (Present 2 x 10^4)

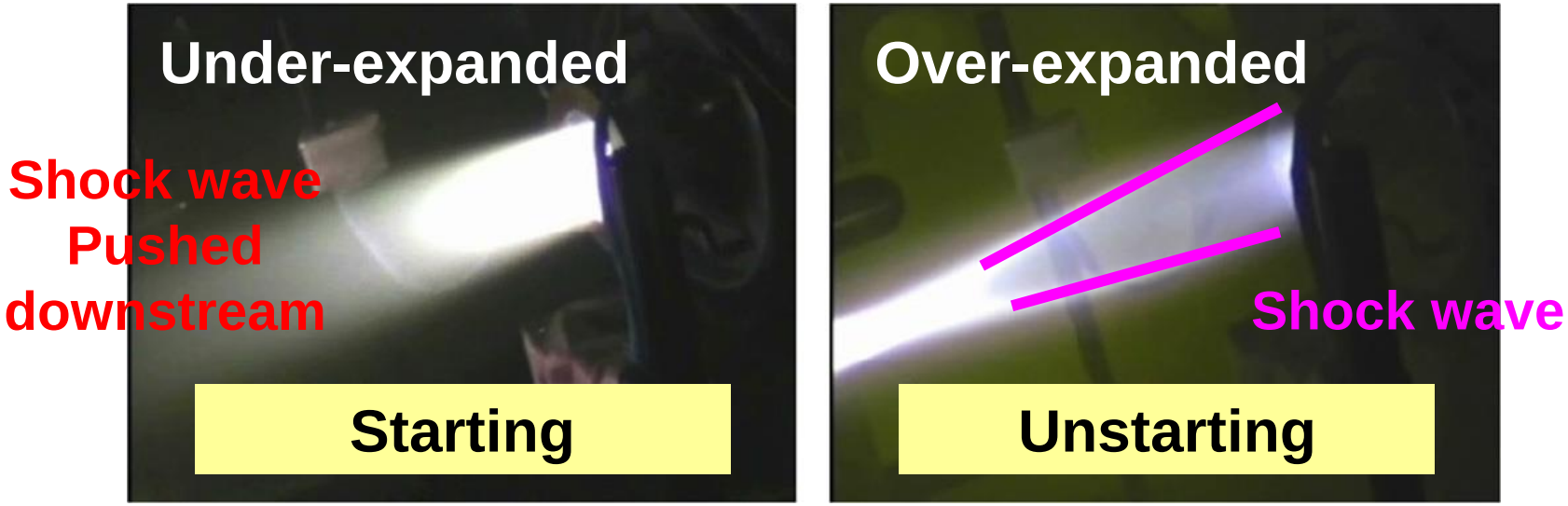
Motivation

- **Prediction of pressure ratio**
  - **Most of literature dealing with it**
  - **Key design parameter to determine**
    - **(1) the type and spec. of the plasma generator**
    - **(2) vacuum facility capacity and spec.**
    - **(3) whether to use a boosting ejector**
  - **Difficulties caused by flow characteristics [2, 6]**

- **Limited literature and information of PWT**
  - **Frequently mentioned this limitation [2, 5, 6, 7]**

Motivation

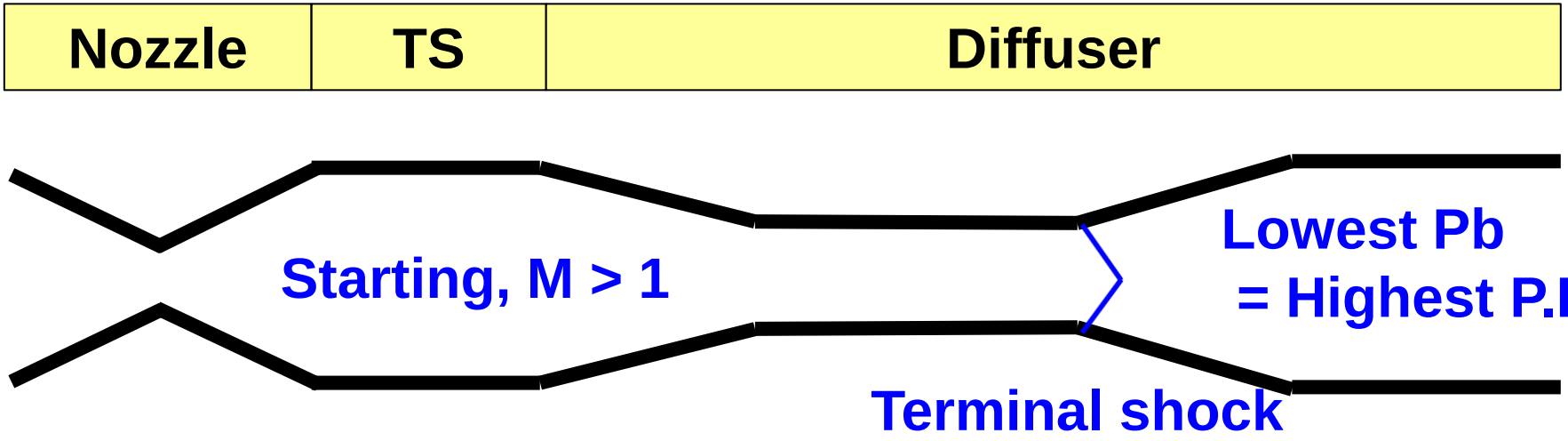
- **Wind tunnel start**
  - **Shock wave pushed downstream**
  - **Sufficient pressure ratio pushing shock wave**



< Under-expanded (left) and over-expanded (right) jet of GHIBLI PWT [8] >

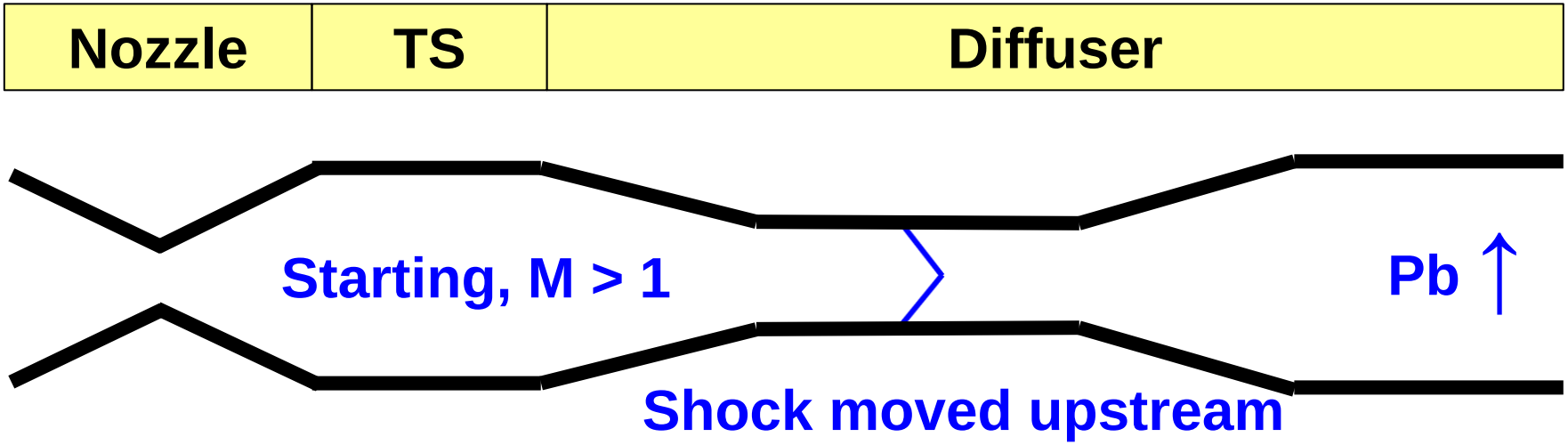
Motivation

- **Literature mainly focused on minimum operable pressure ratio**
  - **Initially assume wind tunnel already started**
  - **Initial condition with very low back-pressure**



Motivation

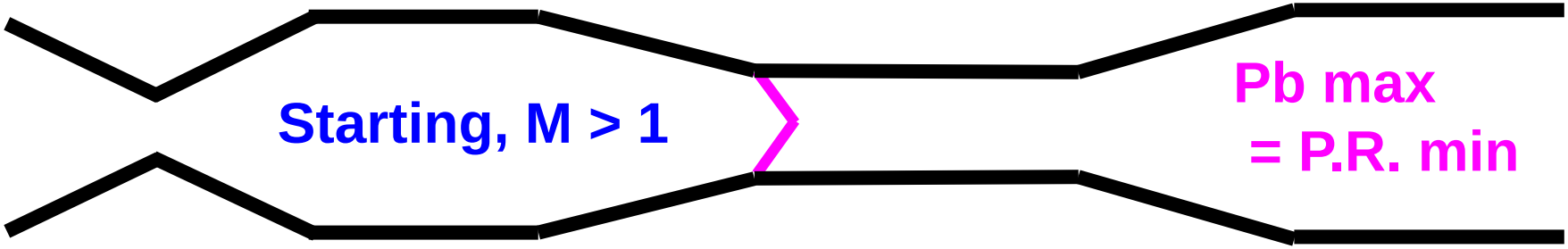
- **Literature mainly focused on minimum operable pressure ratio**
  - **Gradually increasing back-pressure**



Motivation

- **Literature mainly focused on minimum operable pressure ratio**
  - **Gradually increasing back-pressure**
  - **Until the un-starting**

Nozzle	TS	Diffuser

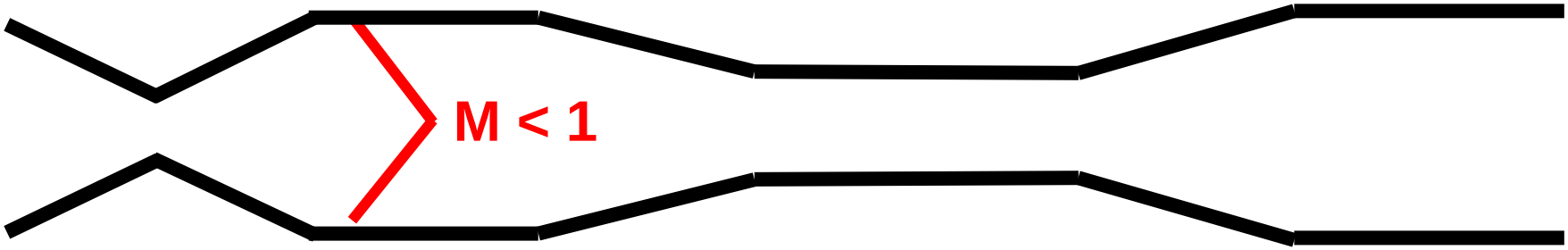


Efficient operating condition = lowest cost

Motivation

- **Literature mainly focused on minimum operable pressure ratio**
  - **Pressure ratio for operation is important**
  - **Necessary to consider starting pressure ratio**

Nozzle	TS	Diffuser



Inoperable

How much P.R. to push the shock?

Objectives

- **Numerical Investigation of the flow in PWT**
  - **Shock train, terminal shock**
  - **Flow variables including total pressure**

- **Investigate starting characteristics**
  - **Decreasing / Increasing back-pressure**
  - **Identifying**
    - **(1) maximum operable back-pressure**
    - **(2) starting back-pressure**
    - **(3) hysteresis**

Materials and Methods

Governing Equations

- **Axisymmetric Reynolds Averaged Navier- Stokes (RANS) Equations**

$$\frac{\partial Q}{\partial t}+\frac{\partial E}{\partial x}+\frac{\partial F}{\partial y}+H=\frac{\partial E_v}{\partial x}+\frac{\partial F_v}{\partial y}+H_v$$

Conservative Variables

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e_t\end{bmatrix}$$

Convective and Diffusive Flux

$$E=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (\rho e_t+p)u\end{bmatrix},F=\begin{bmatrix}\rho v\\ \rho uv\\ \rho v^2+p\\ (\rho e_t+p)v\end{bmatrix}$$

Additional Axisymmetric terms

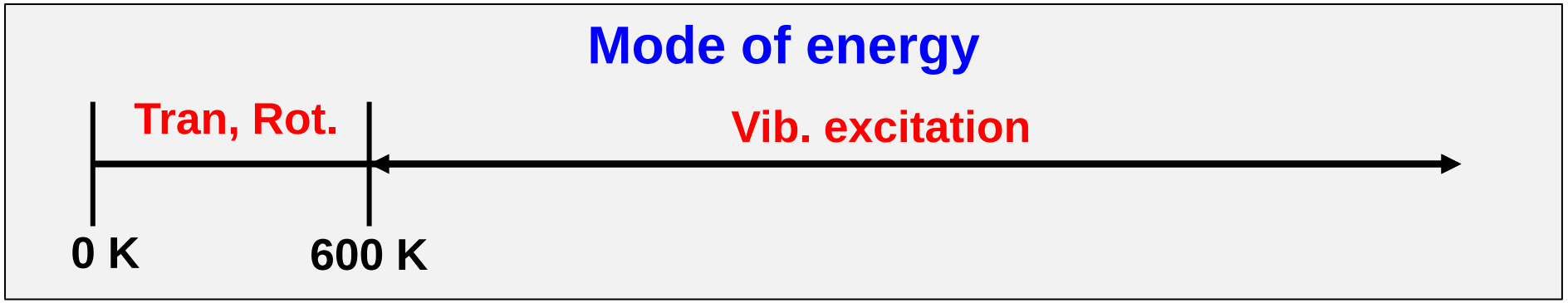
$$H=\frac{1}{y}\begin{bmatrix}\rho u\\ \rho uv\\ \rho v^2\\ (\rho e_t+p)v\end{bmatrix}$$

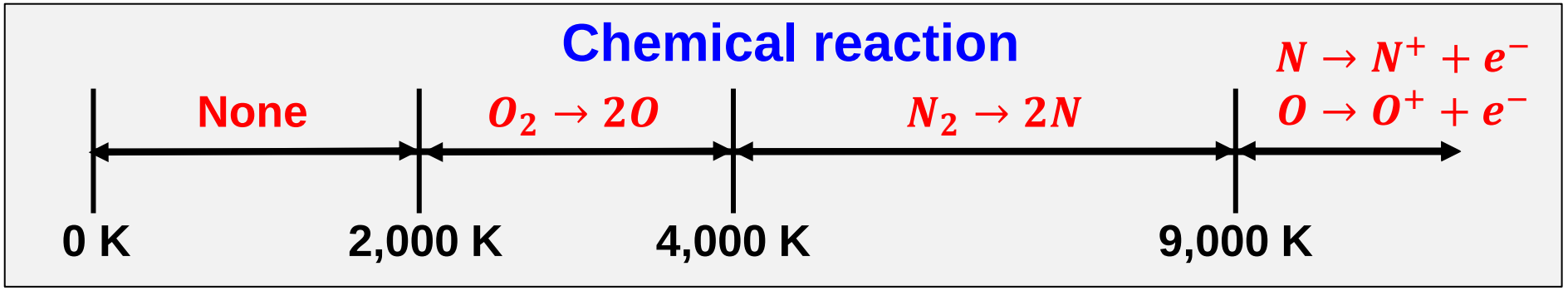
$$E_v=\begin{bmatrix}0\\ \tau_{xx}\\ \tau_{xy}\\ u\tau_{xx}+v\tau_{xy}-\dot{q}_x\end{bmatrix},F_v=\begin{bmatrix}0\\ \tau_{xy}\\ \tau_{yy}\\ u\tau_{xy}+v\tau_{yy}-\dot{q}_y\end{bmatrix}$$

$$H_v=\begin{bmatrix}0\\ (h_v)_2\\ (h_v)_3\\ (h_v)_4\end{bmatrix}$$

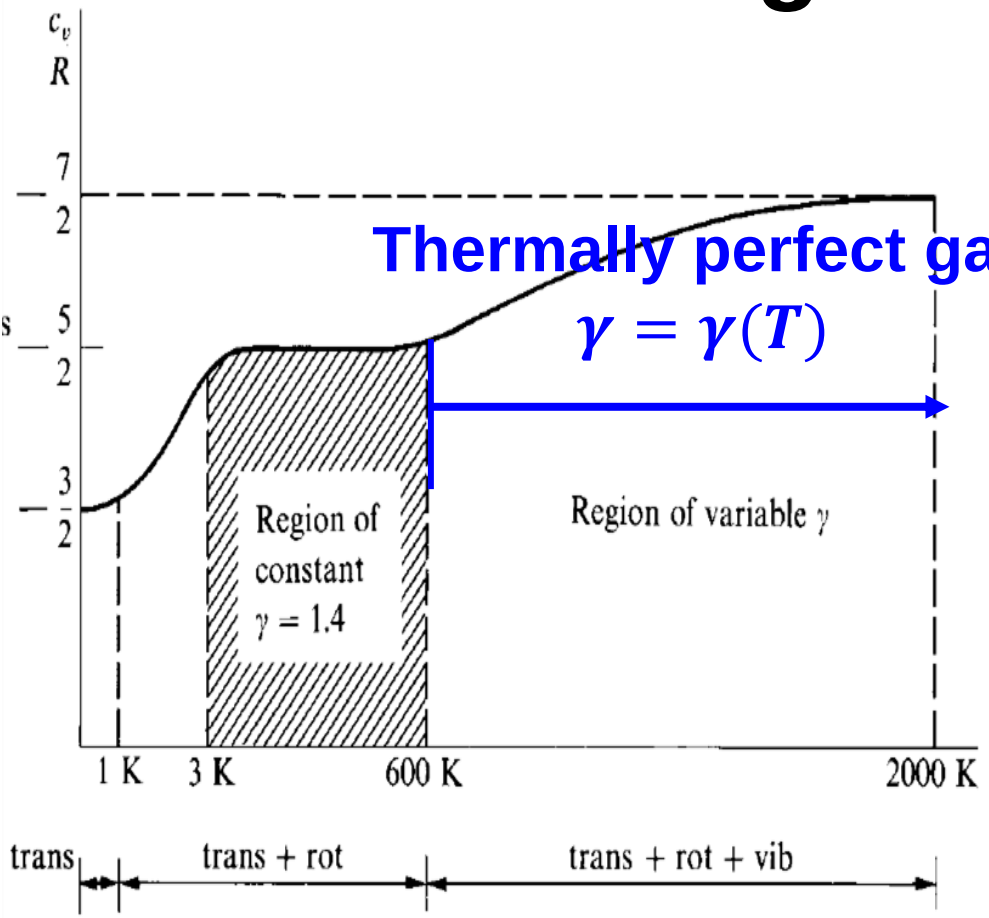
Modeling of Equilibrium

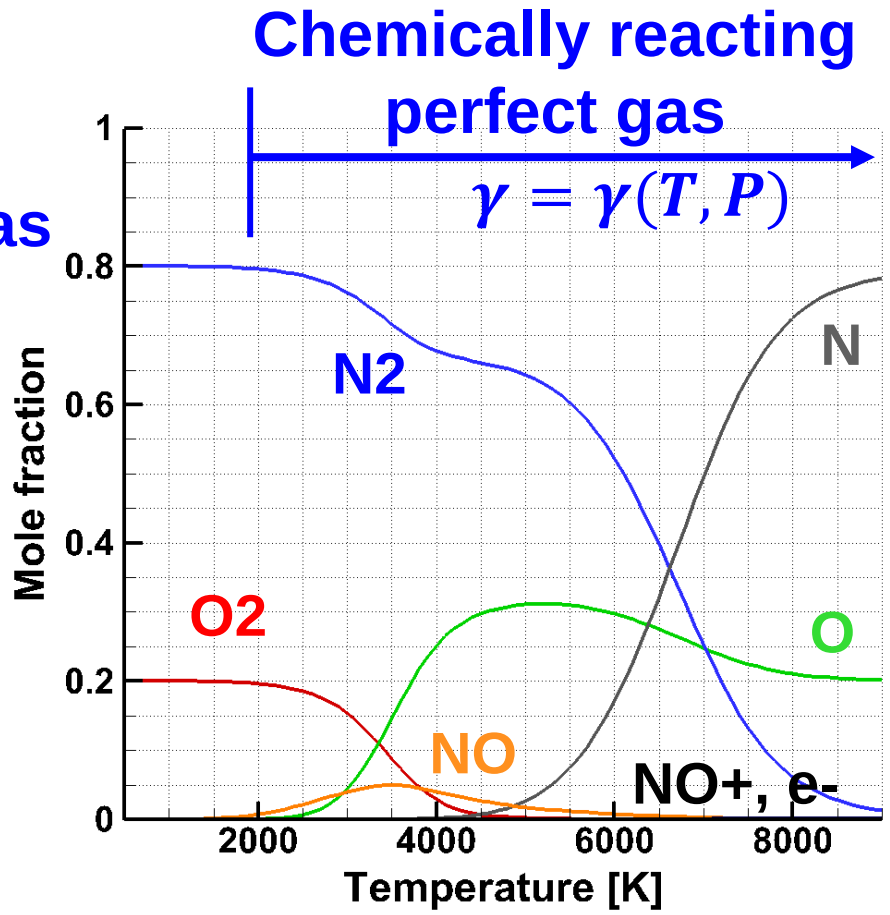
- **(Air) Internal temperature up to 2,500K**
  - **Vibrational excitation, chemical reaction occur [9]**





Modeling of Equilibrium

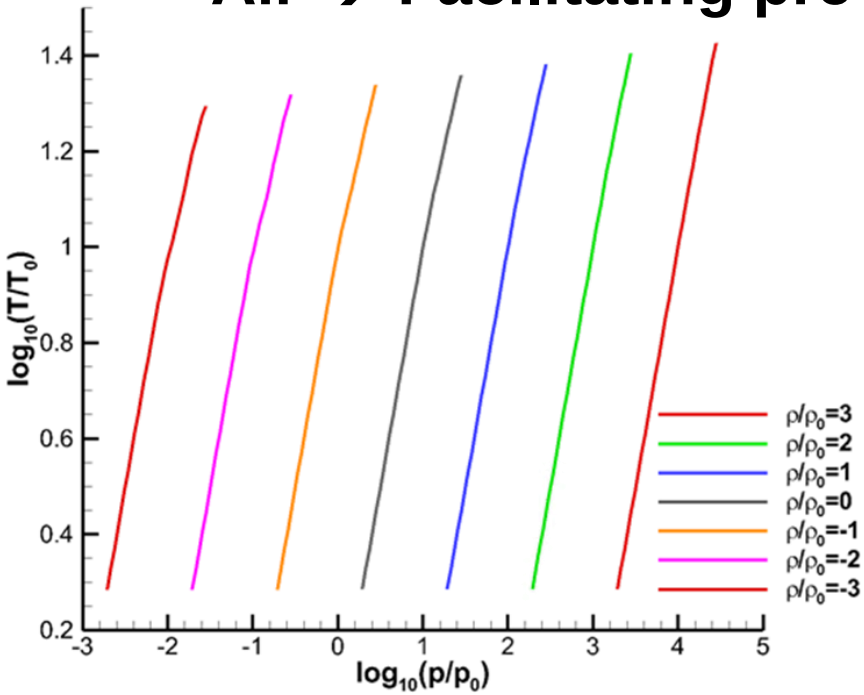


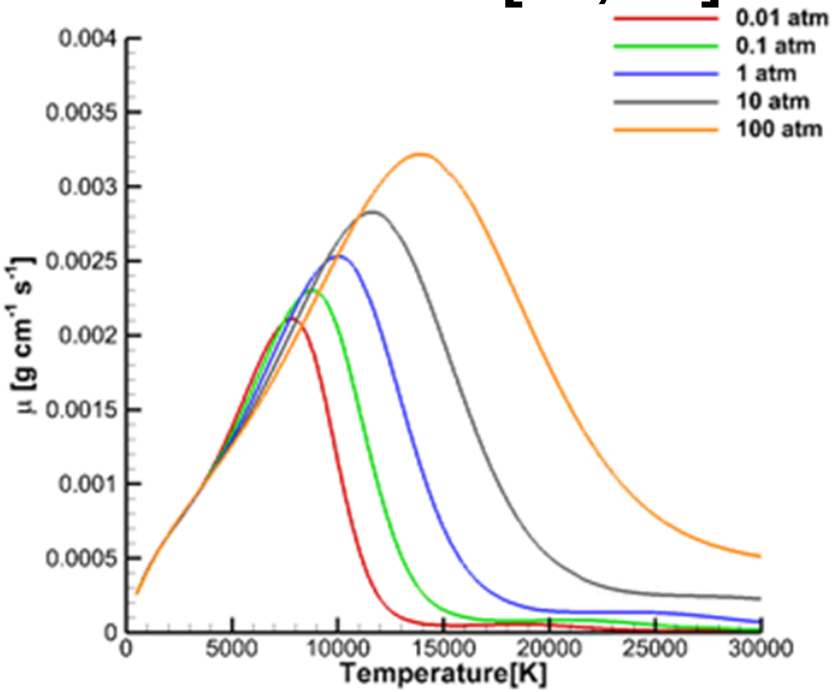


< Variation of specific heat (left) [9] and composition of air (right) >

Modeling of Equilibrium

- **Assume thermal and chemical equilibrium**
  - **Air → Facilitating pre-established data [10, 11]**





< Examples of equilibrium properties of air calculated from correlation >

Modeling of Turbulence

- **Standard k-epsilon turbulence model [12]**
  - **Used in related literatures [4, 6]**
  - **Applicable to wall bounded internal flow**

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot \left(\rho k \vec{V}\right) = \nabla \cdot \left[\left(\mu_l + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] - \rho\varepsilon + 2\mu_t \bar{\bar{E}} \cdot \bar{\bar{E}}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla \cdot \left(\rho \varepsilon \vec{V}\right) = \nabla \cdot \left[\left(\mu_l + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + C_1 \frac{\varepsilon}{k} 2\mu_t \bar{\bar{E}} \cdot \bar{\bar{E}} - C_2 \rho \frac{\varepsilon^2}{k}$$

$$\sigma_k = 1.00, \sigma_\varepsilon = 1.3, C_1 = 1.44, C_2 = 1.92, C_\mu = 0.09$$

$$\mu_T = C_\mu \frac{\rho k^2}{\varepsilon} \qquad \mu = \mu_L + \mu_T$$

Computation

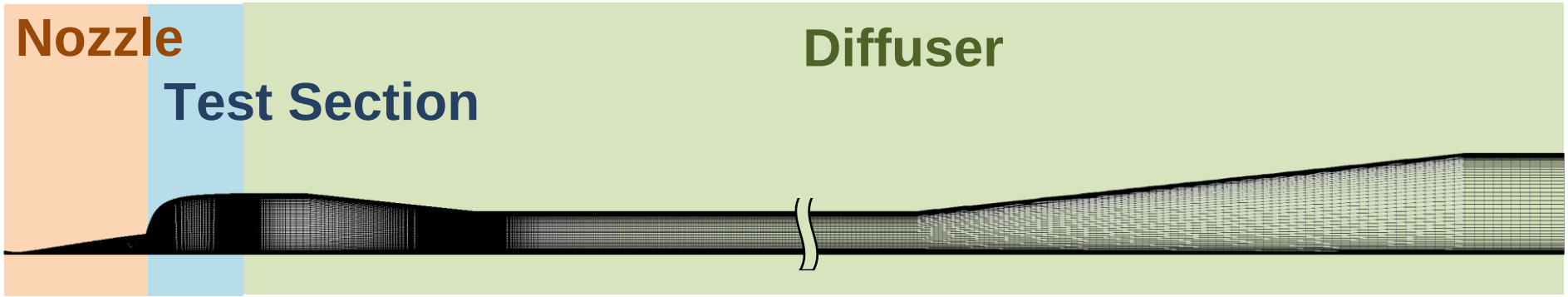
- **Mass flow rate difference** less than 1 %
- **Step-by-step steady calculations** [2]

< Numerical schemes used in the study >

Numerical scheme	
Convective flux Differencing	AUSMPW+ [13]
Spatial Reconstruction	TVD with minmod limiter [14]
Psudo time Integration	LU-SGS [15]

Computational Domain

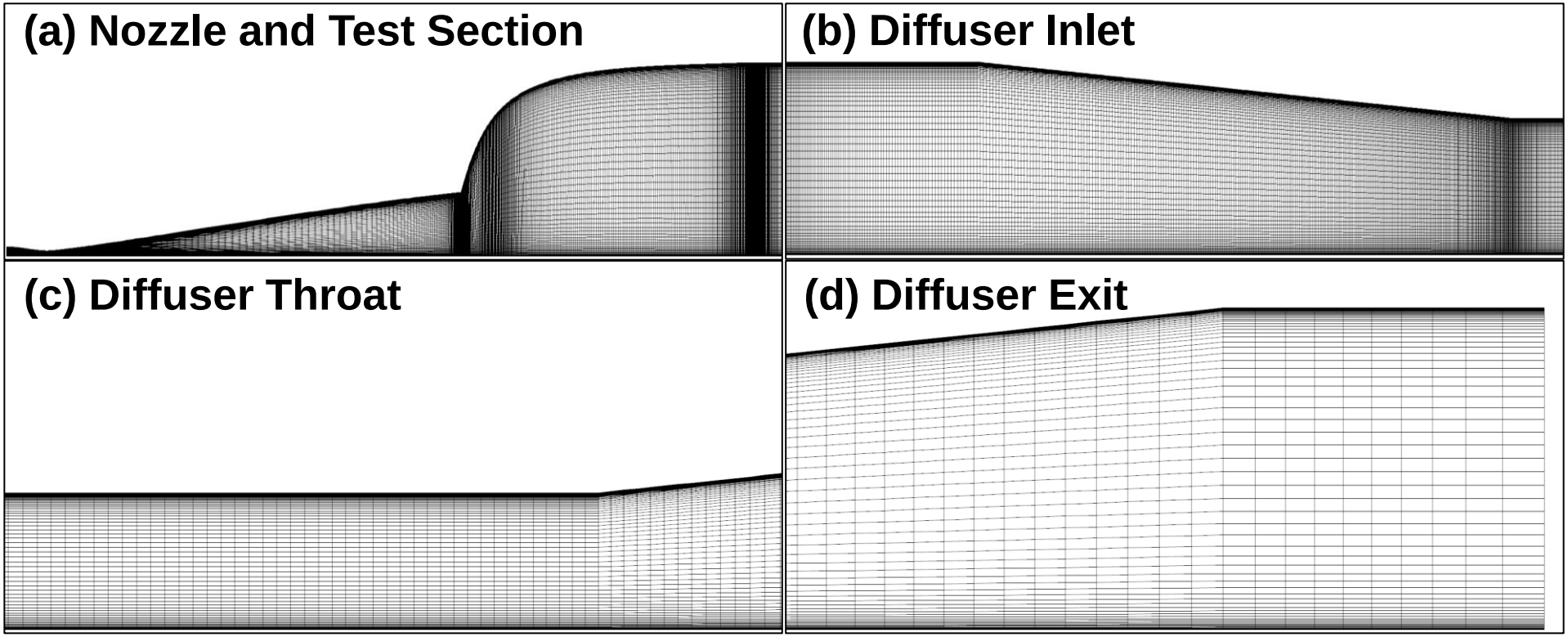
- Mach 7 Nozzle – Test section – Diffuser
- Structured mesh (quadrilateral)
  - Node dimension: 1510 X 91
  - Y+ less than 1.0 near the wall (y+ ~ 0.5)



< Computational domain >

Computational Domain

- **Grid configurations of each parts**



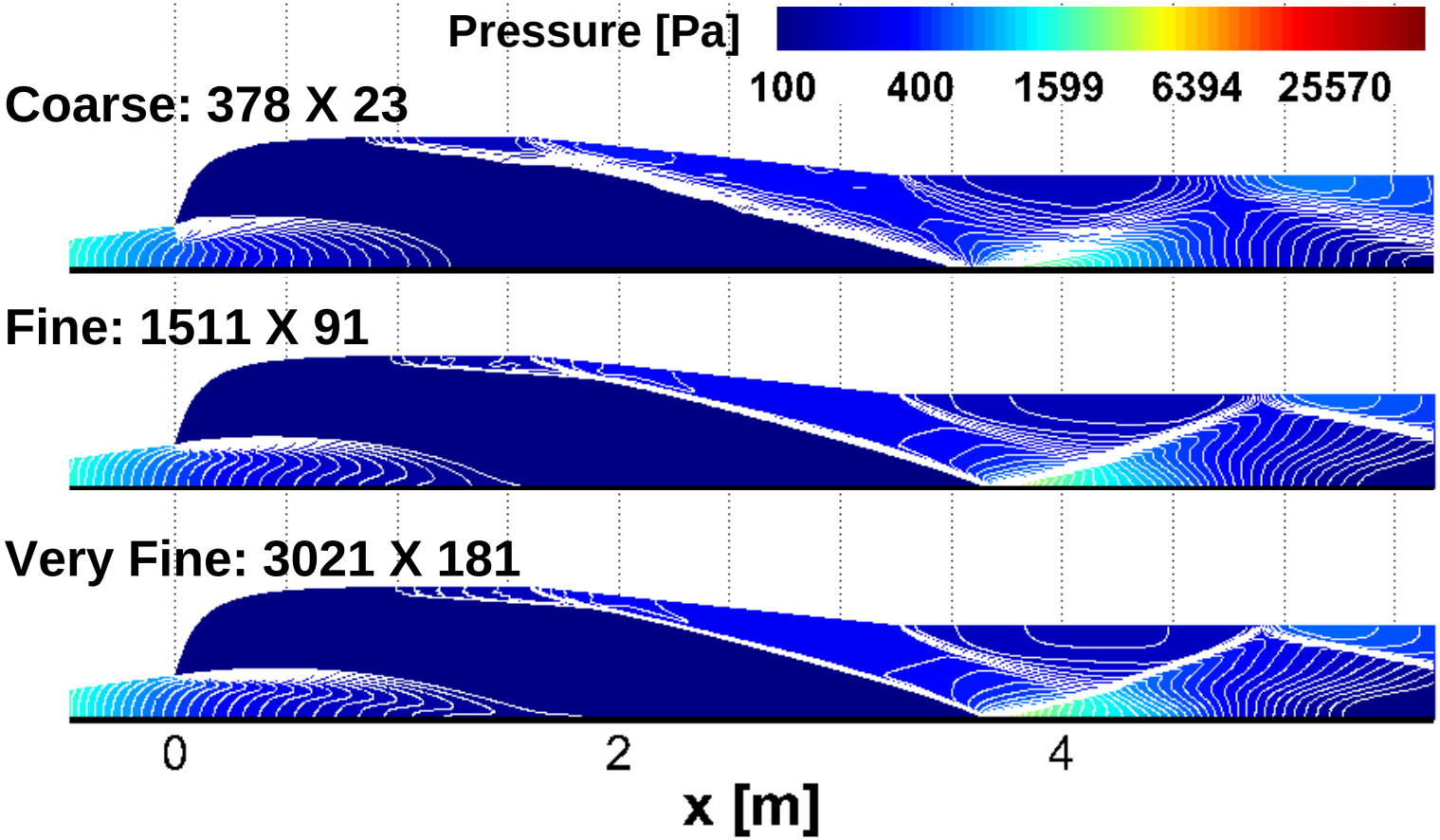
< Grid configuration of each parts >

Grid Convergence Study

- **Grid dimension considered**
  - **Double refined with distribution rules maintained**
  - **378 X 23 / 756 X 46 / 1511 X 91 / 3021 X 181**

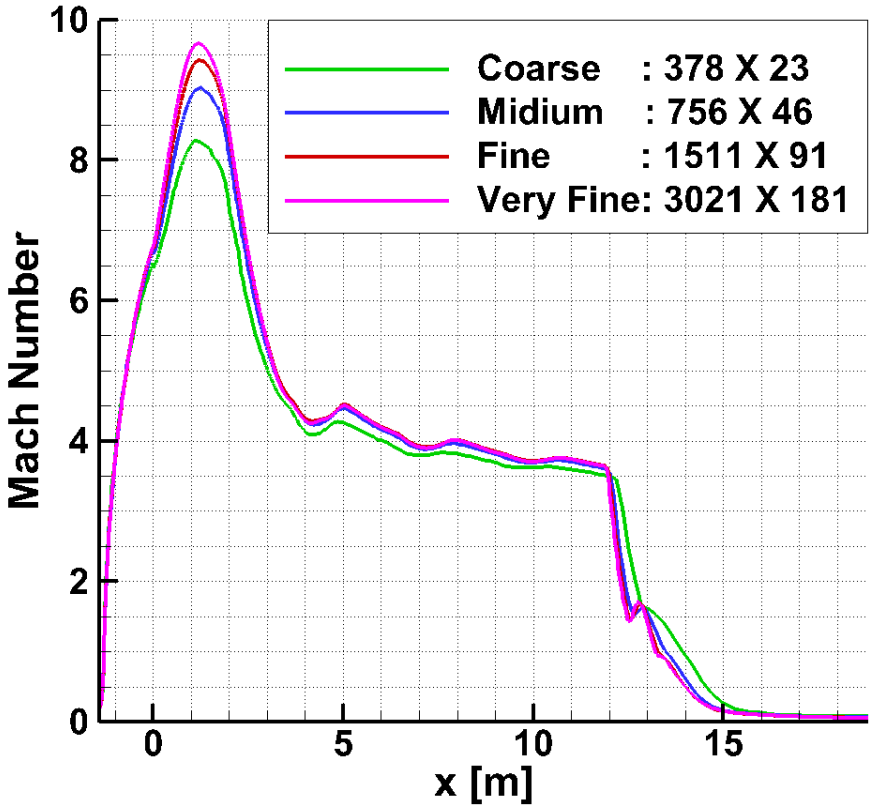
- **Convergence check on**
  - **Shock wave configuration**
  - **Axial distributions of flow variables (Mach number, static pressure, total pressure)**

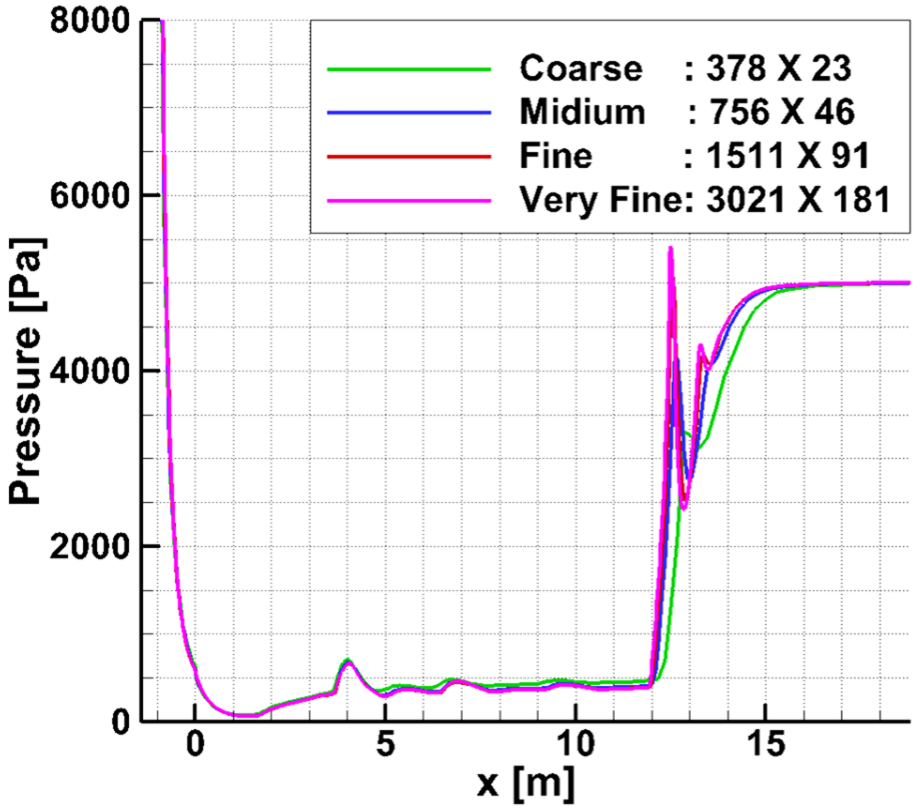
Grid Convergence Study



< Shock wave configurations with various grid levels >

Grid Convergence Study

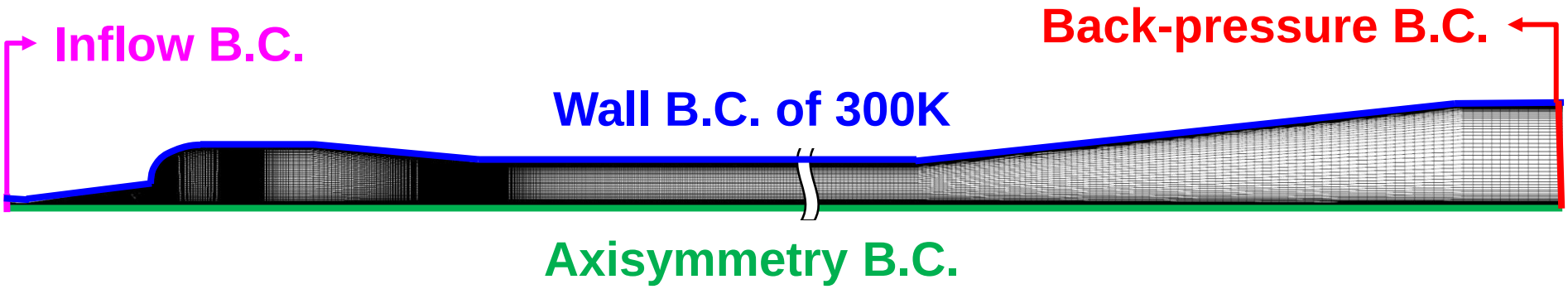




< Mach number (left) and pressure (right) distributions with various grid levels >

Inflow / Boundary Conditions

- **(Wall) Constant temperature of 300K**
- **(Diffuser exit) Constant back-pressure**
  - **Varying back-pressure → control pressure ratio**
- **Axisymmetry**



< Boundary conditions applied >

Inflow / Boundary Conditions

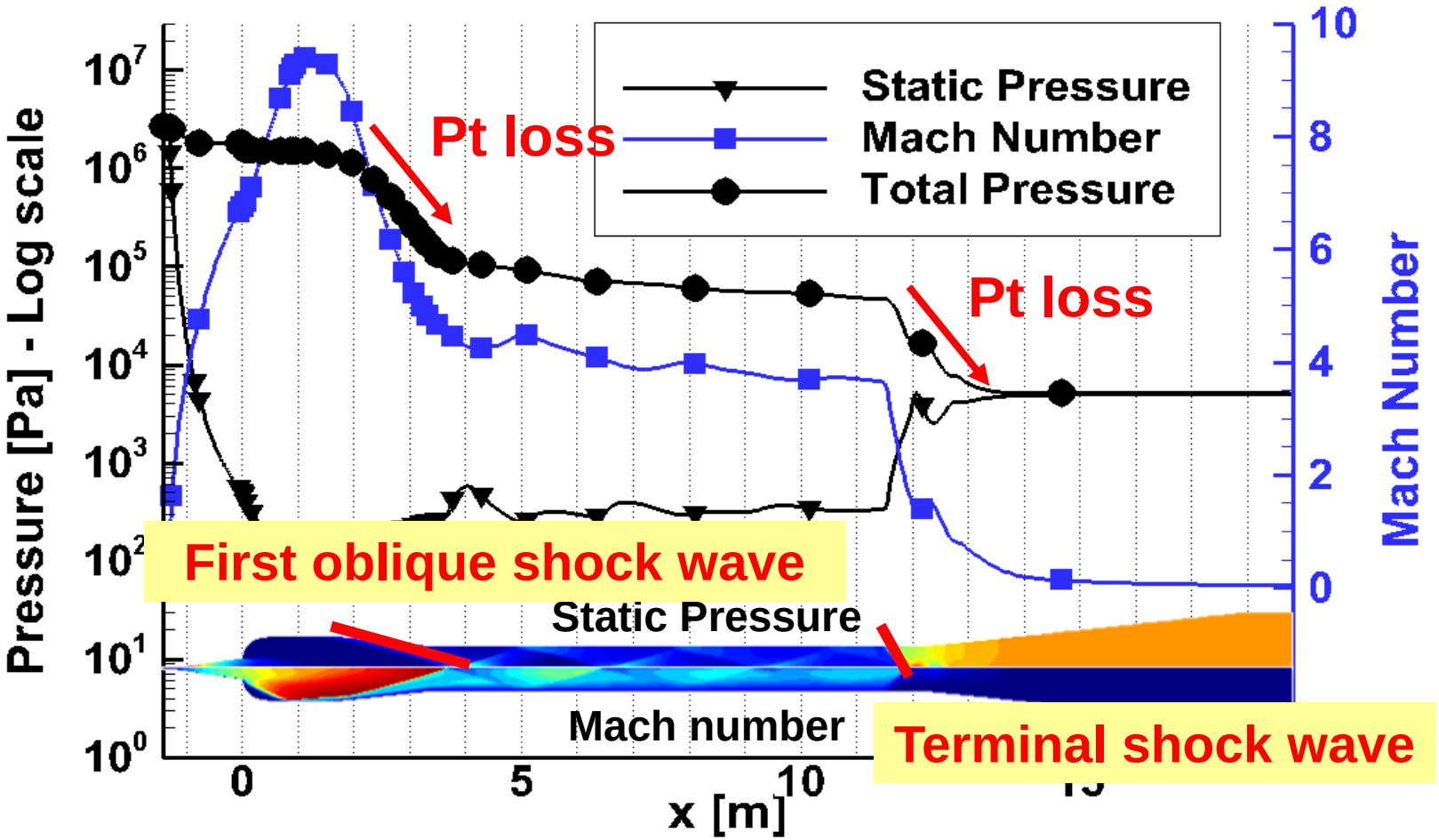
- **(Inflow) NASA Langley AHSTF [16]**
  - **13MW Arc-Heated Scramjet Test Facility**
  - **Based on reservoir condition of Mach 6**
  - **Replace Mach 6 nozzle with Mach 7 nozzle**

< Inflow conditions and Nozzle exit Mach number >

Nozzle inlet (Inflow B.C.)	P_0	28.6 bar
	T_0	2216 K
	$\dot{m}$	2.04 kg/s
Nozzle exit	M	7.0

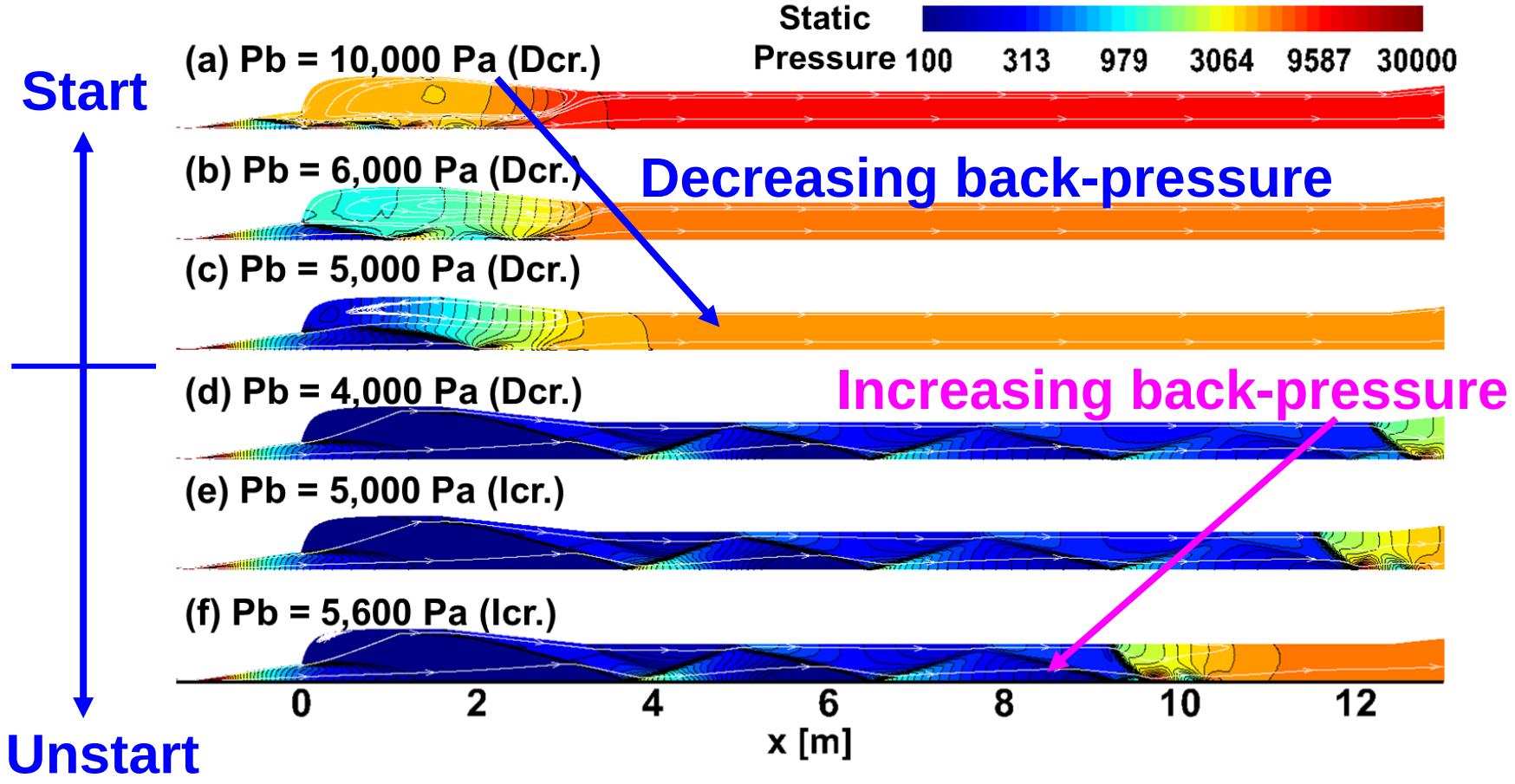
Flow Analysis of Nozzle-Diffuser System

Flow Distribution (General Aspect)



< Flow distributions of pressure, Mach number, and total pressure >

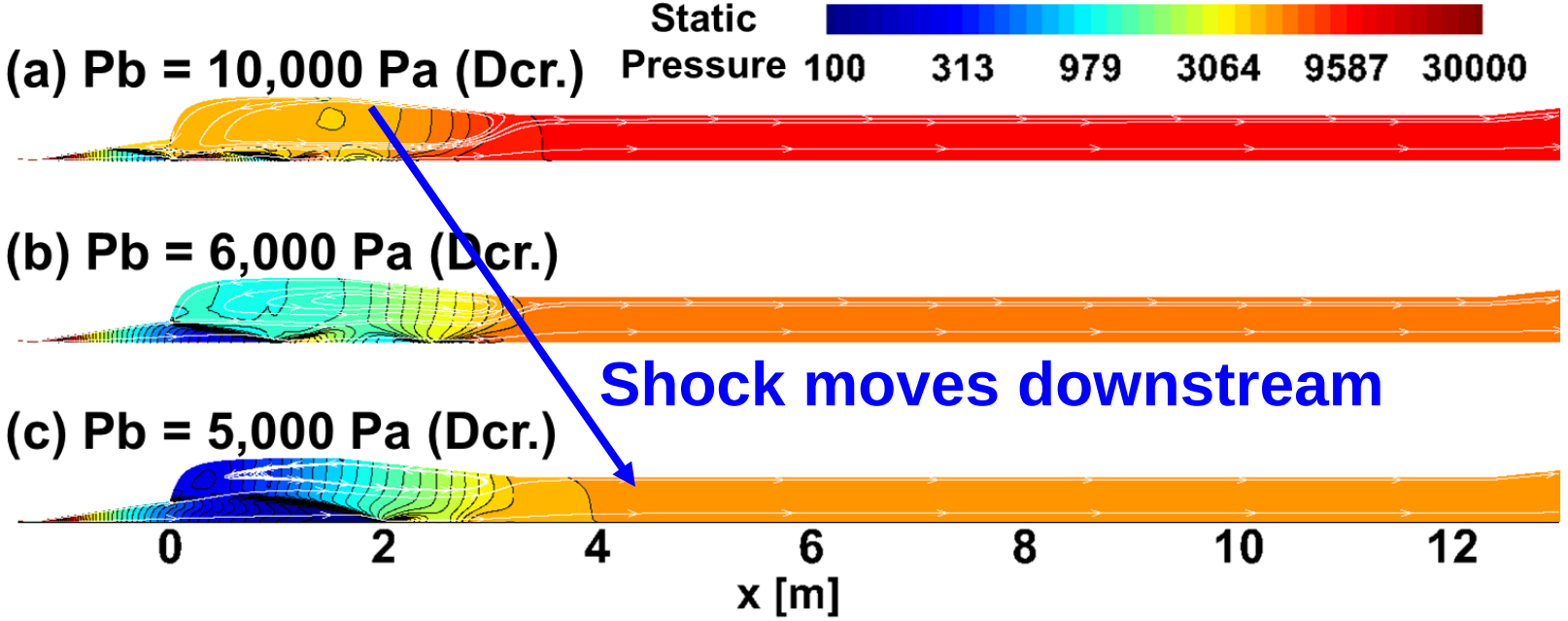
Varying Back-pressures



< Pressure distribution with different back-pressure >

Varying Back-pressures

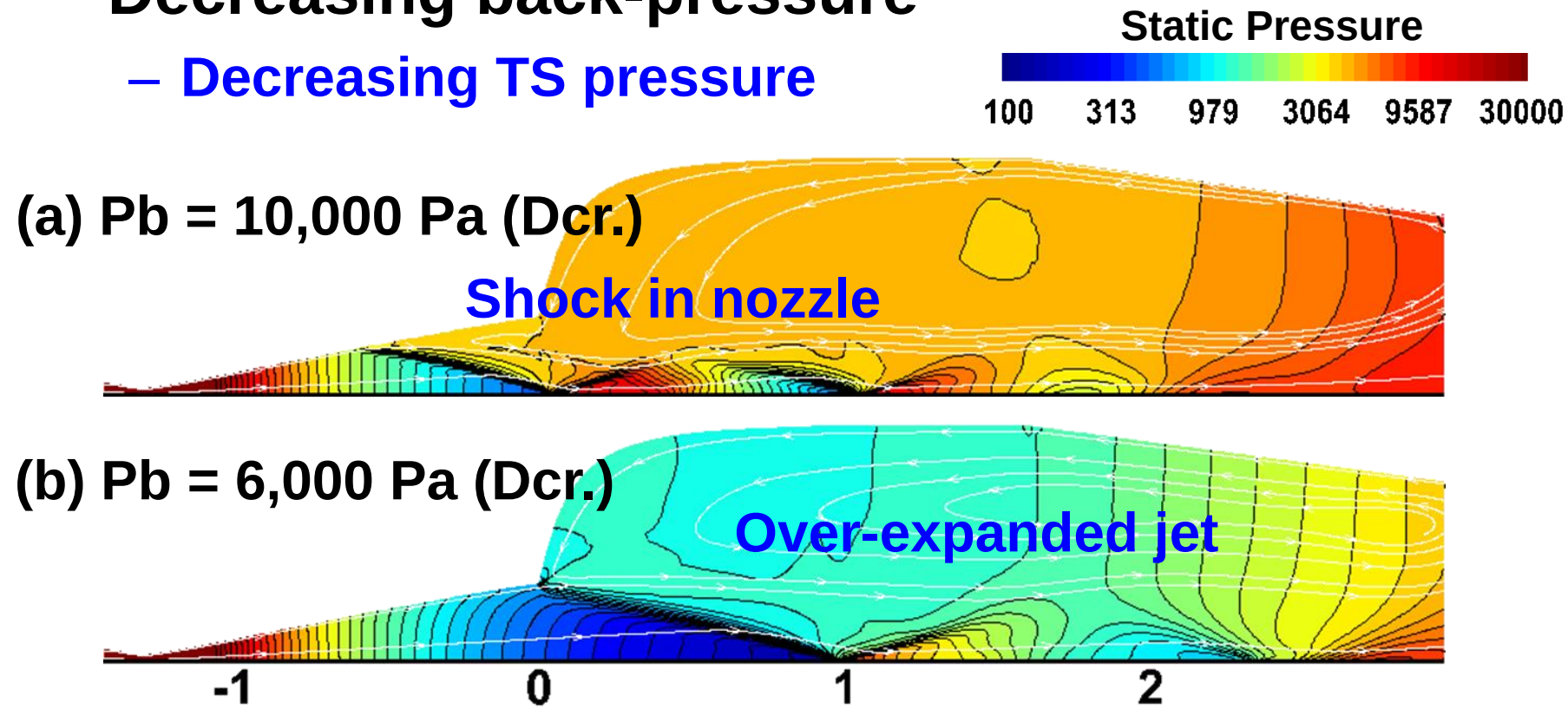
- **Decreasing back-pressure**
  - **Before wind tunnel starting**



< Pressure distribution with different back-pressure (Decreasing) >

Varying Back-pressures

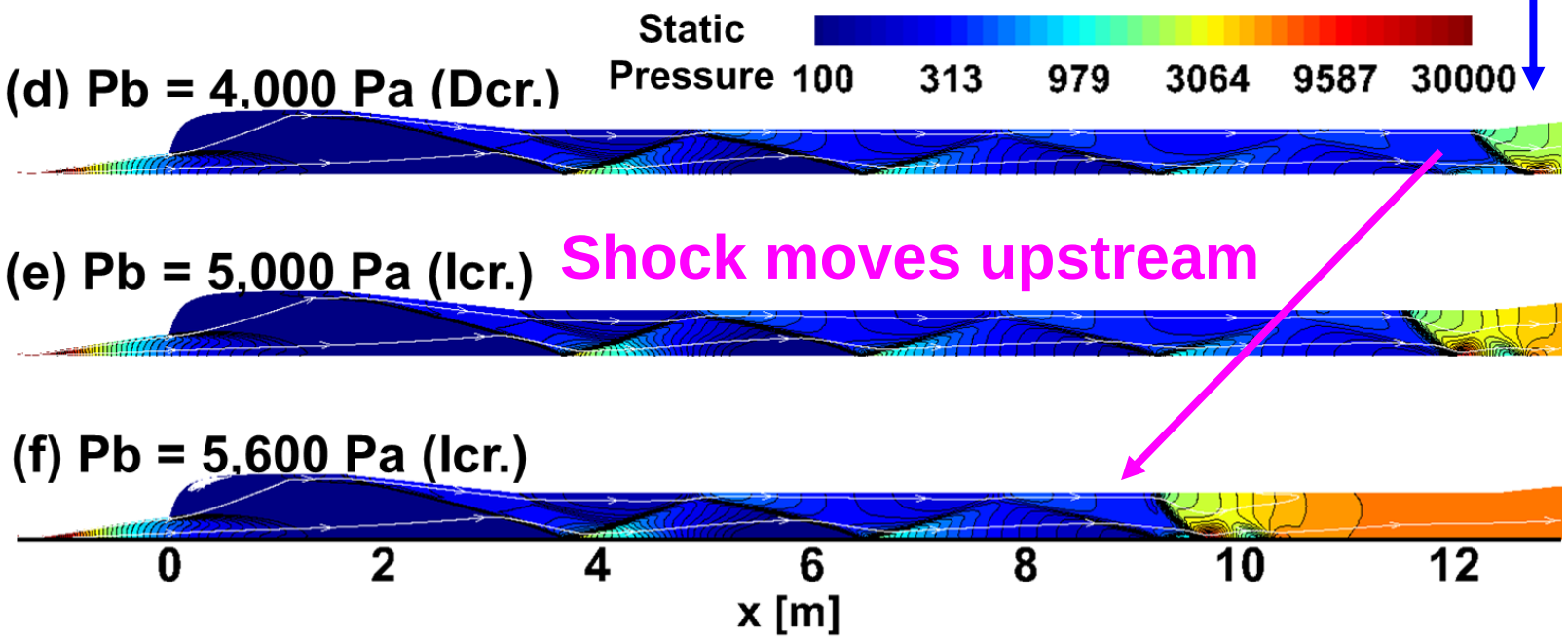
- **Decreasing back-pressure**
  - **Decreasing TS pressure**



< Pressure distribution of nozzle and test section before starting >

Varying Back-pressures

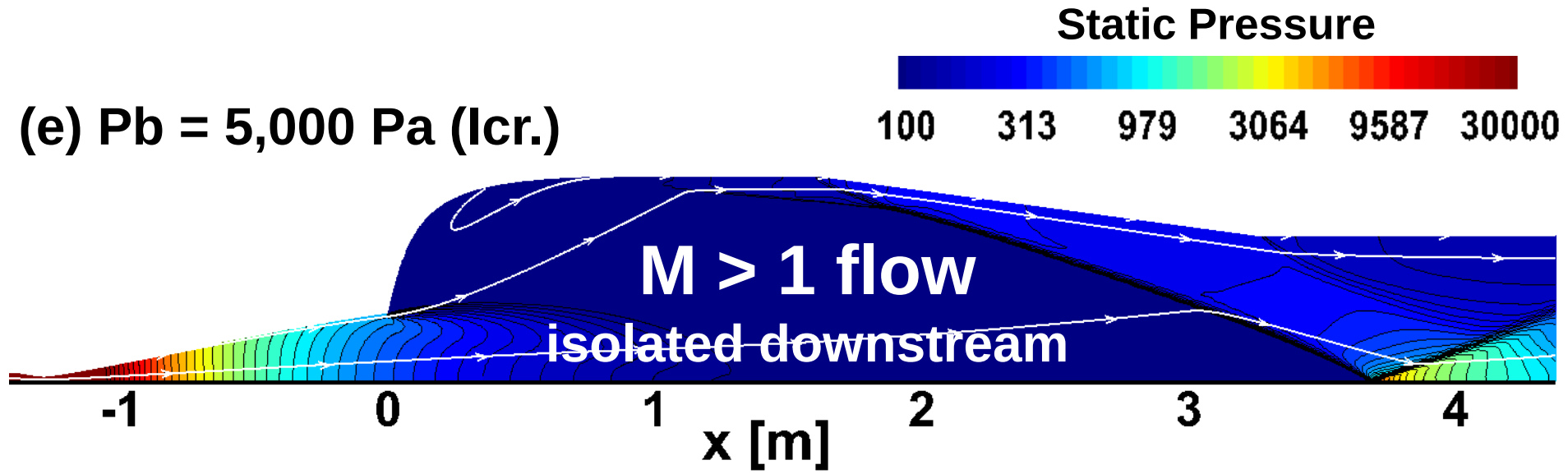
- **Increasing back-pressure**
  - **After wind tunnel starting**



< Pressure distribution with different back-pressure (Increasing) >

Varying Back-pressures

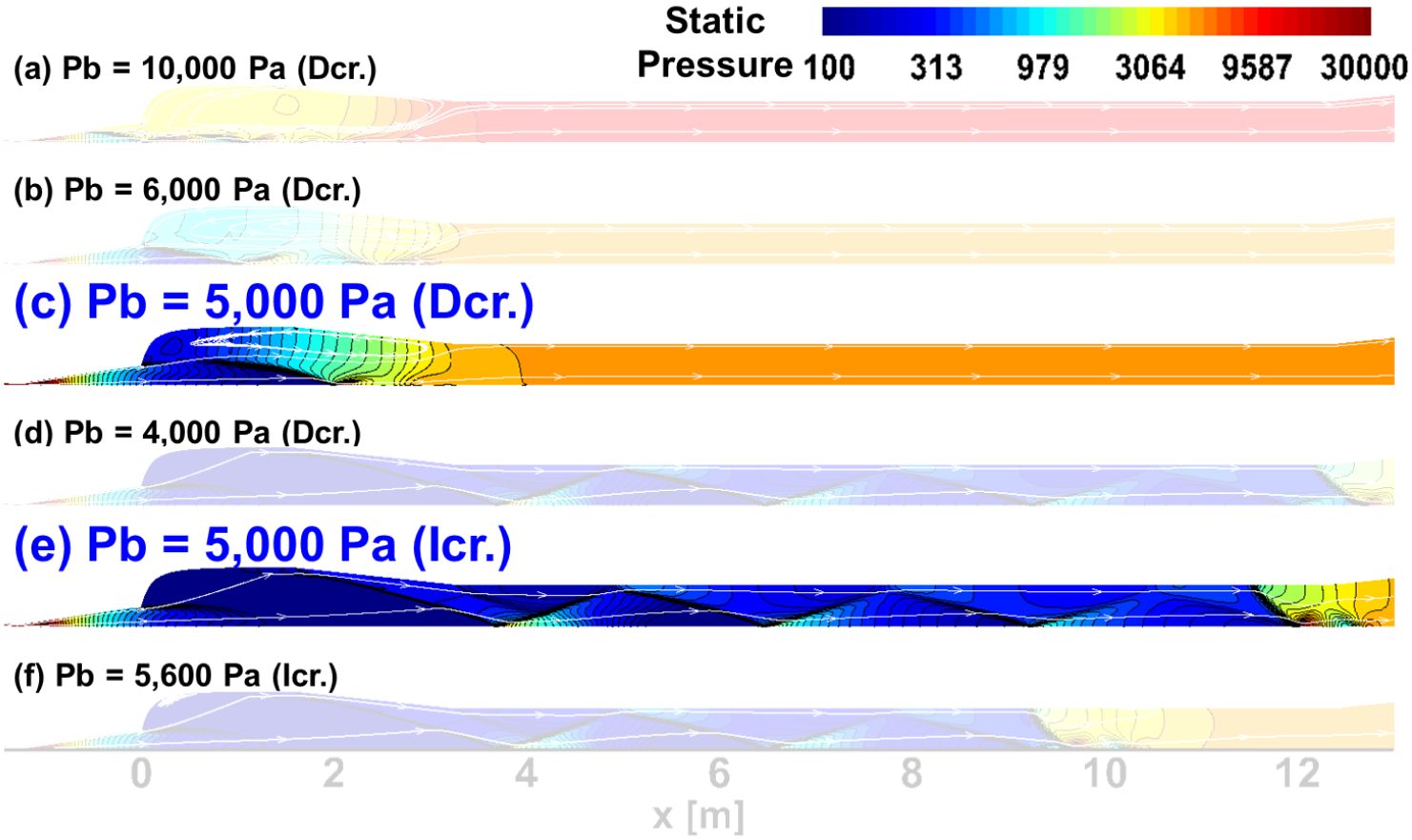
- **Increasing back-pressure**
  - **Under-expanded flow at the nozzle exit**
  - **TS isolated to downstream condition**



< Pressure distribution of nozzle and test section after starting >

Starting Characteristics

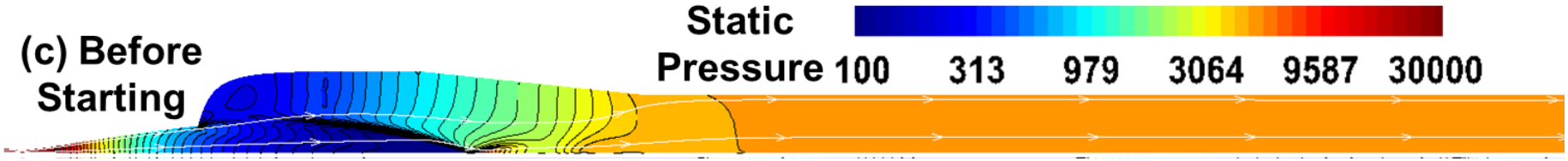
Starting Characteristics

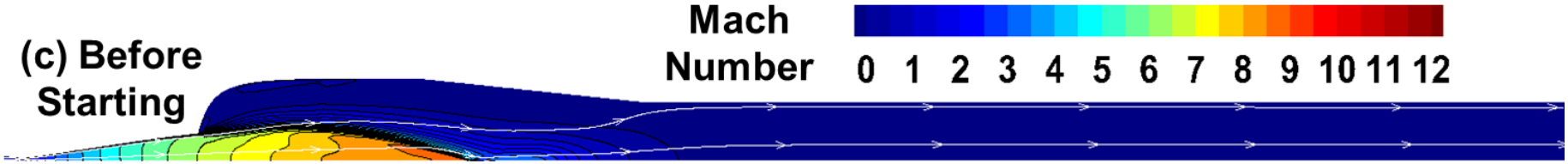


< Pressure distribution with different back-pressure >

Starting Characteristics

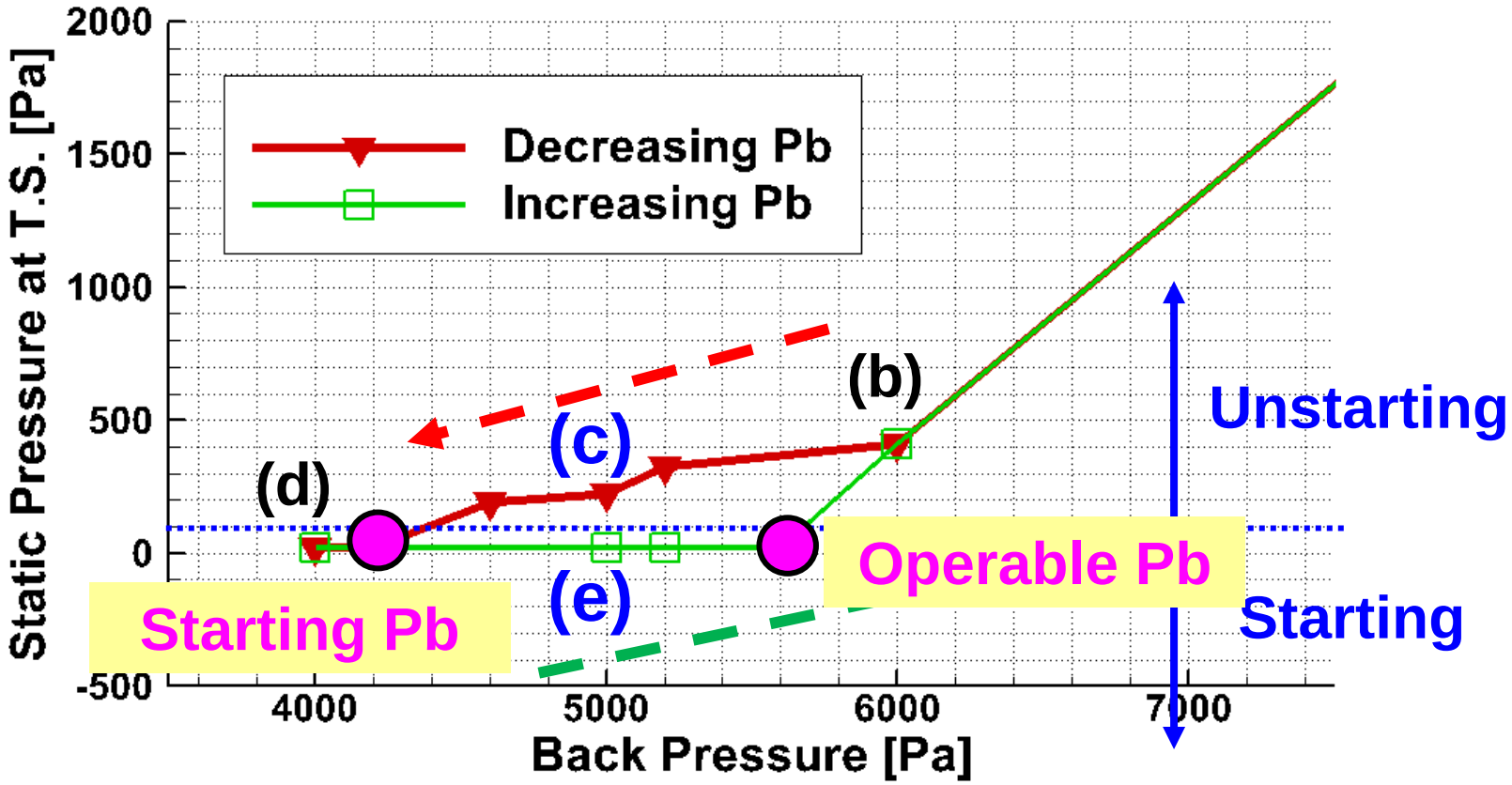
- **Hysteresis**
  - **Dependence of the state on its history**





< Different flow distribution at same back-pressure of 5,000 Pa>

Starting / Operable back-pressure

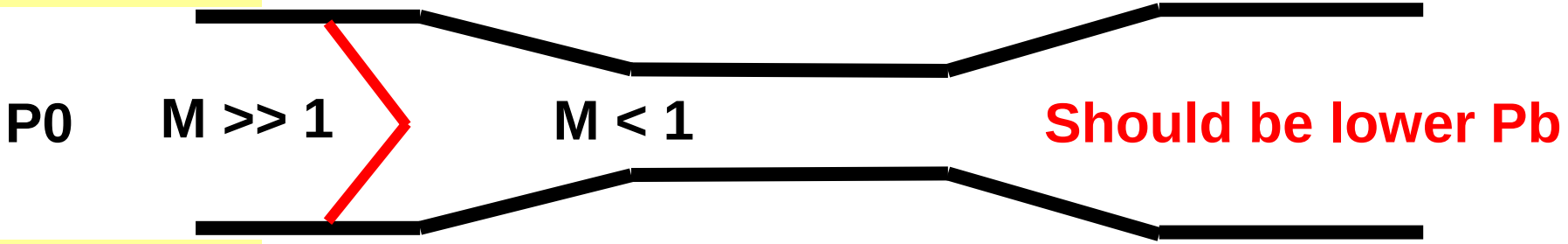


< Pressure at TS (x = 0.5 m) with different history of back-pressure >

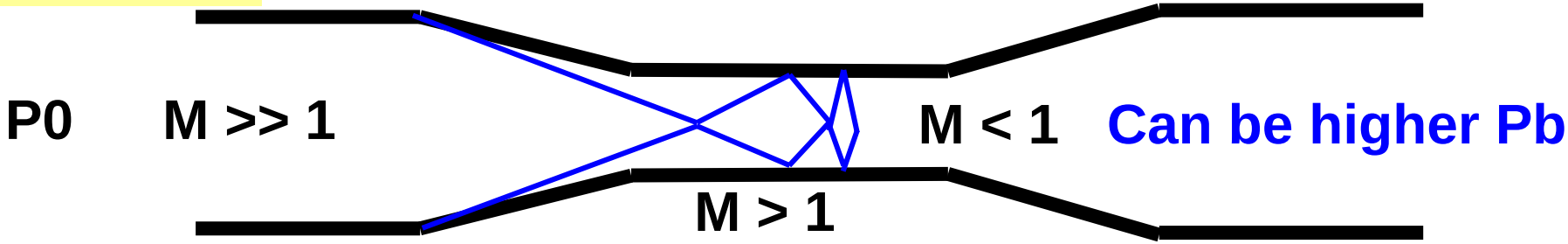
Wind Tunnel Starting

- **Required pressure ratio ~ loss in PWT**
  - **Loss in starting state < Loss in unstarting state**

Unstarting **Strong shock wave → severe loss**



Starting **Series of weak shock waves → less loss**



Conclusion

Summary

- **Investigate the flow in PWT**
  - **Identifying severe total pressure loss**

- **Investigate starting characteristics**
  - **Identifying**
    - **(1) Maximum operable back-pressure**
    - **(2) Starting back-pressure**
    - **(3) Hysteresis**
  - **Necessary to consider hysteresis**

Future Works

- **Unsteady calculation**
  - **Considering starting scenario**
  - **Compare to step-by-step steady calculation**

- **Study “Hot” flow condition**
  - **Temperature > 4,000 K**
  - **Nonequilibrium effect**

Thank you for your attention.

Reference

- **Type of Wind Tunnel - 5p**

[1] D. M. Smith, E.J. Felderman, F.L.Shope, (2002) 'Arc-Heated Facilities'

- **Characteristics of PWT - 6p**

[2] Savino, R., Monti, R. and Esposito, A. (1999) 'Behaviour of hypersonic wind tunnels diffusers at low Reynolds nwaabers', Aerospace Science and Technology, (1), pp. 11–19.

- **Characteristics of PWT - 7p**

[3] B. Monnerie, Study of a family of diffusers for a low-Reynolds-number hypersonic wind tunnel (Diffuser use in low density hypersonic wind tunnel and method of evaluating global performance for diffusers with conical inlet followed by cylindrical mixing section), LA RECH. AEROSP. (1967) 9–16.

[4] R.S Pugazenthi and Andy C. McIntosh (2011) 'Design and Performance Analysis of a Supersonic Diffuser for Plasma Wind Tunnel'. doi: doi.org/10.5281/zenodo.1330939.

[5] T.A. Shams, S.I.A. Shah, M.A. Ahmad, Capability Analysis of Global Hypersonic Wind Tunnel Facilities for Aero-thermodynamic Investigations, in: Proc. 2020 17th Int. Bhurban Conf. Appl. Sci. Technol. IBCAST 2020, 2020: pp. 481–501. https://doi.org/10.1109/IBCAST47879.2020.9044523.

- **Motivation - 8p**

[6] R. Monti, D. Paterna, R. Savino, A. Esposito, Low-Reynolds number supersonic diffuser for a plasma-heated wind tunnel, Int. J. Therm. Sci. 40 (2001) 804–815. DOI: 10.1016/S1290-0729(01)01267-4.

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