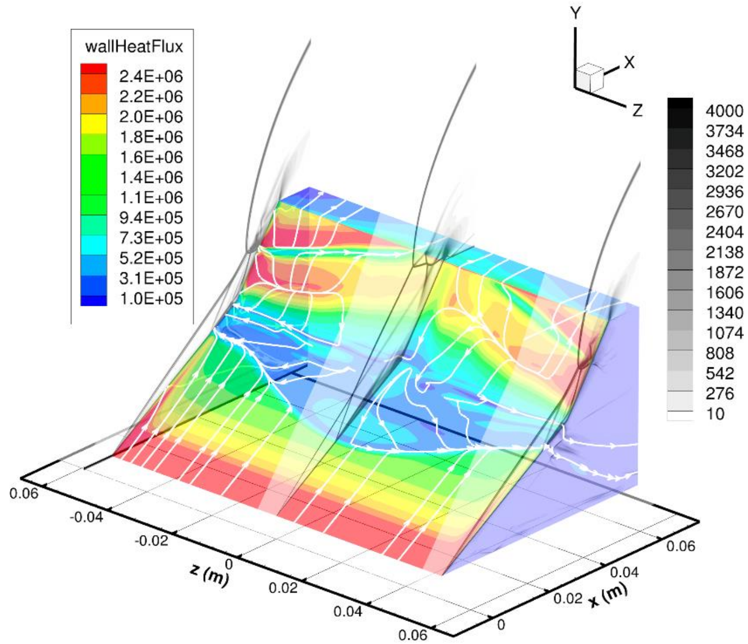
Effect of Spanwise Instabilities on Hypersonic Flows

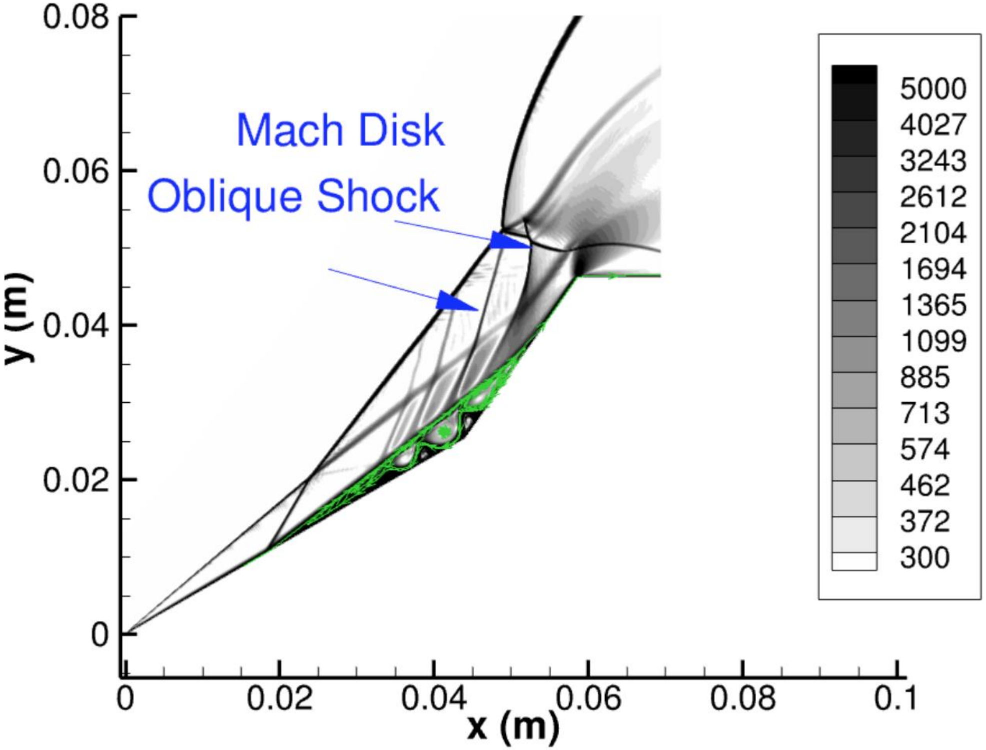


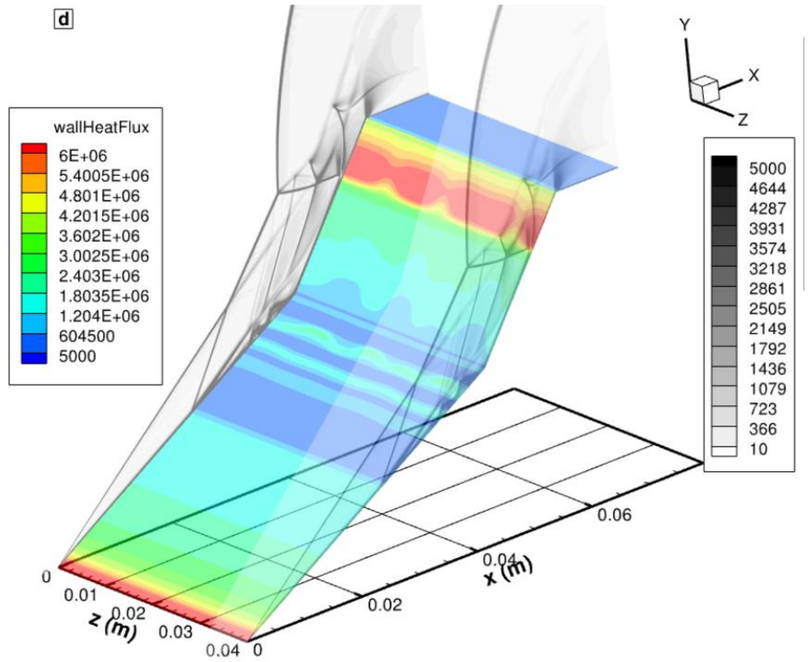
Ozgur Tumuklu

Rensselaer Polytechnic Institute

AIAA Paper 2024-3834

Motivation

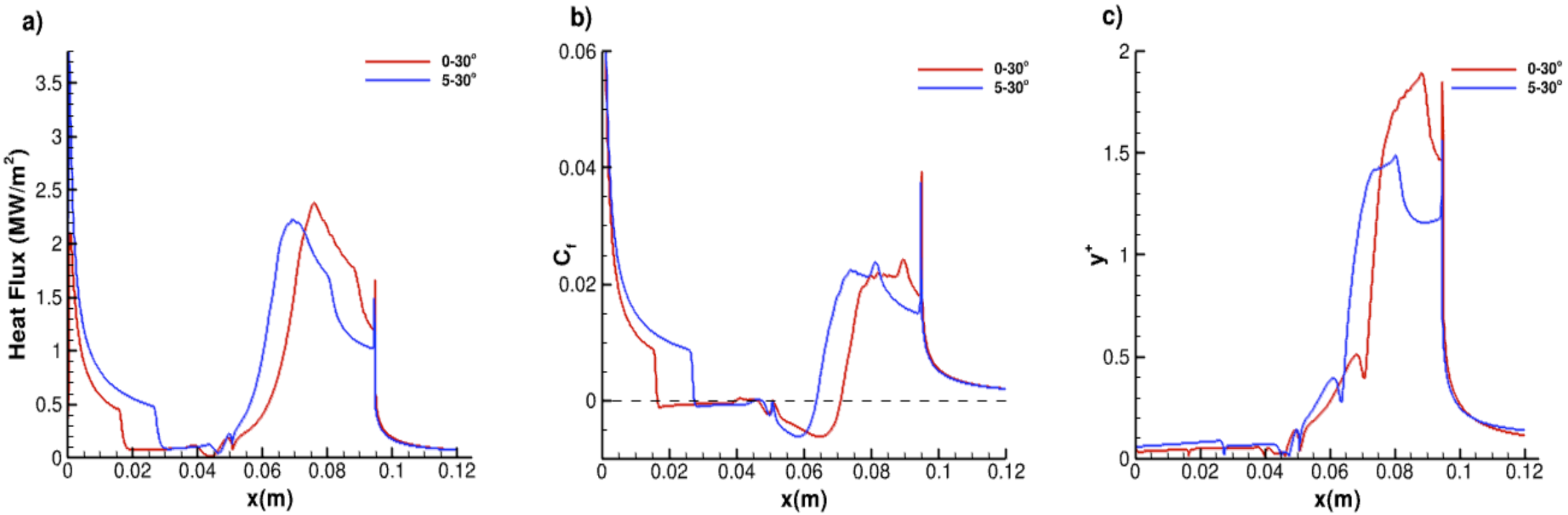




This works briefly aims to:

- investigate the *self-induced* **instabilities** resulted from complex shock wave boundary layer interactions (SWBLIs) over double wedges.
- estimate **temporal characteristics** of flows to provide data to experimentalists using 2-D and full 3-D configurations at different wedge angles.
- characterize the 3D instabilities with different Reynolds numbers and wedge angles.

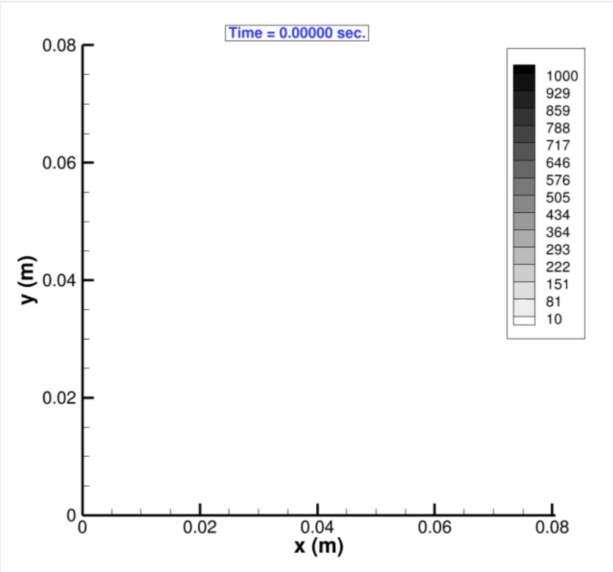
Variation of the Flow Field with Wedge Deflection Angles



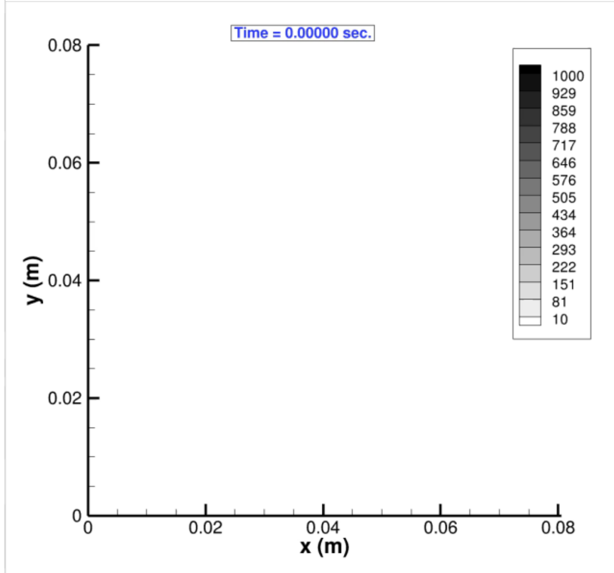
- **Edney VI** interactions significantly alter the spatial distribution of flow structures.
- The vibrational temperatures are too low to clearly observe **the real gas effects**.
- The size of the separation region is reduced for the 5-30^o configuration.
- A larger separation region in the former case shifts the skin friction maxima downstream.

Variations of 2D Self-induced Shock Oscillations* with P_∞ = 196 Pa at Mach = 7.1

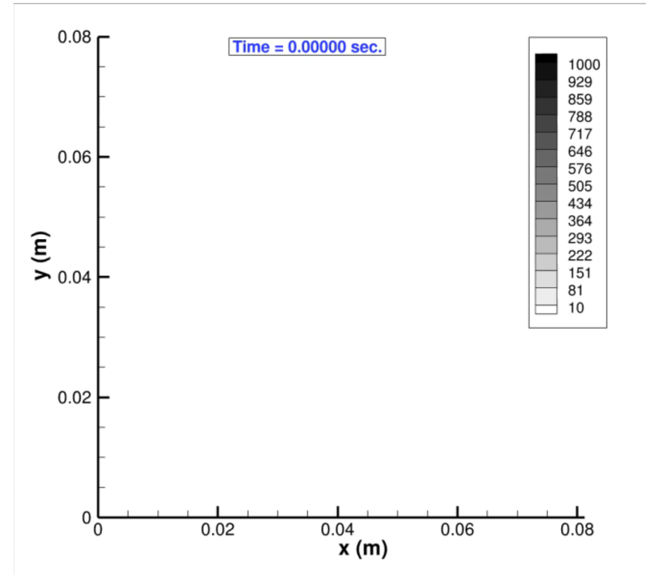
P_∞ = 150 Pa



P_∞ = 175 Pa



P_∞ = 196 Pa

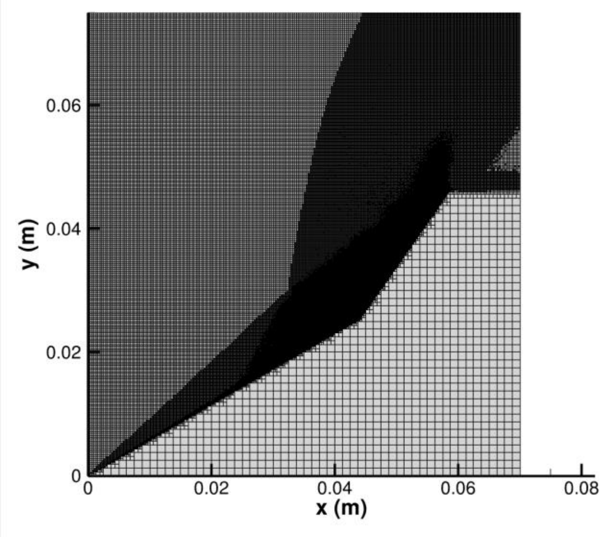


- The **self-induced oscillations** are observed at moderate pressure cases at Mach= 7.1.
- The presence of a **Mach disk** is obvious for all cases**.**

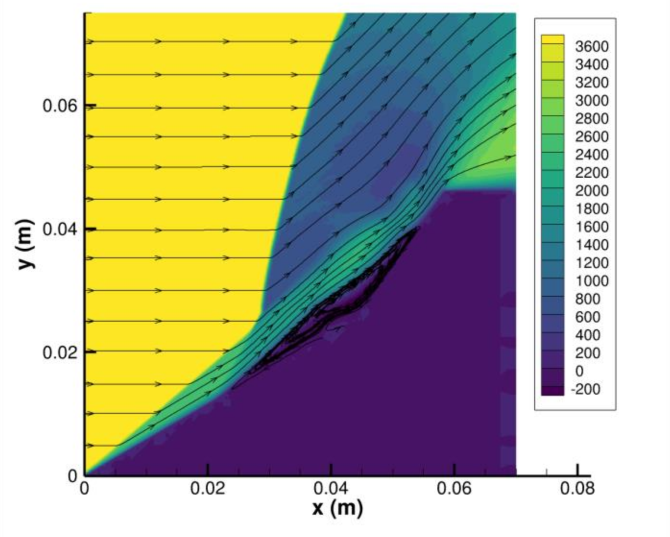
* Ben-Dor, G., Vasilev, E., Elperin, T., and Zenovich, A., "Self-induced oscillations in the shock wave flow pattern formed in a stationary supersonic flow over a double wedge," Physics of Fluids, Vol. 15, No. 12, 2003, pp. L85–L88

Kinetic Modeling of Hysteresis Processes

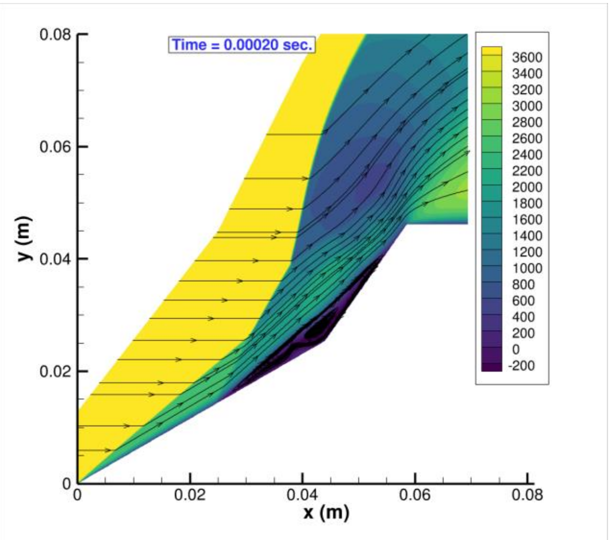
DSMC Mesh



Kinetic Solver (DSMC)



Continuum Solver

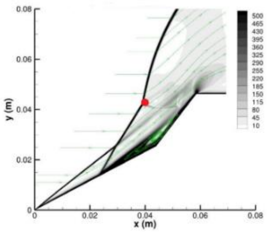


- The **SPARTA** DSMC* solver, developed by Sandia, is used to validate the 2D hysteresis process over the double cone.

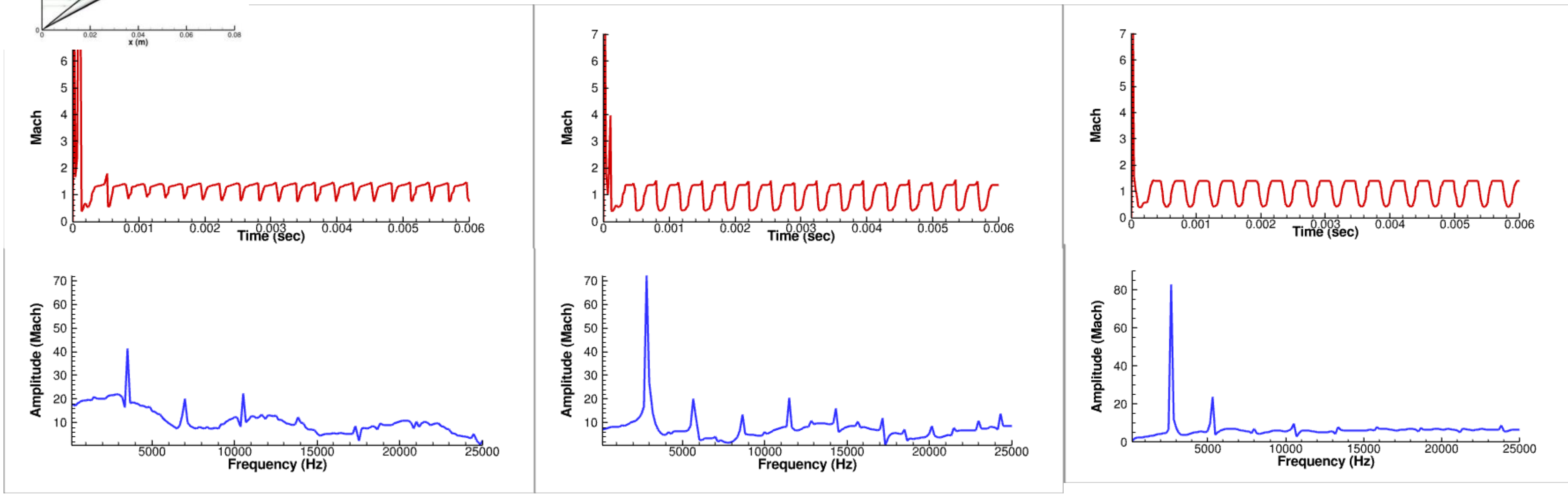
- Ongoing simulations demonstrate that the **hysteresis phenomenon** is also observed using kinetic approach.

* Direct Simulation Monte Carlo on petaflop supercomputers and beyond, S. J. Plimpton, S. G. Moore, A. Borner, A. K. Stagg, T. P. Koehler, J. R. Torczynski, M. A. Gallis, Physics of Fluids, 31, 086101 (2019).

Hysteresis Process at Mach = 7.1



P_∞ = 150 Pa | P_∞ = 175 Pa | P_∞ = 196 Pa

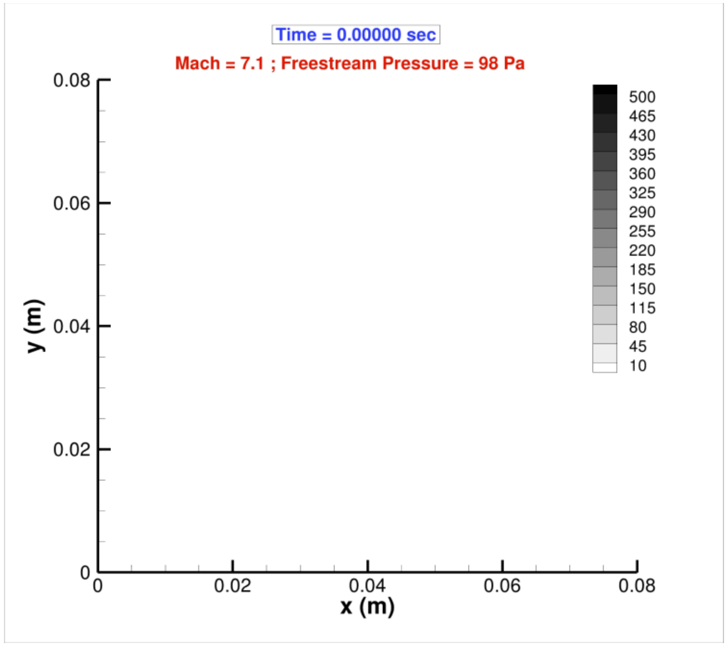


Flow	1st mode [Hz]	2nd mode [Hz]	3rd Mode [Hz]	4th Mode[Hz]
P_∞ = 150 Pa	3483	6970	10509	138034
P_∞ = 175 Pa	2820	5684	8673	11508
P_∞ =196 Pa	2666	5337	8007	10460

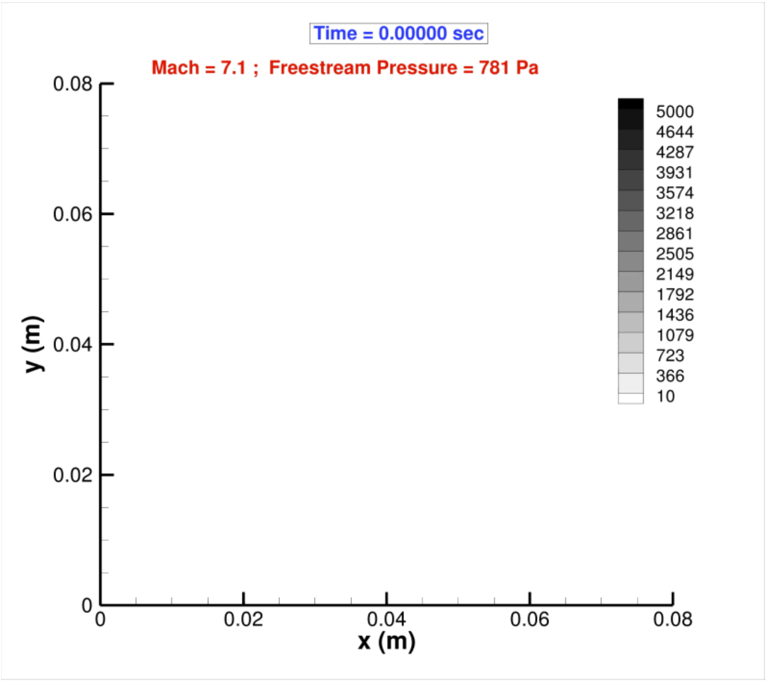
- The frequency of the oscillations tends to decrease with pressure.
- The dominant frequency remains nearly constant across different Mach numbers (not shown).
- More detailed analysis will be presented by S. Pan (AIAA-2024-4188) in the Modal Flow Analysis session tomorrow.

Shock Steadiness at Lower and Higher Pressures*

P_∞ = 98 Pa



P_∞ = 781 Pa**



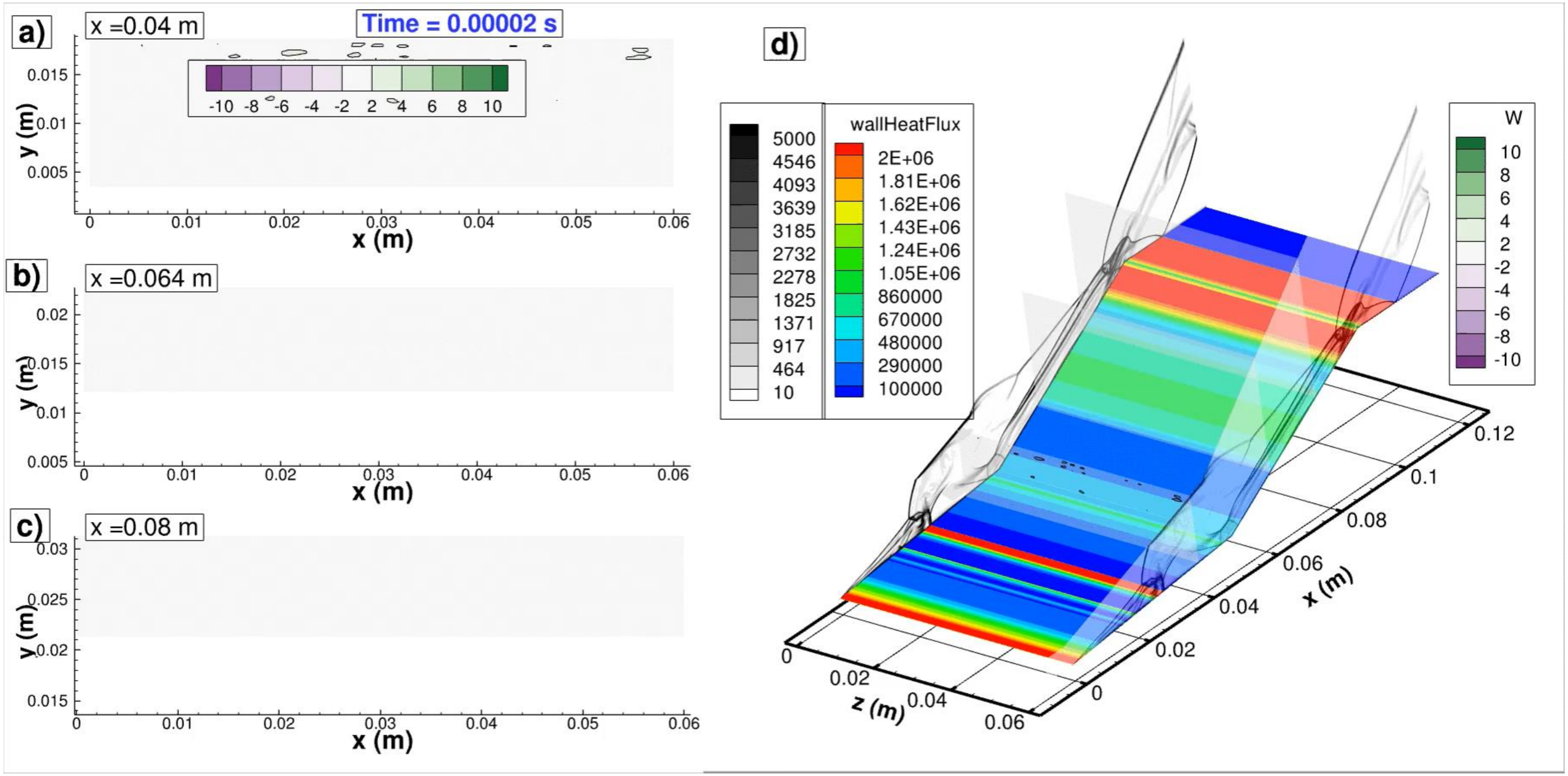
- The lowest pressure case reaches steady state at about 0.75 ms, consistent with the previous DSMC simulation.

- The oscillations disappear for the P_∞ =780 Pa (Joanna Austin's experiment**) case but flow reaches steady state about 2 ms (**10X times** larger than the duration of the experiment).

*Tumuklu, O., & Hanquist, K. M. (2023). Temporal characteristics of hypersonic flows over a double wedge with Reynolds number. *Physics of Fluids*, *35*(10).

**Swantek, A., and Austin, J., "Flowfield establishment in hypervelocity shock-wave/boundary-layer interactions," AIAA Journal, Vol. 53, No. 2, 2015, pp. 311–320.

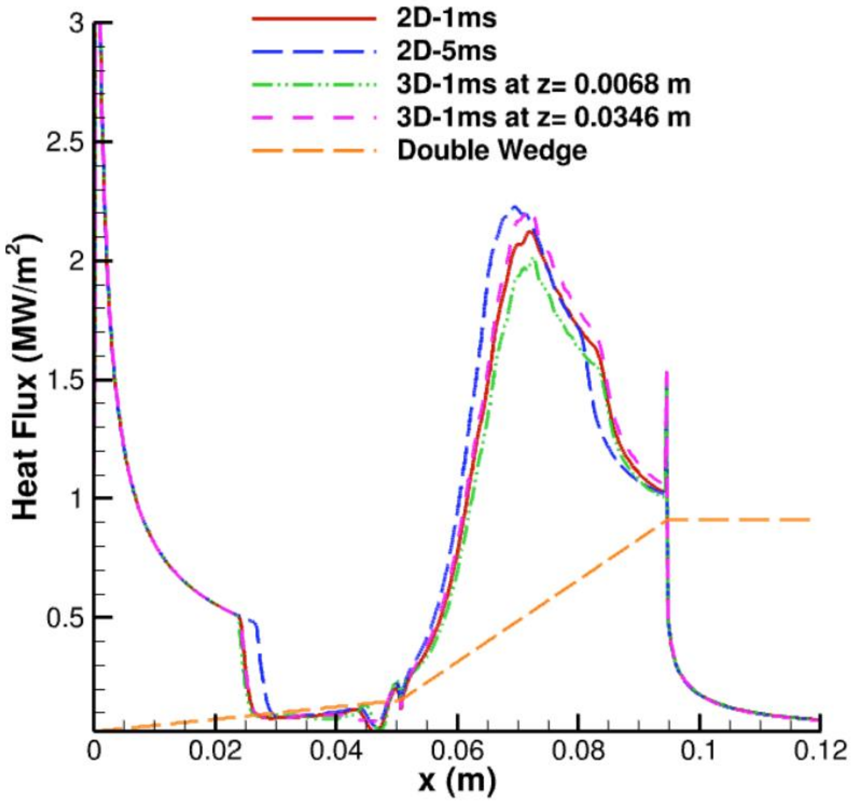
3-D Effects over the 5º-30º Configuration 1/2

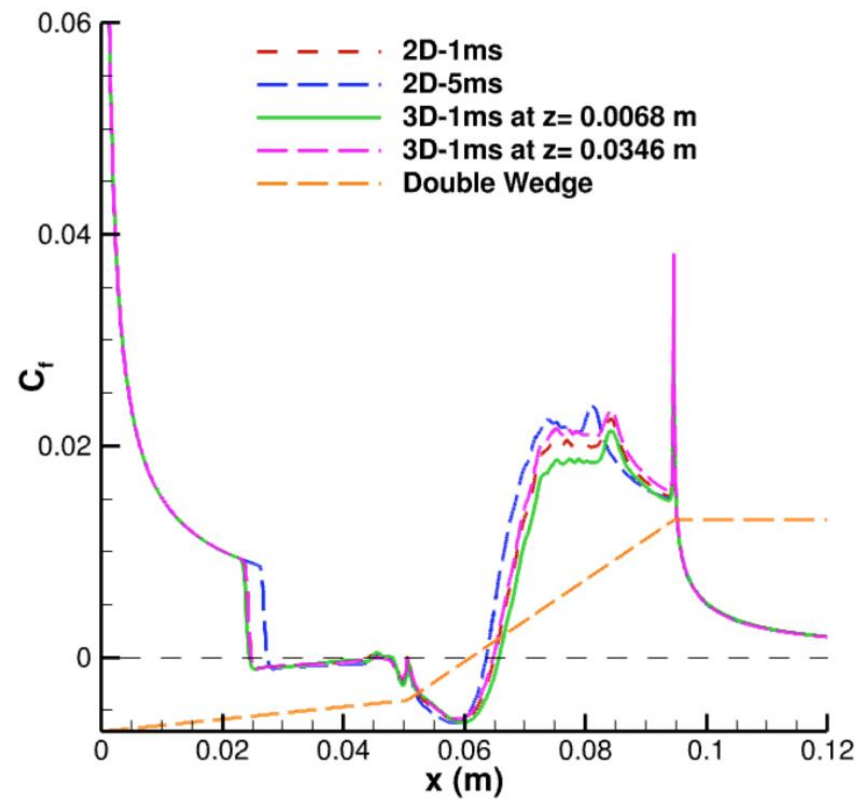


- The magnitude of the spanwise velocity decreases in the downstream direction, indicating that the magnitude of the vortices is maximum in the separation region.

- The spanwise instabilities are not **stationary.**

3-D Effects over the 5º-30º wedge 2/2



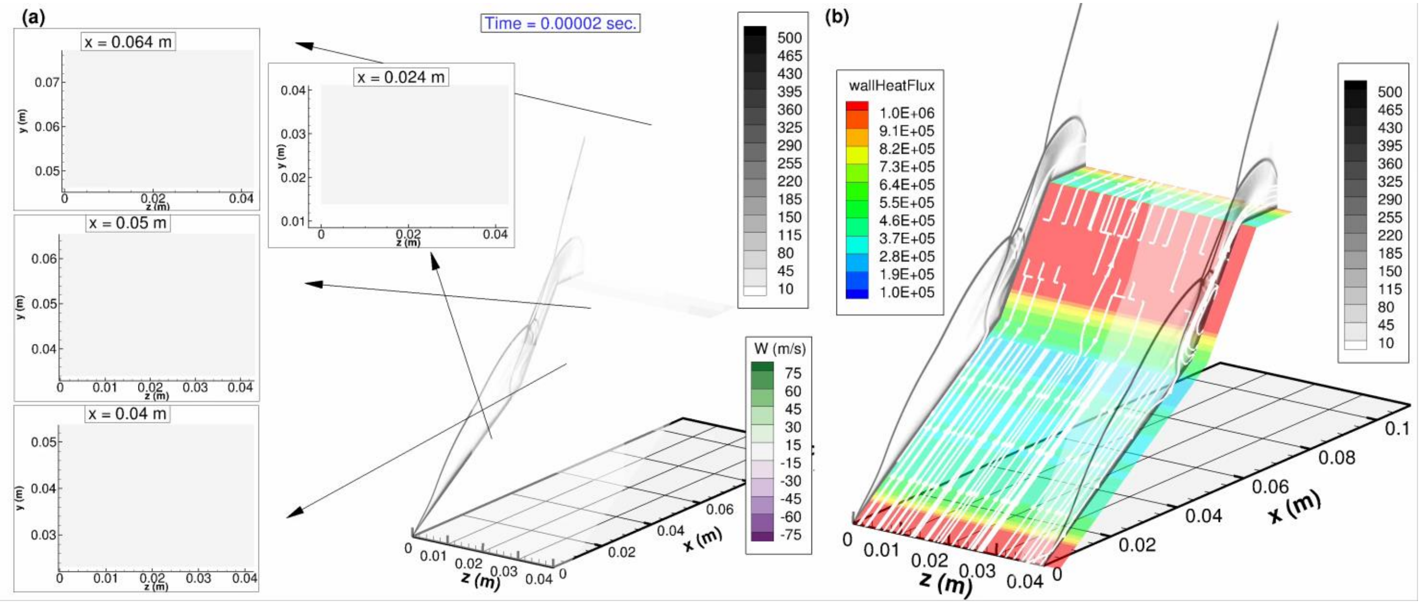


- The spanwise velocities display an almost oscillatory pattern, while the pressure field decreases within the separation region and increases at the reattachment point.

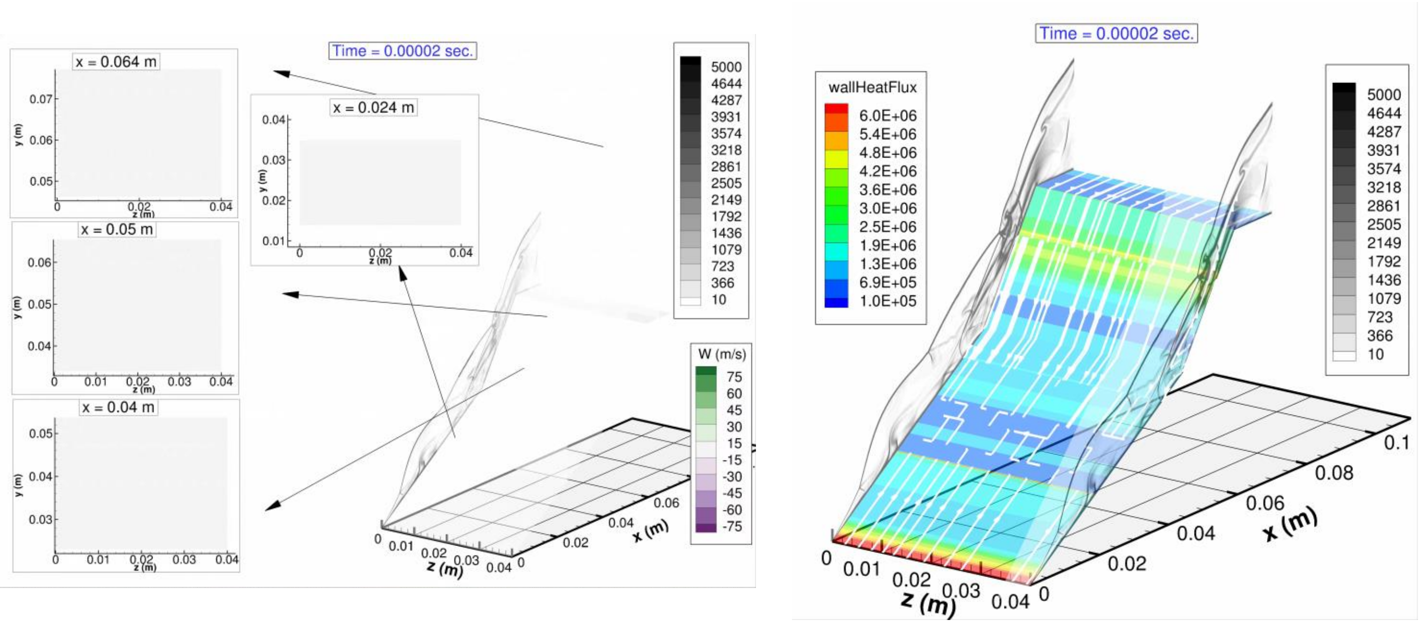
- The heating values vary by approximately 10% in the spanwise direction, and the maxima align closely with predictions from the 2D model.

Freestream Pressure Effects on Instabilities

P_∞ = 98 Pa

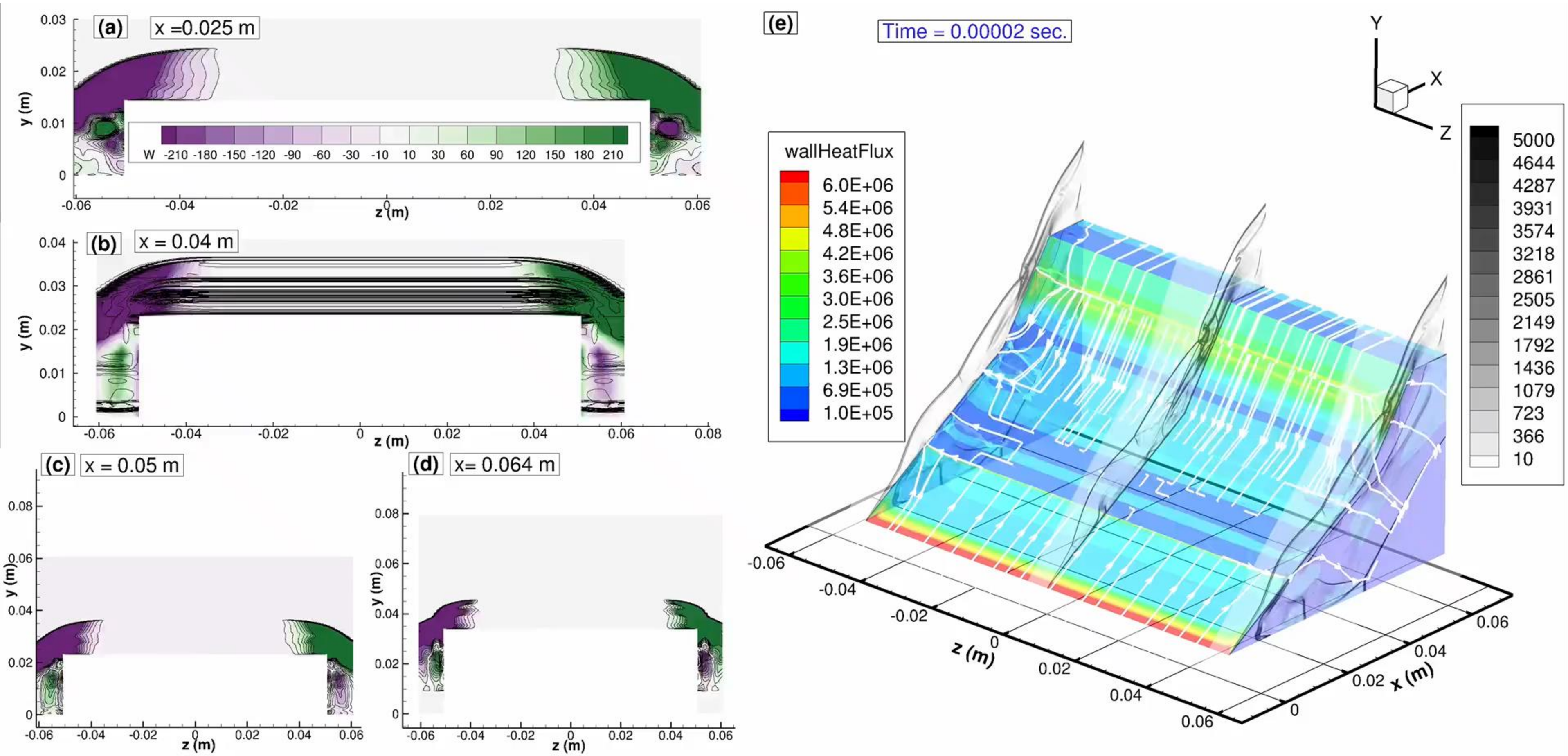


P_∞ = 781 Pa



Full 3D Simulations over Double Wedge at P_∞ = 781 *

P = 781 Pa

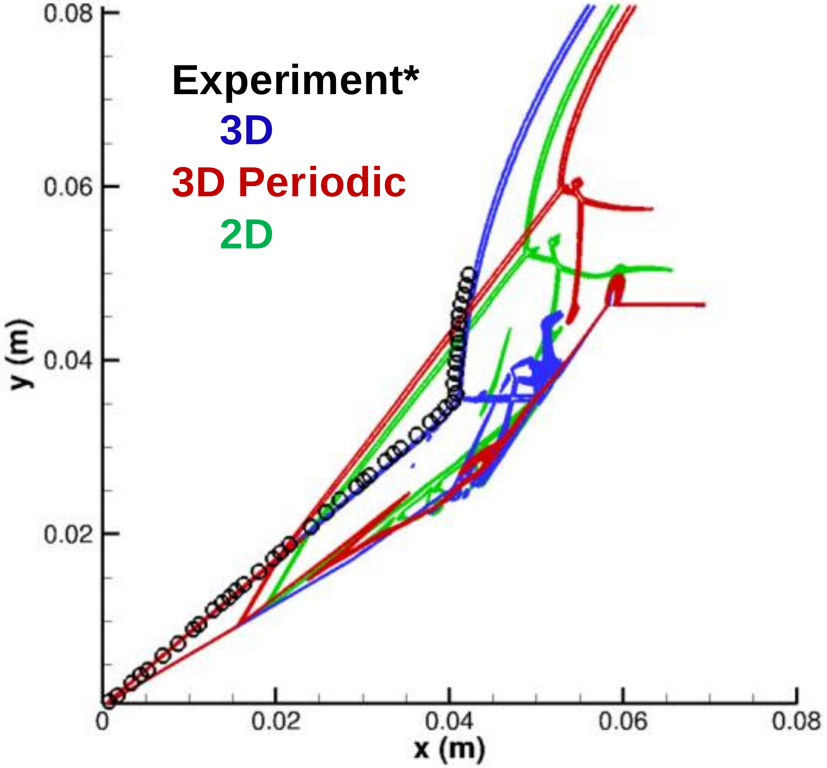


- The structure of the spanwise instabilities close to the center is found to be **similar** to 3D periodic cases.

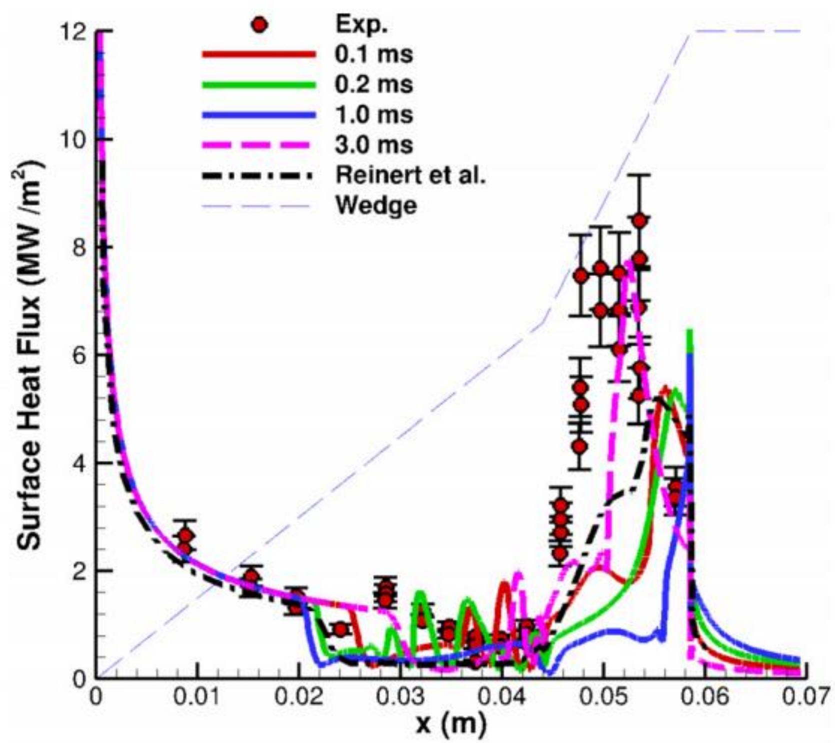
*Tumuklu, O., and Hanquist, K. M., "Temporal characteristics of hypersonic flows over a double wedge with Reynolds number," Physics of Fluids, Vol. 35, No. 10, 2023.

Effect of Geometric Configurations at $P_\infty = 781$ *

Shock Structures



3D Surface Heating

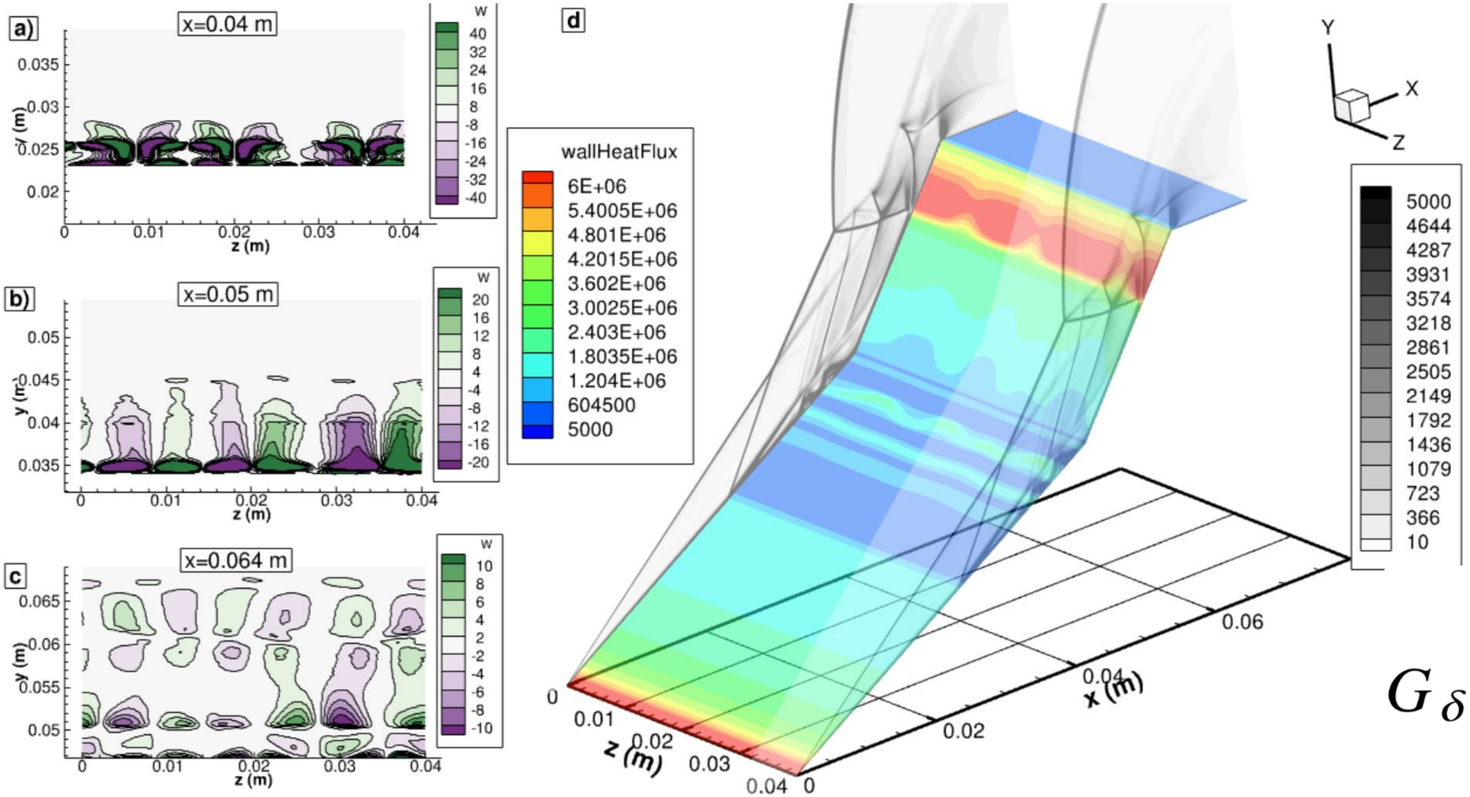


- Good agreement is achieved between the full 3D calculations and experiments.

*Tumuklu, O., and Hanquist, K. M., “Temporal characteristics of hypersonic flows over a double wedge with Reynolds number,” Physics of Fluids, Vol. 35, No. 10, 2023.

Reinert, J. D., Candler, G. V., and Komives, J. R., “Simulations of unsteady three-dimensional hypersonic double-wedge flow experiments,” AIAA Journal, Vol. 58, No. 9, 2020, pp. 4055–4067.

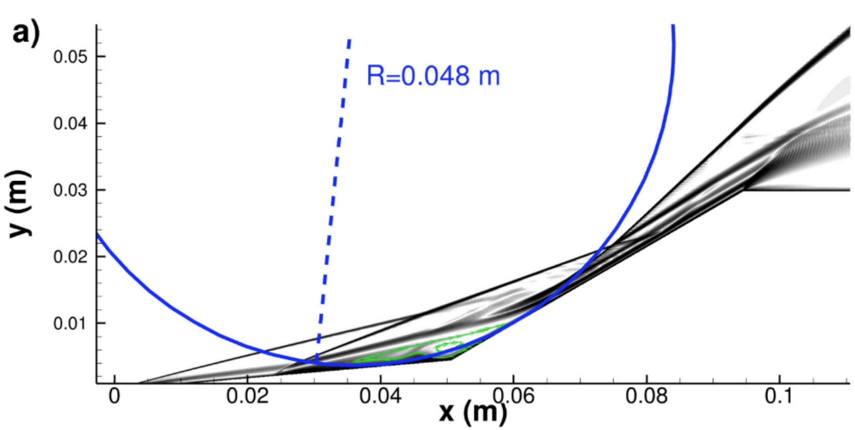
Characterization of Spanwise Instabilities

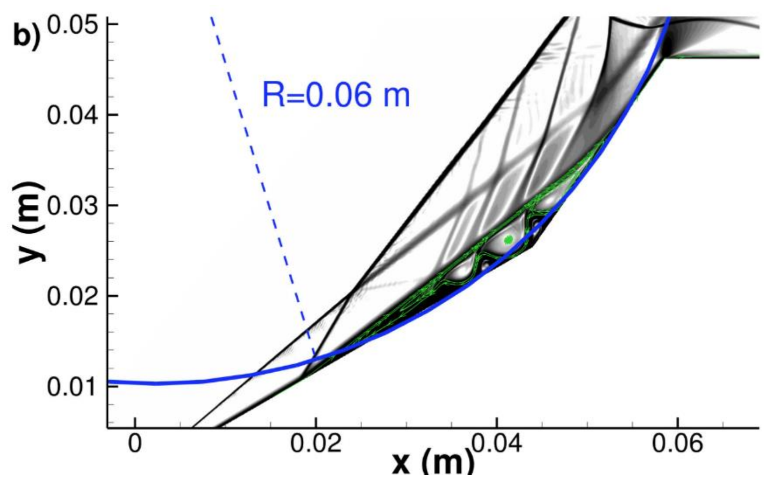


$$\beta_\delta = \frac{2\pi\delta}{\lambda}$$

$$\Lambda = Re_\lambda \left(\frac{\lambda}{R}\right)^{1/2}$$

$$G_{\delta,l} = \Lambda \left(\frac{\beta_\delta}{2\pi}\right)^{3/2}$$





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Thank you.