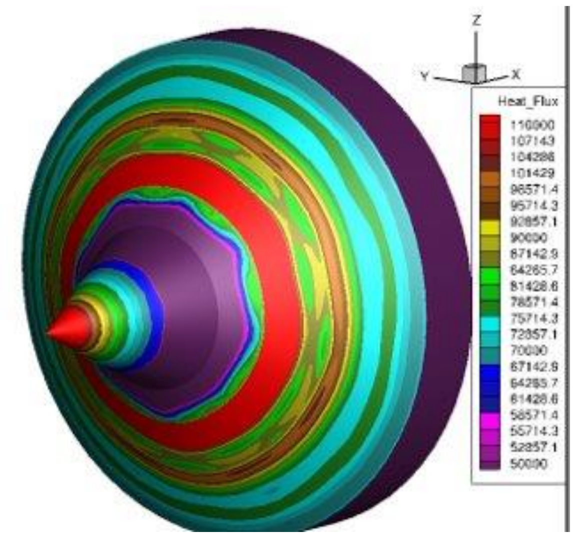
Characterization of Hypersonic Instabilities over a Double Cone



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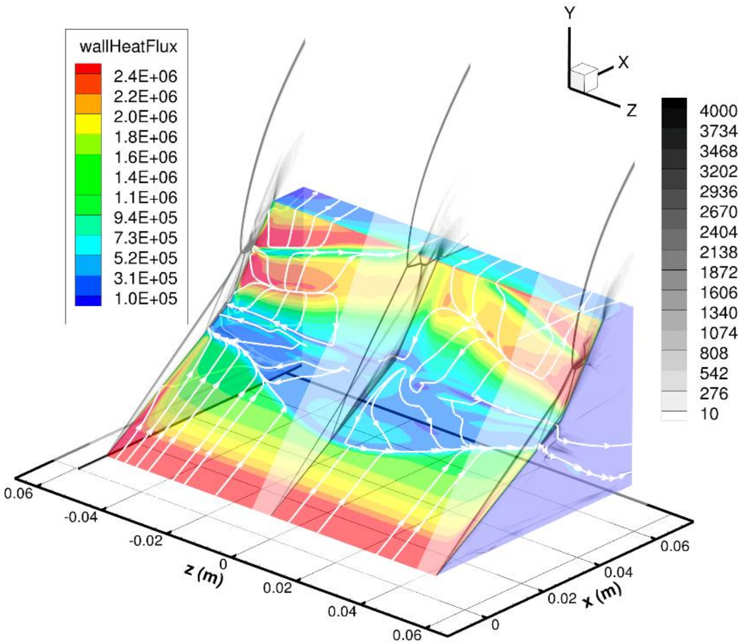
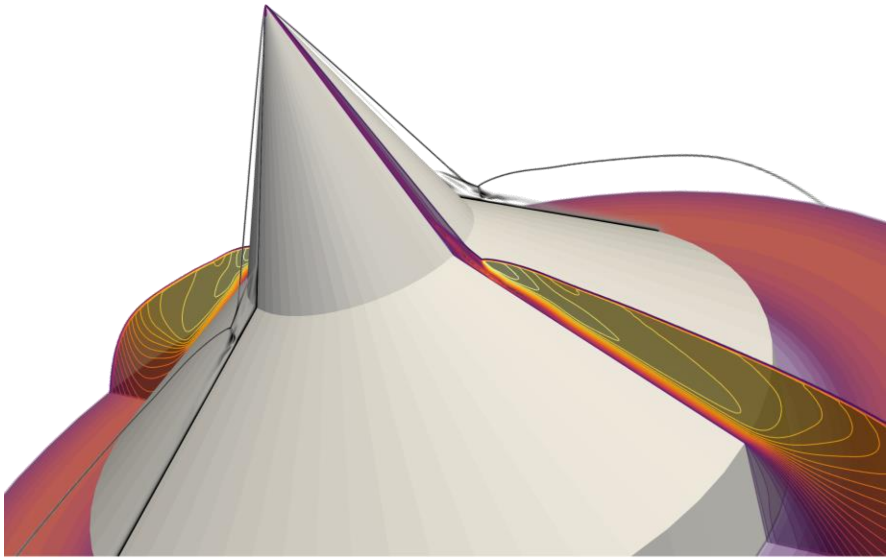
AIAA Paper 2024-1481

Background





This works briefly aims to:

- investigate the **instabilities** resulted from complex shock wave boundary layer interactions (SWBLIs) over double wedges and doubles cones.
- compare findings with measured data and high-fidelity previous DSMC simulations.
- estimate **temporal characteristics** of flows to provide data to experimentalists using 2-D and full 3-D configurations.
- characterize the 3D instabilities with different Reynolds numbers.

- An open-source frameworks*,** were used to model SWBLIs.

*Casseau,V.,Palharini,R.C.,Scanlon,T.J.,andBrown,R.E.,"Atwo-temperatureopen-source CFD model for hypersonic reacting flows, part one: zero-dimensional analysis," *Aerospace*, Vol. 3, No. 4, 2016, p. 34.

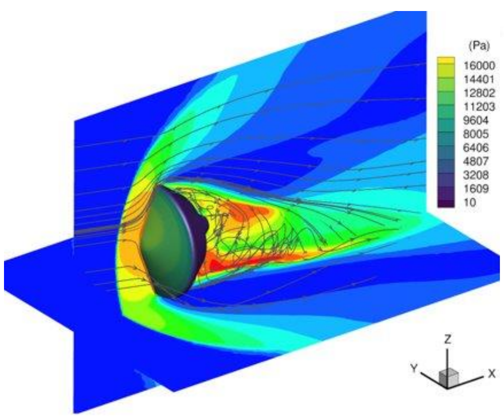
** Maier, et al., "Development of Physical and Numerical Nonequilibrium Modeling Capabilities within the SU2-NEMO Code," AIAA Paper 2023-3488.

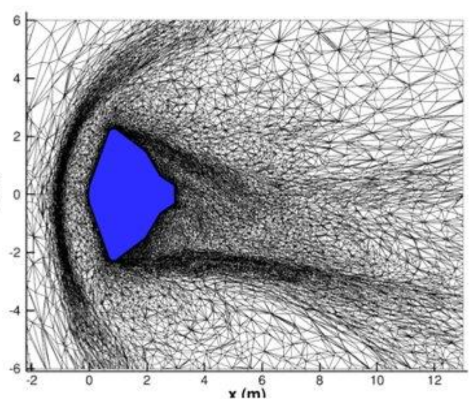
SU2-NonEquilibriumMOdels (NEMO)*

- Extension of SU2 for nonequilibrium, high-temperature, and high-speed flows,
- Continuum/slip regime, steady, viscous, multi-component, gas mixtures in thermochemical nonequilibrium,
- Finite-rate chemistry and thermal nonequilibrium,
- Catalytic wall, slip BC, and radiative equilibrium BC,
- Inherits, a lot of strengths from SU2 (design, multi-physics),
- Convective fluxes with MUSCL and limiting on primitives (MSW, AUSM, AUSM+up2).

$$\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F}^c(\mathbf{U}) - \nabla \cdot \mathbf{F}^v(\mathbf{U}, \nabla \mathbf{U}) - \mathbf{Q}(\mathbf{U}) = \mathbf{0}$$

$$\mathbf{U} = \left\{ \begin{array}{c} \rho_1 \\ \vdots \\ \rho_{n_s} \\ \rho \mathbf{u} \\ \rho e \\ \rho e^{ve} \end{array} \right\}, \quad \mathbf{F}^c = \left\{ \begin{array}{c} \rho_1 \mathbf{u} \\ \vdots \\ \rho_{n_s} \mathbf{u} \\ \rho \mathbf{u}\mathbf{u}^T + P\mathcal{I} \\ \rho h \mathbf{u} \\ \rho e^{ve} \mathbf{u} \end{array} \right\}, \quad \mathbf{F}^v = \left\{ \begin{array}{c} -\mathbf{J}_1 \\ \vdots \\ -\mathbf{J}_{n_s} \\ \sigma \\ \mathbf{u}^T \sigma - \sum_k \mathbf{q}^k - \sum_s \mathbf{J}_s h_s \\ -\mathbf{q}^{ve} - \sum_s \mathbf{J}_s e^{ve} \end{array} \right\}, \quad \mathbf{Q} = \left\{ \begin{array}{c} \dot{\omega}_1 \\ \vdots \\ \dot{\omega}_{n_s} \\ \mathbf{0} \\ 0 \\ \dot{\Theta}^{tr:ve} + \sum_s \dot{\omega}_s e_s^{ve} \end{array} \right\}$$





SU2 nemo

Mutation++

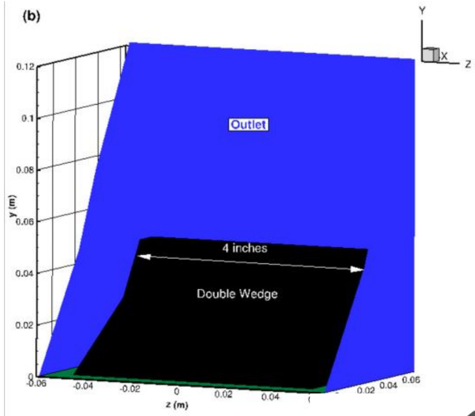
Inria

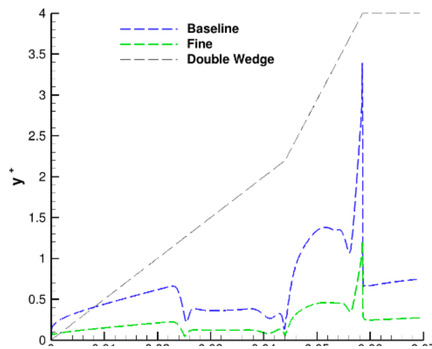
https://github.com/su2code/SU2.git

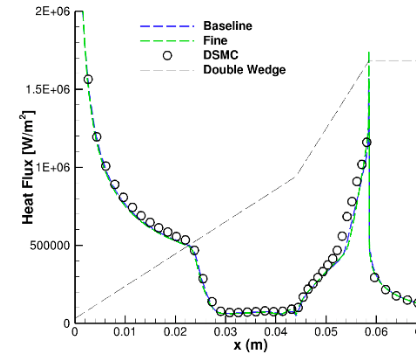
*Maier, et al., “Development of Physical and Numerical Nonequilibrium Modeling Capabilities within the SU2-NEMO Code,” AIAA Paper 2023-3488.

Grid Convergence

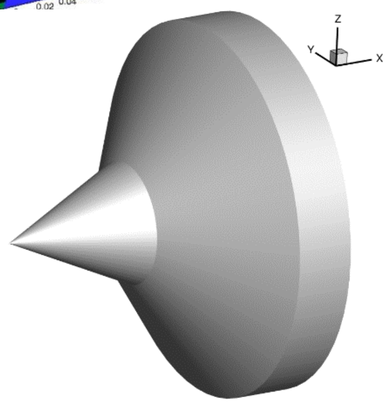
Double Wedge*

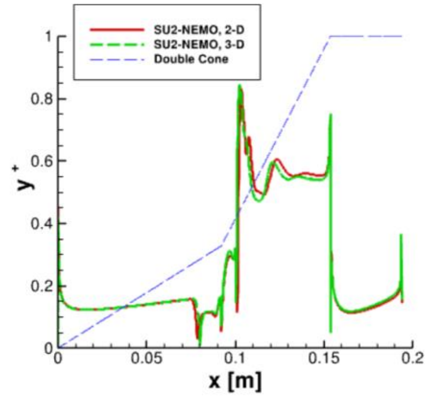


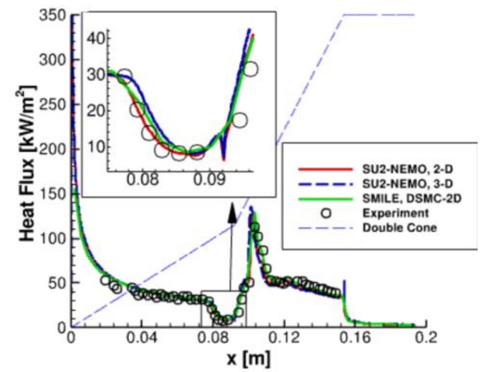




Double Cone





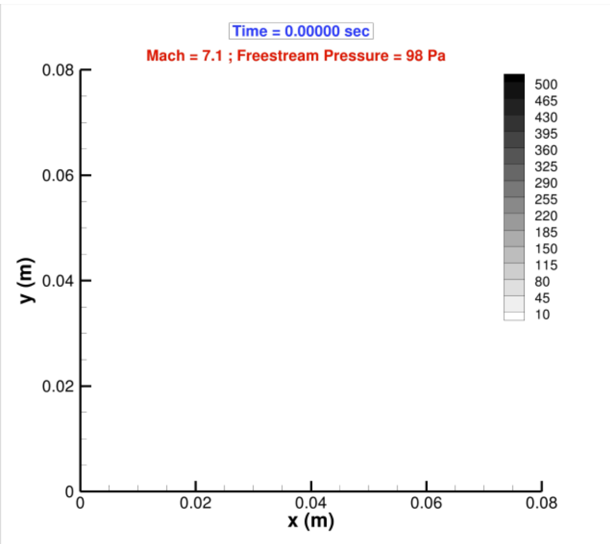


- Structured meshes with two different number of grids are used.
- Rigorous grid study is carried out to ensure that the results are independent of grid resolutions
- 71,000 surface elements along with about **28M grids** were used for the double cone cases whereas 50M grids were used for 3D double wedge calculations.

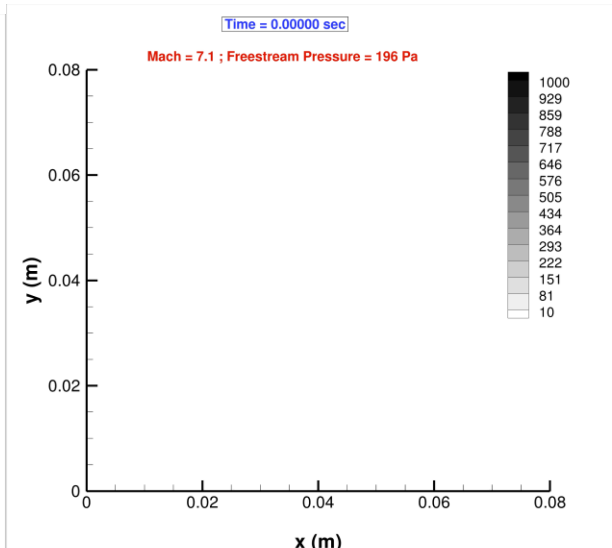
Tumuklu, O., and Hanquist, K. M., "Temporal characteristics of hypersonic flows over a double wedge with Reynolds number," Physics of Fluids, Vol. 35, No. 10, 2023.

Temporal Characteristics of Shock Structure 2D Double Wedge*

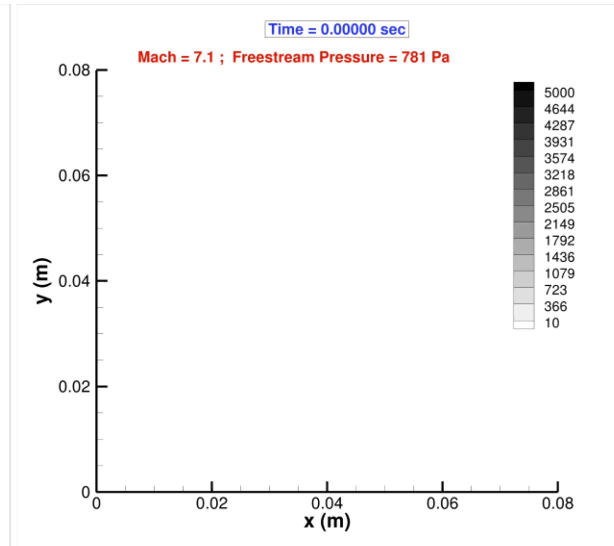
P = 98 Pa



P = 196 Pa

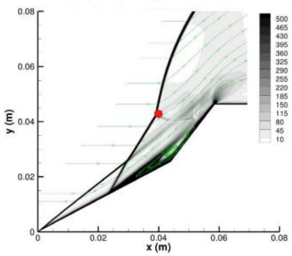


P = 781 Pa



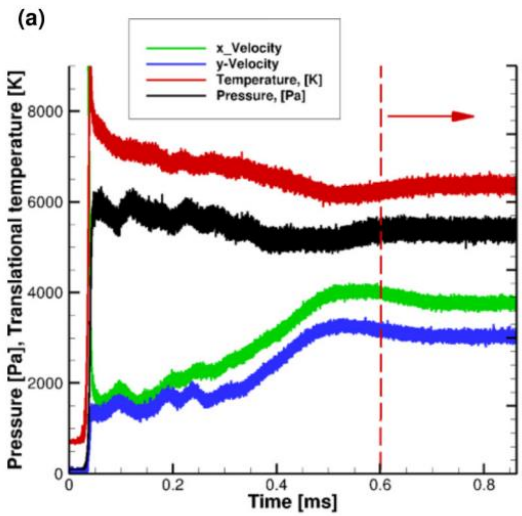
- The lowest pressure case reaches steady state at about 0.75 ms
- Periodic oscillations seen in the medium pressure (P=196 Pa) case.
- The oscillations disappear for the highest-pressure case but flow reaches steady state about 2 ms (**10X times** larger than the duration of the experiment).

*Tumuklu, O., & Hanquist, K. M. (2023). Unsteadiness of hypersonic flows over a double wedge. In *AIAA SCITECH 2023 Forum* (p. 0860).

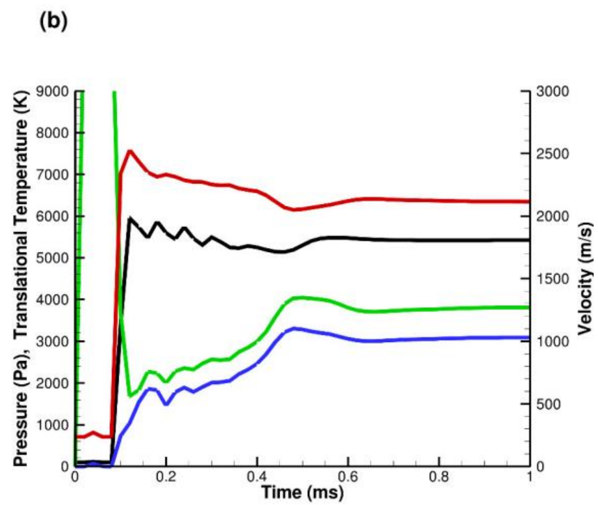


Accuracy Current Continuum Simulations over Double Wedge

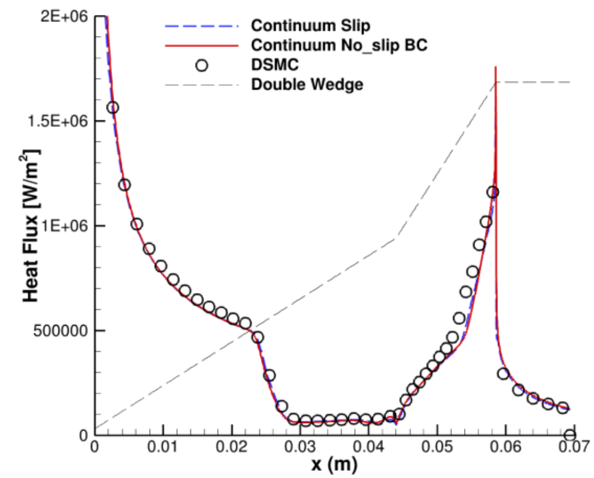
2D, DSMC, 98 Pa*



2D, NS, 98 Pa**



Rarefied effects**

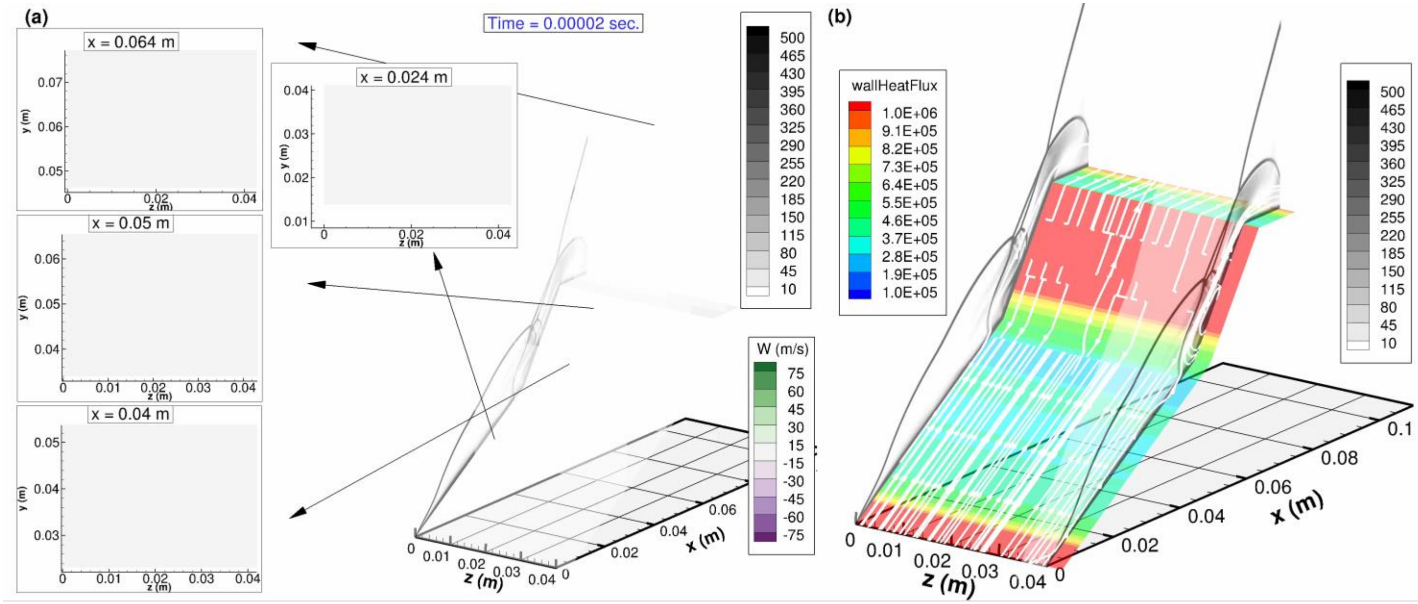


- The temporal evolutions are found to be **the same** for DSMC and NS.
- The impact of rarefied effects, even for **the lowest Re**, is negligible.

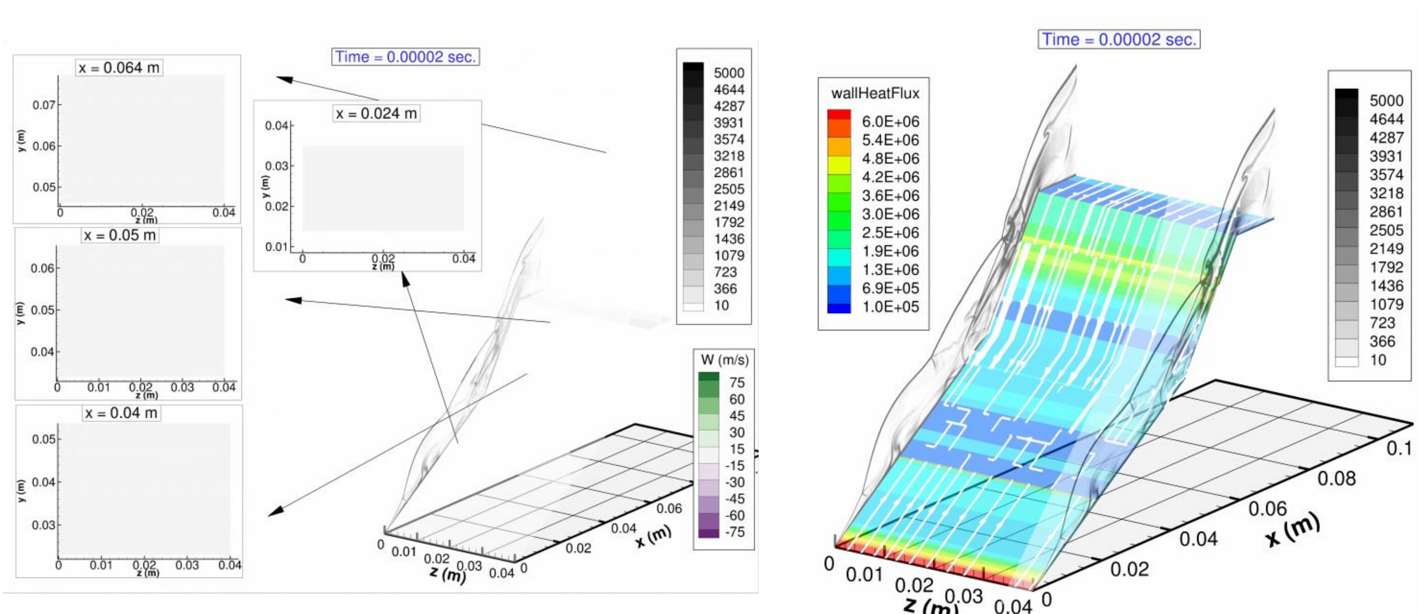
*Tumuklu, O., Levin, D. A., and Theofilis, V., "On the temporal evolution in laminar separated boundary layer shock-interaction flows using DSMC," AIAA Paper 2017-1614, 2017.
**Tumuklu, O., and Hanquist, K. M., "Temporal characteristics of hypersonic flows over a double wedge with Reynolds number," Physics of Fluids, Vol. 35, No. 10, 2023.

Periodic 3-D Simulations over Double Wedge

P = 98 Pa

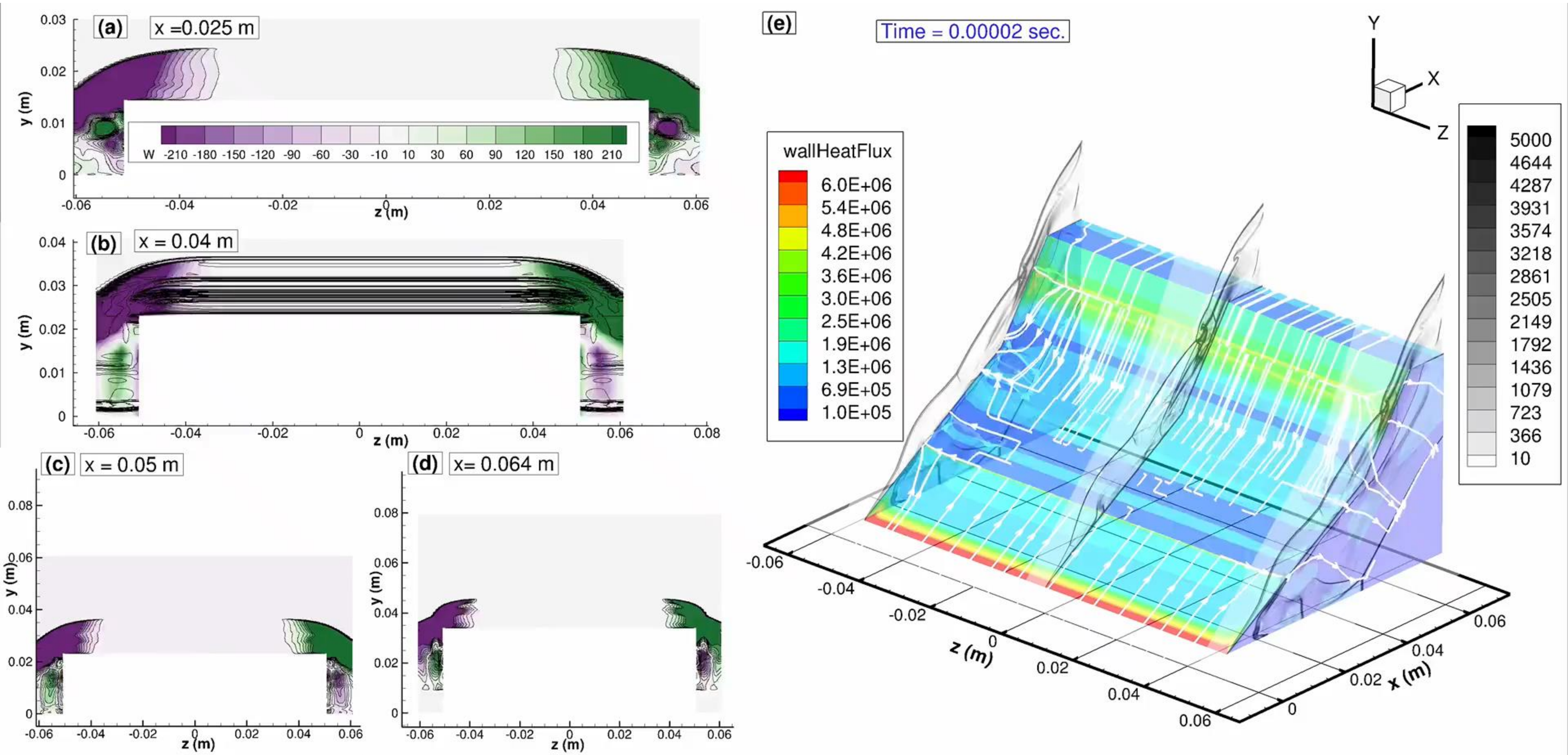


P = 781 Pa



Full 3D Simulations over Double Wedge*

P = 781 Pa

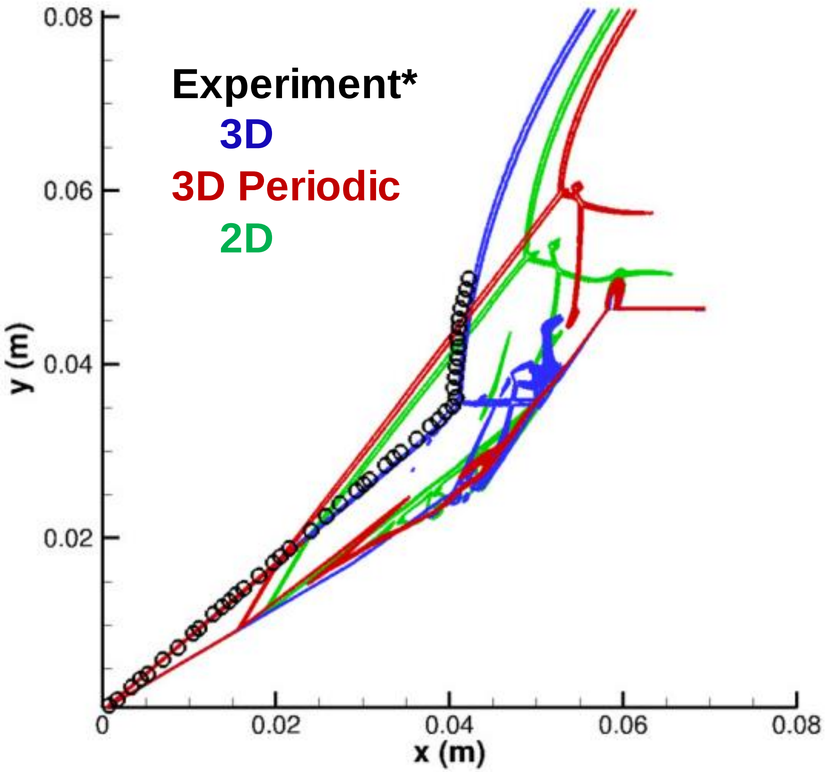


- The structure of the spanwise instabilities close to the center is found to be very similar to 3D periodic cases.

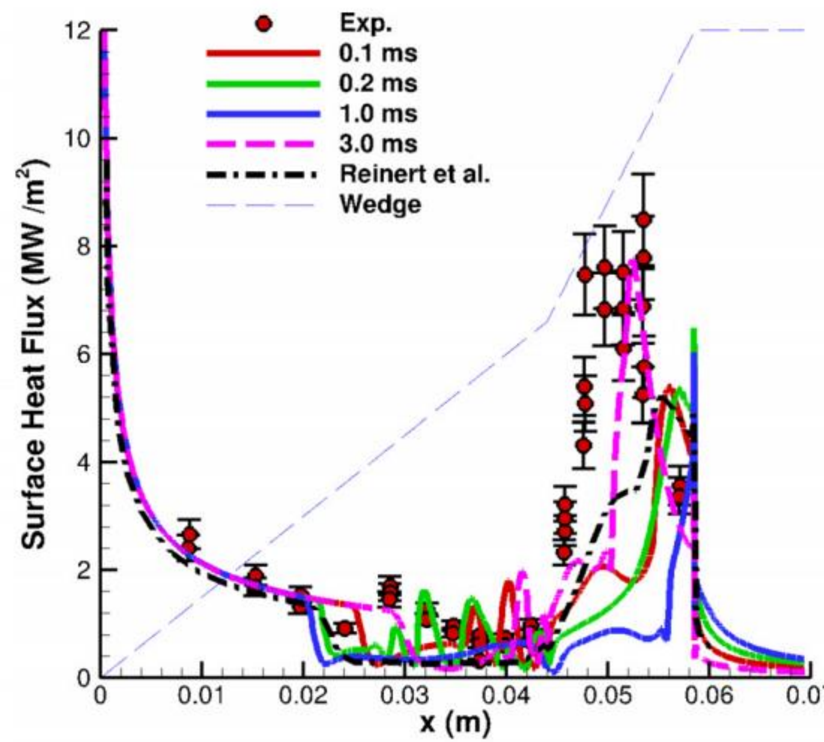
*Tumuklu, O., and Hanquist, K. M., “Temporal characteristics of hypersonic flows over a double wedge with Reynolds number,” Physics of Fluids, Vol. 35, No. 10, 2023.

Effect of Geometric Configurations*

Shock Structures



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.

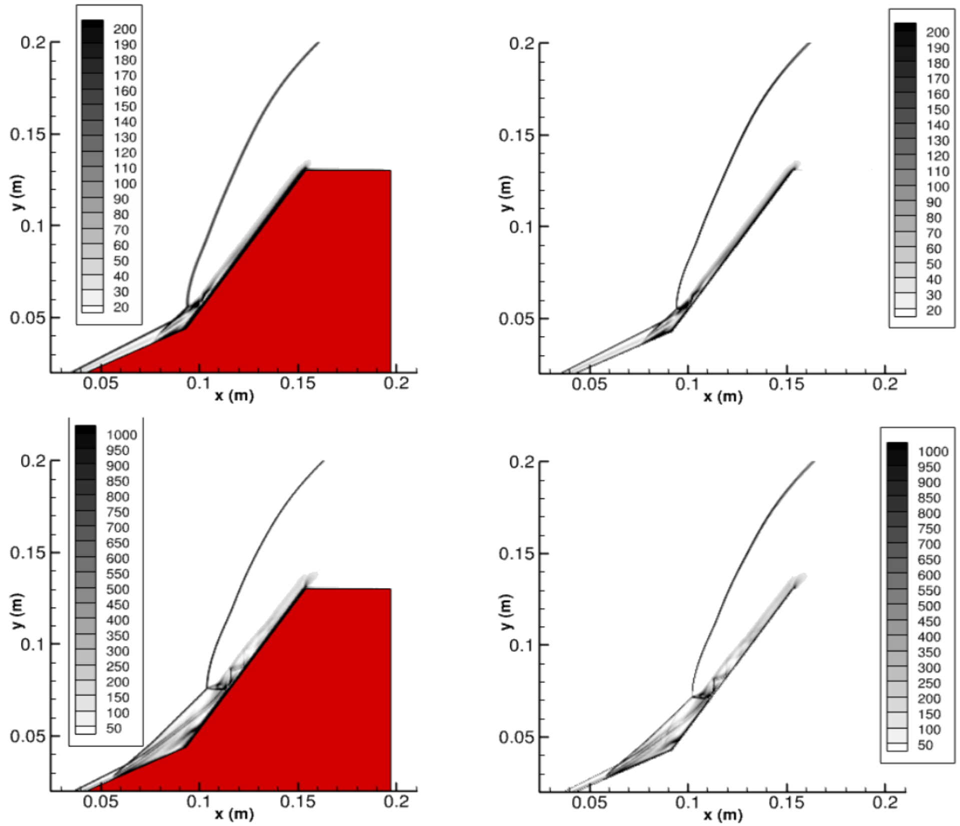
Reinert, J. D., Candler, G. V., and Komives, J. R., “Simulations of unsteady three-dimensional hypersonic double-wedge flow experiments,” AIAA Journal, Vol. 58, No. 9, 2020, pp. 4055–4067.

Comparison of Shock Structure with DSMC over Double Cone

Kinetic Approach DSMC* | **Continuum Approach**

P = 2.2 Pa

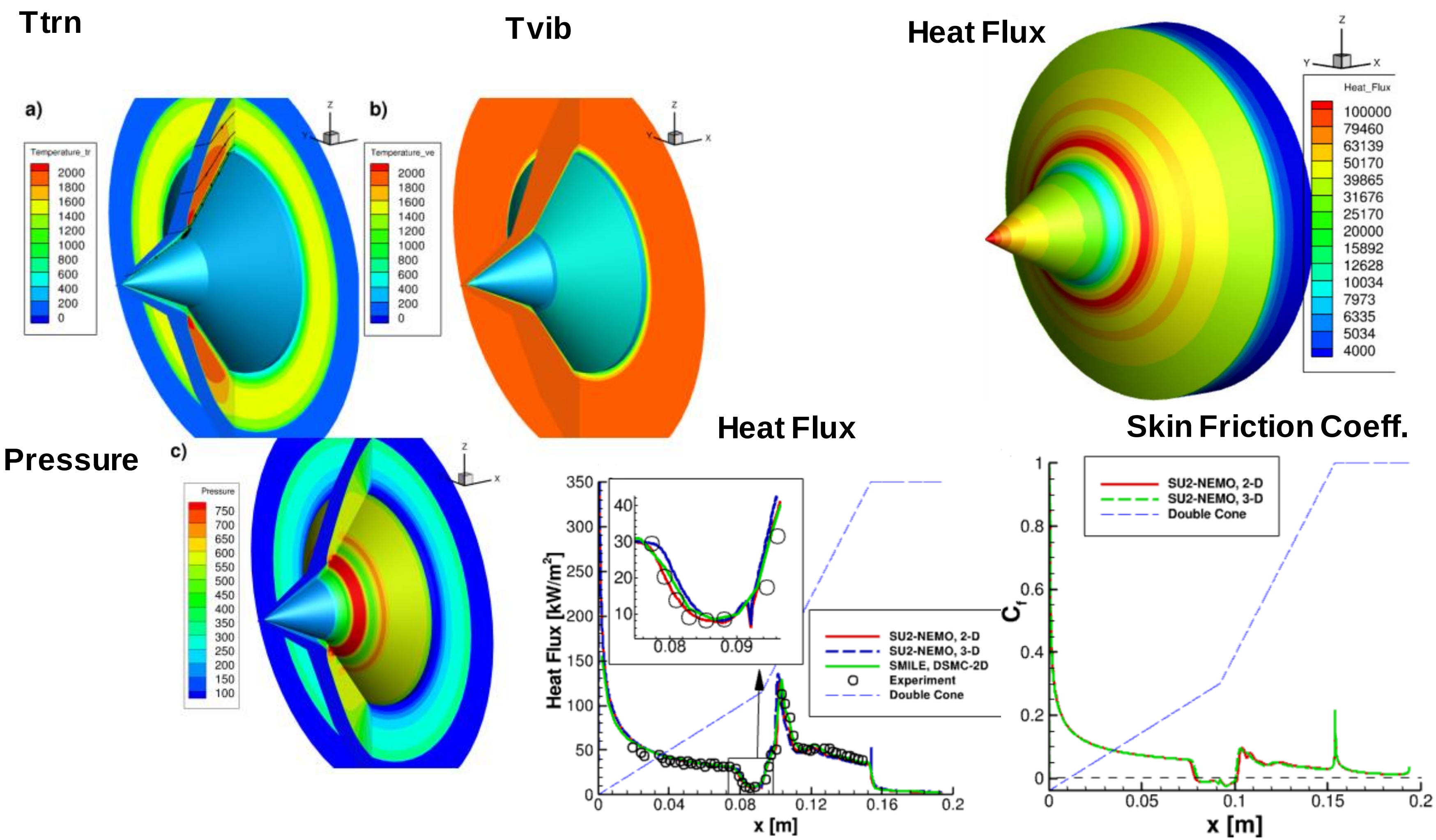
P = 8.8 Pa



- Excellent agreement is achieved with the previous DSMC work*.
- The reflection of the compression and expansion waves through the shear layer is captured accurately.

* Tumuklu, O., Levin, D. A., and Theofilis, V., "Investigation of unsteady, hypersonic, laminar separated flows over a double cone geometry using a kinetic approach," Physics of Fluids, Vol. 30, No. 4, 2018, p. 046103.

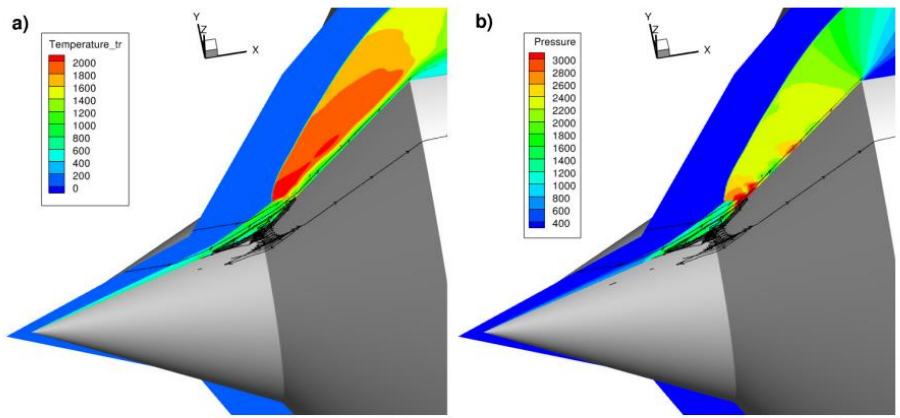
3-D Effects on the Flowfield for P_∞ = 2.2 Pa



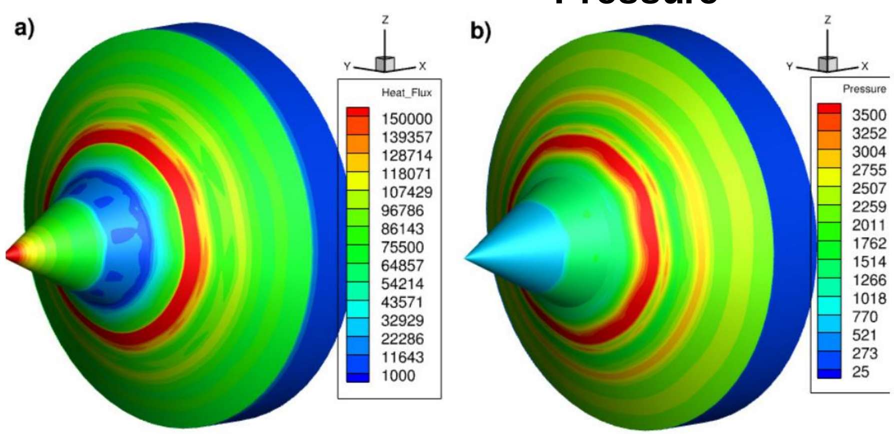
- Excellent agreement is achieved with 2-D and full 3-D calculations, indicating that **the absence of spanwise instabilities**.

3-D Effects on the Flow for P_∞ = 8.8 Pa

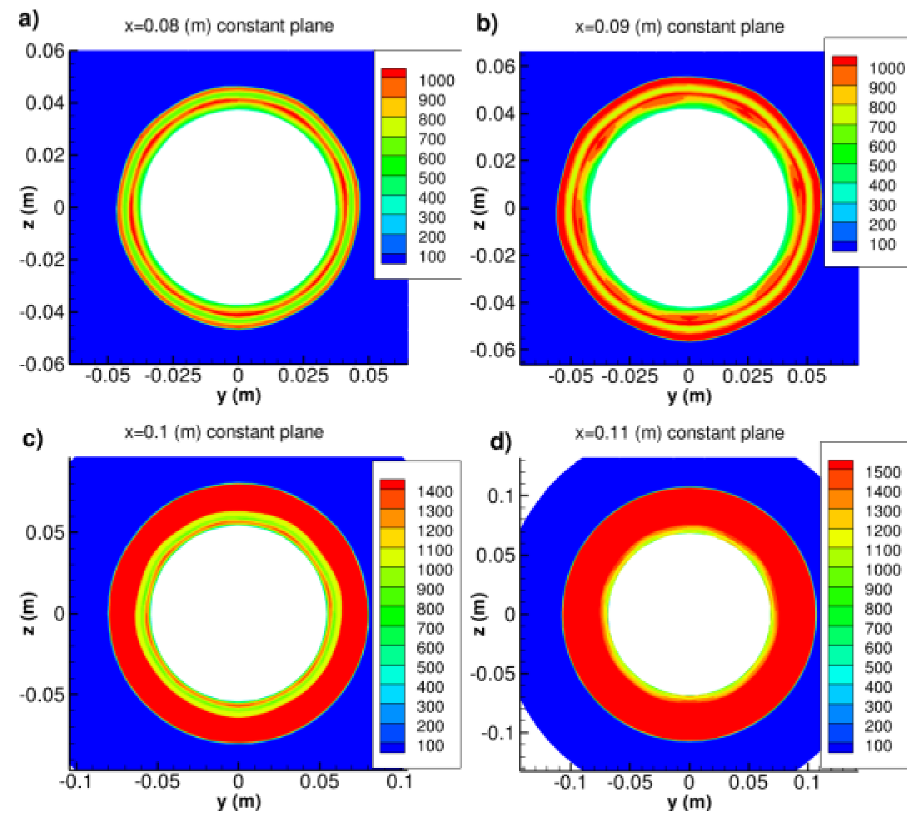
Ttrn **Pressure**



Heat Flux **Pressure**

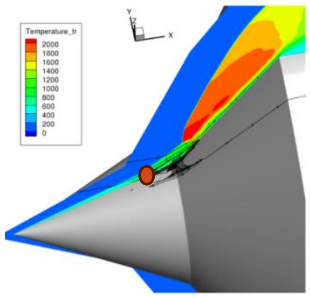


Ttrn

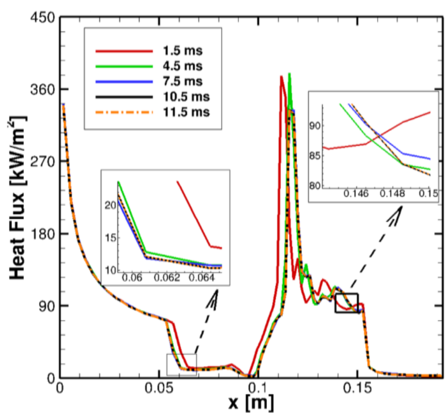


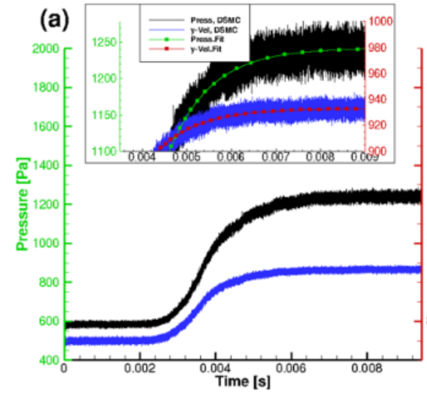
- The **onset of 3-D instabilities** is reported for the high Re case.

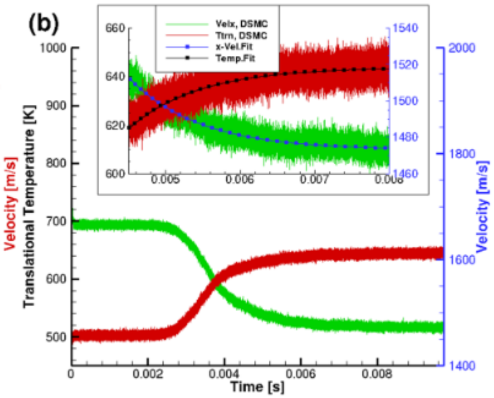
Temporal Comparison of the Surface and Flow Fields for Double Cone



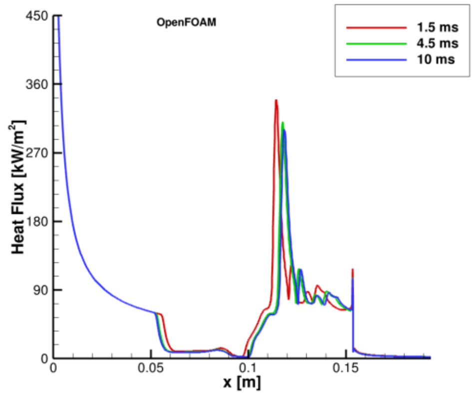
DSMC

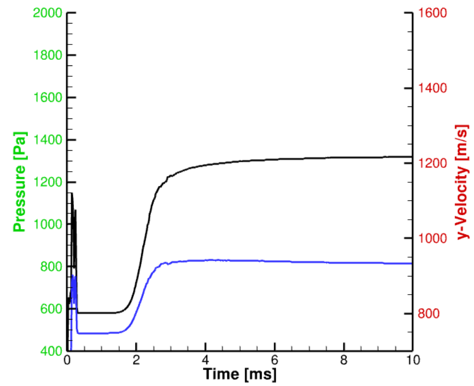


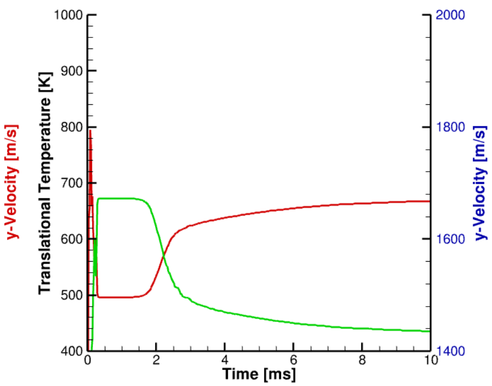




NS



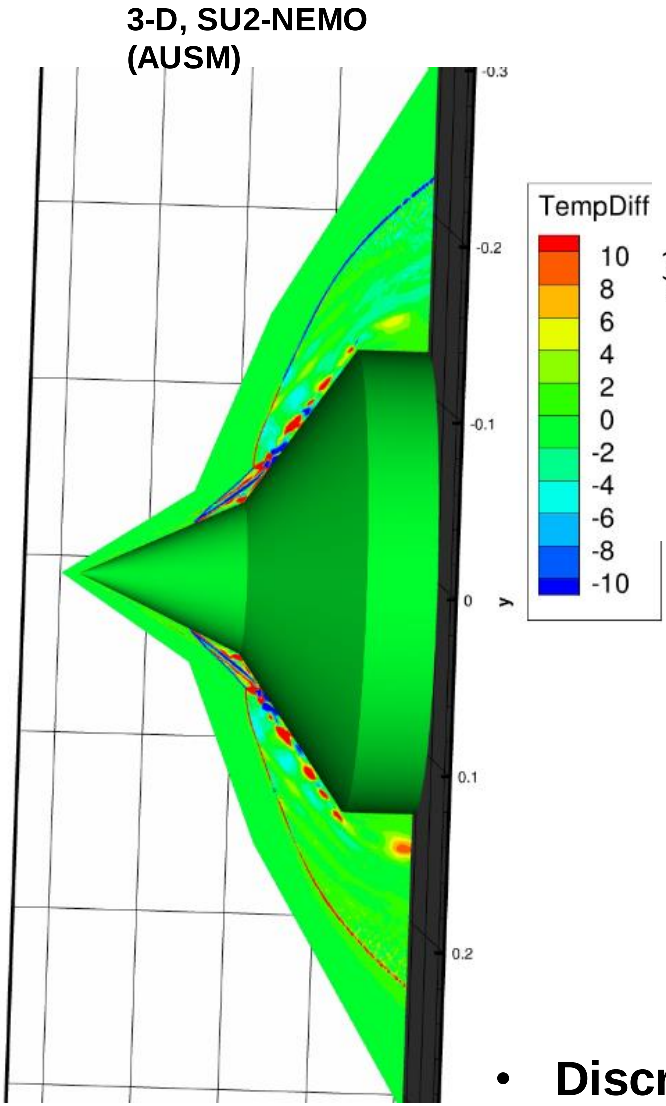


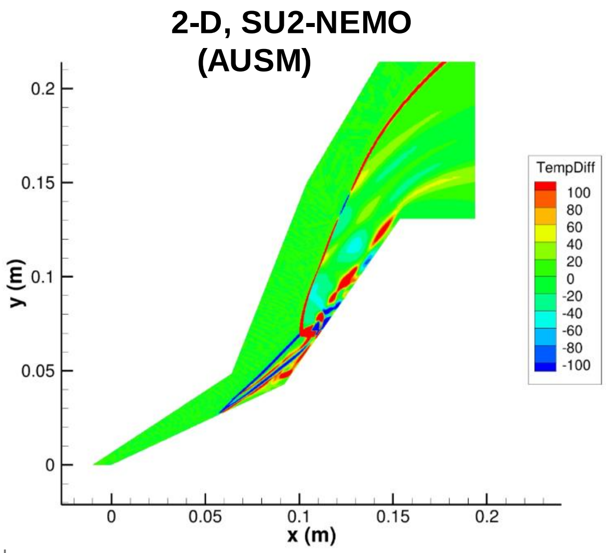


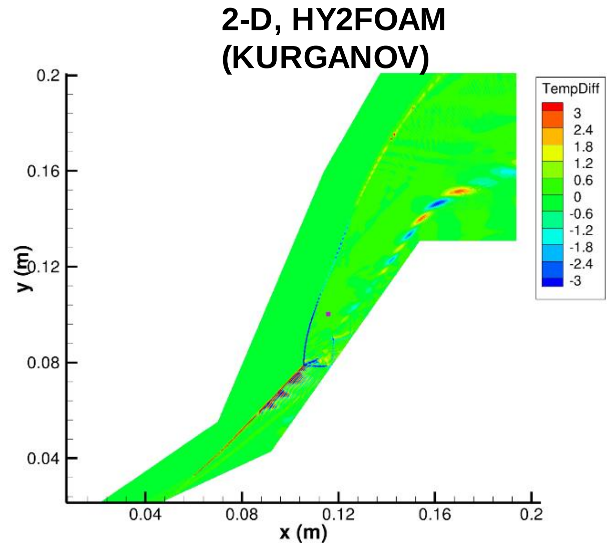
- **Temporal characteristics** of both kinetic and continuum solvers are compared, and very good agreement is achieved.
- Slight differences are seen in the temporal evolutions, but the decay rates are consistent with the previous DSMC data.

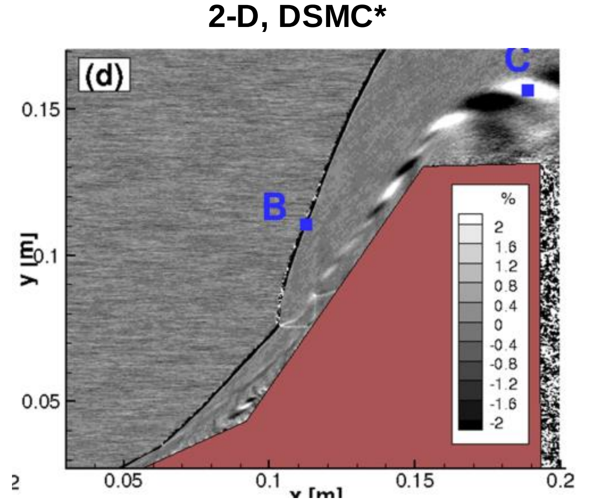
* Tumuklu, O., Levin, D. A., and Theofilis, V., "Investigation of unsteady, hypersonic, laminar separated flows over a double cone geometry using a kinetic approach," Physics of Fluids, Vol. 30, No. 4, 2018, p. 046103.

Characterization of KH instability on the Flow Field









- **Discrepancies** are observed when employing different convective schemes.

* Tumuklu, O., Levin, D. A., and Theofilis, V., "Investigation of unsteady, hypersonic, laminar separated flows over a double cone geometry using a kinetic approach," Physics of Fluids, Vol. 30, No. 4, 2018, p. 046103.

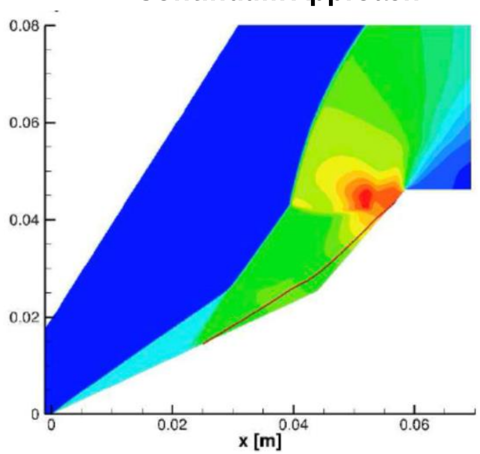
Conclusions

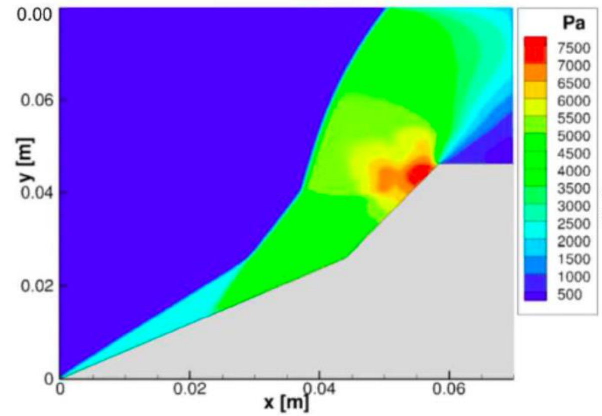
- Rigorous comparisons were made previous DSMC work, excellent agreement was achieved.
- Ongoing efforts focus on the **characteristics of 3-D instabilities** at different Re and wedge/cone angles.
- The implementation of **WMLES** using GPUs is under consideration to study a wide spectrum of **Re**.
- The effect of the real gas effects using **Mutation++** is under consideration.
- The impact of the surface temperature on the structure of the spanwise instabilities will be investigated.

Comparison of Pressure Field with DSMC

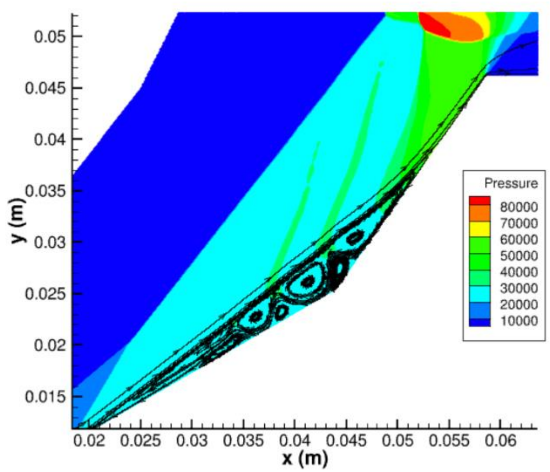
Continuum Approach | **Kinetic Approach DSMC***

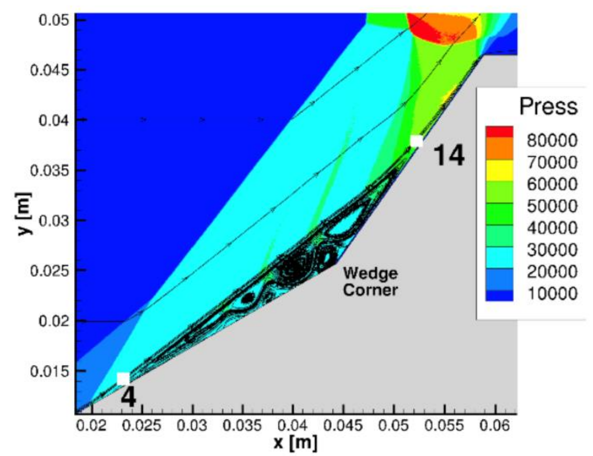
P = 98 Pa





P = 781 Pa





- Excellent agreement is achieved with the previous DSMC work.

*Tumuklu,O.,Levin,D.A., and Theofilis V., Onthetemporalevolutioninlaminarseparatedboundarylayershock-interactionflowsusing DSMC, *55th AIAA Aerospace Sciences Meeting*, 2017, p. 1614