San Francisco to Paris in 60 Minutes

Capturing the hypersonic flow physics to make it happen.

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San Francisco and Charles De Gaulle Airport are 5,600 miles apart, taking about 11 hours to travel. With the new generation of hypersonic aircraft, traveling at Mach 7, that flight time is only 60 minutes! However, simulating and capturing the flow physics of these extreme environments is challenging. Understanding what is happening in hypervelocity flows is the next step toward hypersonic travel.

INTRODUCTION

Hypersonic flows are characterized by intense heating, altering the chemical kinetics and ionization physics not seen in other flow regimes. The highly-coupled interactions make modeling vehicles difficult, often leading to their demise. This work focuses on the following:

- Build on SU2 Code[1] Structure
- Incorporating and validating a model for thermo-chemical non-equilibrium
- Test models in a high-speed flow, with complex shock interactions
  - $15° - 35°$ *and* $15° - 45°$ double wedges

NON-EQUILIBRIUM MODELS

This work leverages Park's Two-Temperature model in SU2[2].

- General solvers tend to assume the flow is always in a state of equilibrium, leading to inaccurate results
- The model uses one temperature to track the translation-rotation energy modes of molecules and another to track the vibrational-electronic energy
- Finite-Rate chemistry is incorporated using Arrhenius Coefficients

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \vec{u} - \rho_s \vec{u}_{d,s}) = \dot{w}_s$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \otimes \vec{u} + P\bar{I} - \bar{\tau}) = 0$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho e \vec{u} + P\bar{I} \cdot \vec{u} - \bar{\tau} \cdot \vec{u} + \vec{q}) = \nabla \cdot (-\textstyle\sum_s h_s \rho_s \vec{u}_{d,s}) - \nabla \cdot \vec{q}_v$$

$$\frac{\partial \rho e_v}{\partial t} + \nabla \cdot (\rho e_v \vec{u} + \vec{q}_v + \textstyle\sum_s e_{v,s} \rho_s \vec{u}_{d,s}) = \textstyle\sum_s Q_s^v + \sum_s Q_S^{t-v}$$

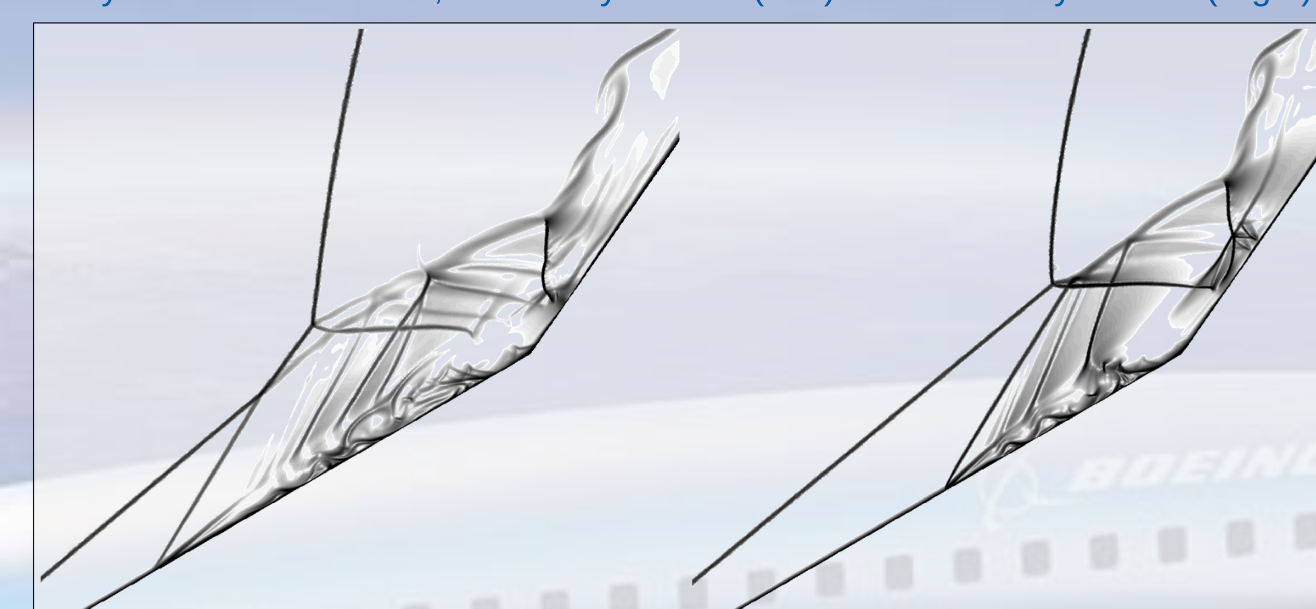
The general equations of state used in the SU2 model formulation. These are simply the Navier-Stokes' equations extended for multiple species and temperatures.

RESULTS

The results below were generated using the following test conditions[3]:

- Mach Number = 9
- 5-Species Model: Freestream air mixture of 79% N2 and 21% O2
- Freestream Pressure = 390.0 Pa, Freestream Temperature = 190 K
- Inviscid, AUSM/AUSM+Up Scheme, 2nd Order Reconstruction

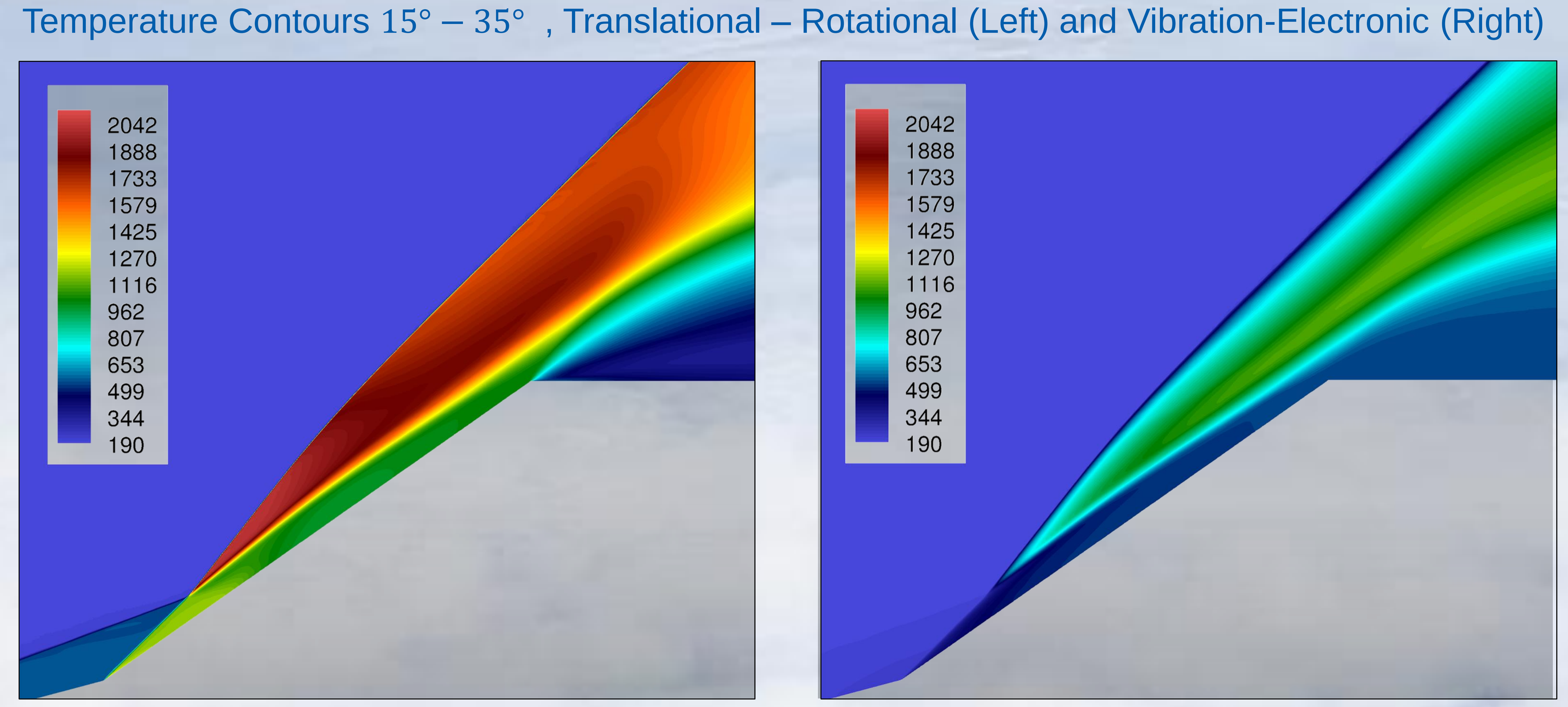
Density Gradient 15° – 45°, Calorically Perfect (Left) and Thermally Perfect (Right)



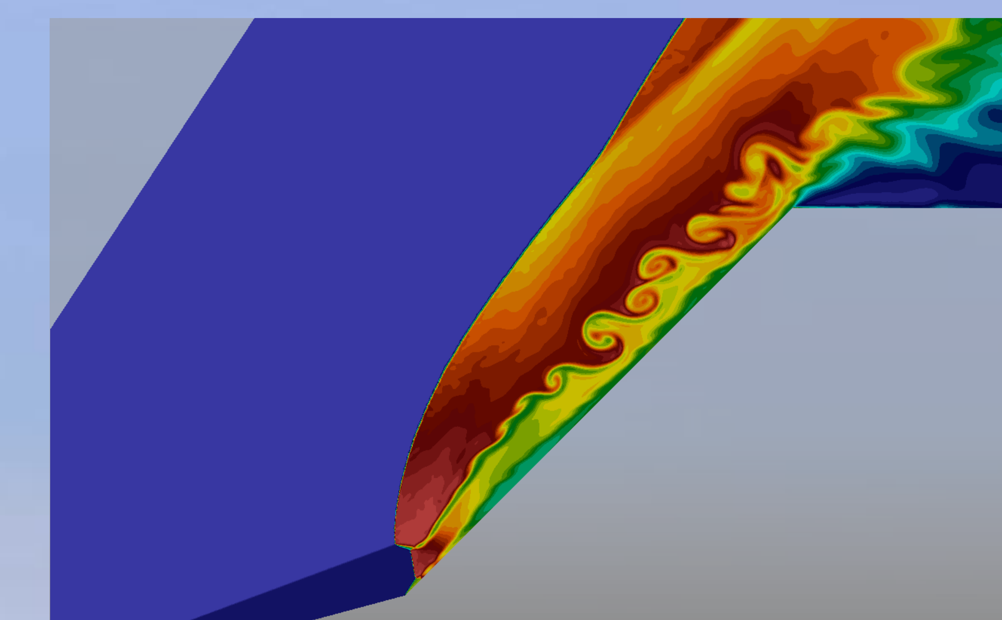
Double wedge test case provide complex shock-shock and shock-boundary interactions

- Major flow differences can be seen when including non-equilibrium models
  - Approximately 1/3 of energy stored in vibrational modes
- Lower temperatures observed using Non-Equilibrium Models

Temperature Contours 15° – 35°, Translational – Rotational (Left) and Vibration-Electronic (Right)



Temperature Contour 15° – 45°, Inviscid



- Unsteady simulation necessary to capture complex flow structures
- Shock-Shock/Shock-Boundary interactions mimic turbulent flow patterns

CONCLUSIONS & FUTURE WORK

The double wedge provides test-case not unlike many hypersonic vehicles will experience. SU2 proves it is capable of handling complex multi-physics problems and provides a clear launching point for higher-fidelity and robust hypersonic physics simulations.

- These simulations require vast computer resources to compute (thanks LLNL!)
- Further validation of non-equilibrium models is required
- Addition of turbulent flows and transition modeling in progress

REFERENCES

[1] Thomas D. Economon, Francisco Palacios, Sean R. Copeland, Trent W. Lukaczyk, and Juan J. Alonso. "SU2: An Open-Source Suite for Multiphysics Simulation and Design", AIAA Journal, Vol. 54, No. 3 (2016), pp. 828-846. https://doi.org/10.2514/1.J053813

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[3] Catarina Garbacz, Marco Fossati, Walter T. Maier, Juan J. Alonso, James B. Scoggins, Thierry Magin, and Thomas D. Economon," Numerical Study of Shock Interference Patterns for Gas Flows with Thermal Nonequilibrium and Finite-Rate Chemistry", AIAA AVIATION Forum, (AIAA 2019). (submitted)

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SU2 The Open-Source CFD Code

Improved modeling capabilities are critical to the development of hypersonic vehicles.

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