One-dimensional modeling methodology for shock tubes: Application to the EAST facility

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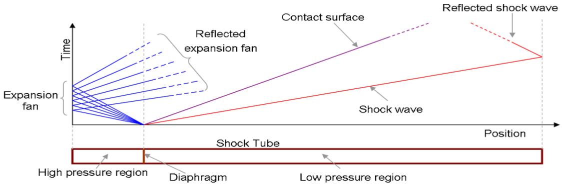
Motivation and Background

Overview of EAST



- Shock initiated by an electric arc discharge
- Test section is 7.5 m downstream
- Piezoelectric shock sensors used to track the shock in space and time
- 4 spectrometers with different wavelength ranges

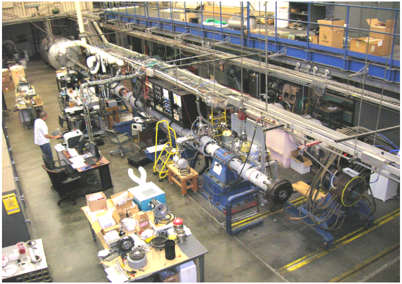


Figure: Overall view of EAST facility at ARC. Credits: NASA Ames

Motivation

- Shock deceleration observed
- **Importance**: Deceleration affects the radiance and hence the kinetics of the system
- **Reason**: Interaction of the shock with the boundary layer
- **Objective**: Study the effect of the boundary layer growth on shock deceleration and kinetics of the system

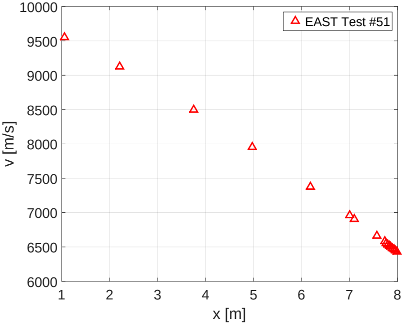
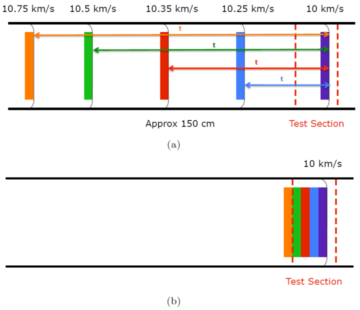
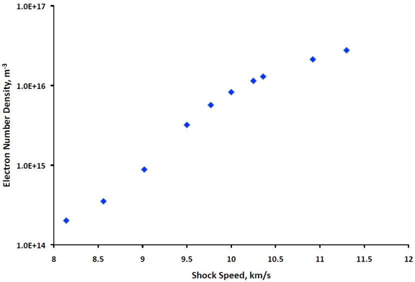


Figure: Velocity Profile from EAST

Motivation



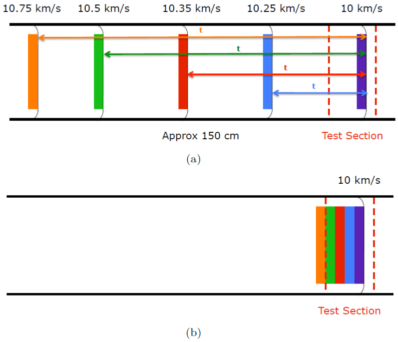


Gas is shocked at different speeds. Enthalpy strongly depends on the shock speed

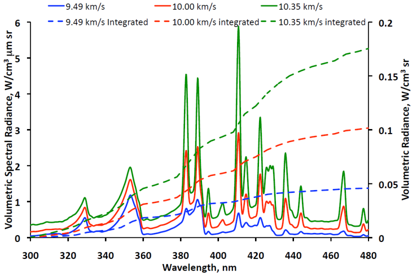
Electron number density and temperature depend on the enthalpy

A. M. Brandis *et al*, "Analysis of Air Radiation Measurements Obtained in the EAST and X2 Shocktube Facilities", 10th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, 2010

Motivation



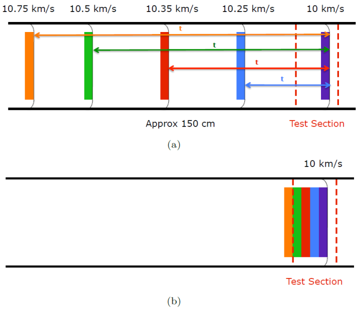
Gas is shocked at different speeds

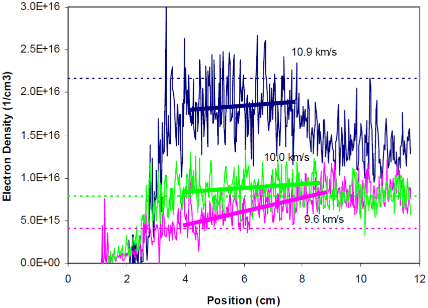


The level of radiation depends on the enthalpy and hence on the shock speed

A. M. Brandis *et al*, “Analysis of Air Radiation Measurements Obtained in the EAST and X2 Shocktube Facilities”, 10th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, 2010

Motivation





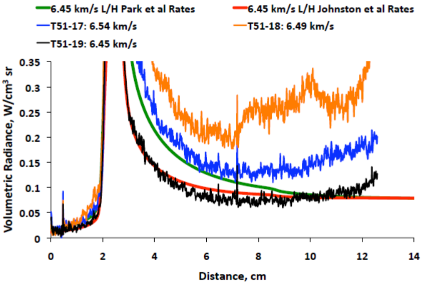
Electron density increases along the length of the shock tube. The temperature values observed are above the equilibrium temperature.

Brett A. Cruden, "Absolute Radiation Measurements in Earth and Mars Entry Conditions", Lecture Series, 2014

A. M. Brandis *et al*, "Investigation of Nonequilibrium Radiation for Mars Entry", AIAA paper, 1055, 2013

Previous Methodologies

- Steady state solution obtained from CFD simulations of a blunt body with an appropriate shock stand off distance.



Do not take into account the shock tube effects on the velocity profile of the shock

- Time accurate, 2-D/ axi-symmetric, CFD simulations of the EAST shock tube

The 2-D simulations take 2-3 months to run and are still not able to match the deceleration profiles of EAST

Current Methodology

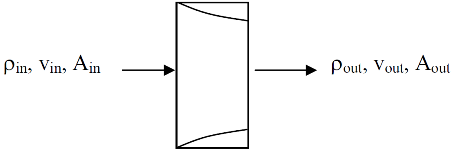
CFD Solver

- HEGEL - High fidElity tool for maGnEtogas-dynamic appLications
- The code is MPI parallelized and uses PETSc library for managing communication among processors.
- Thermodynamic and kinetics library: Plato - PLAsmas in ThermOdynamic non-equilibrium

Euler equations for chemical non-equilibrium flow

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho_i \\ \rho u \\ \rho E\end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix}\rho_i u \\ (\rho u^2 + p) \\ u(\rho E + p)\end{pmatrix} = \begin{pmatrix}\omega_i \\ 0 \\ 0\end{pmatrix}$$

Shock Deceleration Modeling



$$\frac{\partial}{\partial t}\begin{pmatrix} \rho_i \\ \rho u \\ \rho E \end{pmatrix} + \frac{\partial}{\partial x}\begin{pmatrix} \rho_i u \\ (\rho u^2 + p) \\ u(\rho E + p) \end{pmatrix} = \begin{pmatrix} \omega_i - \epsilon \rho_i u \\ -\epsilon \rho u^2 \\ -\epsilon u(\rho E + p) \end{pmatrix}$$

ϵ is the area change coefficient.

The source terms added to the equation represent the mass, momentum and energy lost into the boundary layer which in turn lead to deceleration of the shock

Derivation done by Dr. Brett Cruden

Boundary Layer Modeling

- Interaction of the shock with the boundary layer is one of the reasons for the deceleration of the shock.
- Hence, to simulate the shock deceleration we model the boundary layer growth within the shock tube.

$$\delta = \beta\sqrt{t - t_{arr}(x)}, \quad \text{where} \quad \beta = 4\sqrt{\frac{\mu}{\rho}}$$

To compute the shock arrival time accurately a Lagrangian approach is adopted

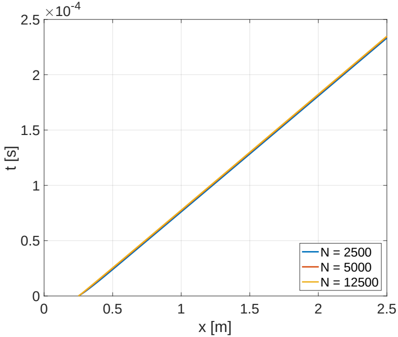
Radiation Calculation

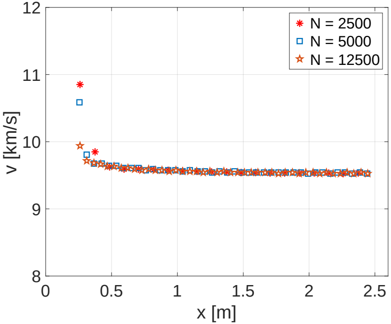
- The mole fractions and vibrational temperatures obtained from the CFD simulations are used to compute the radiance in different wavelength regions
- Line by line radiation code: NEQAIR - Non-equilibrium Air Radiation code is used to compute the radiance from the simulations which is compared against the experiments

Results

Grid Independence Study

Initial Temperature : 10,000 K			
Δx	1 mm	0.5 mm	0.2 mm
Nodes	2500	5000	12500

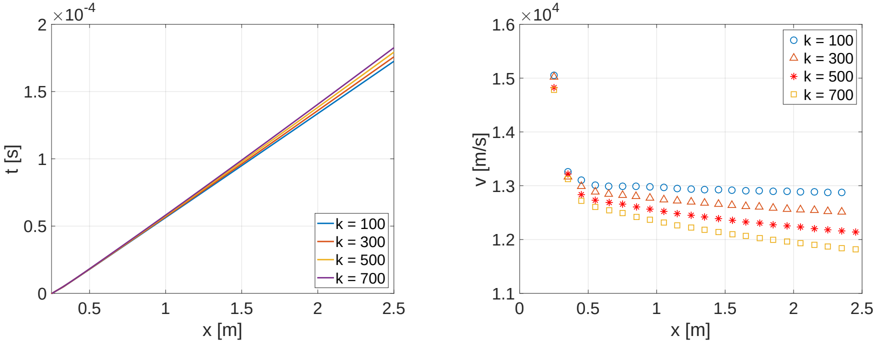




The simulation is grid converged

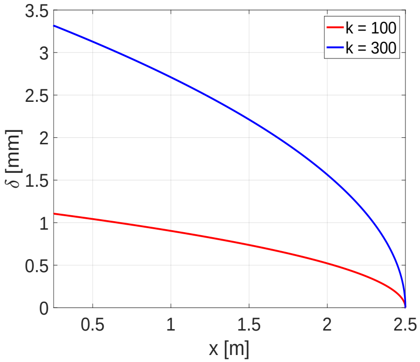
Effect of the Boundary Layer Growth on Shock speed

$$\delta = k\beta\sqrt{t - t_{arr}(x)}$$



As the scaling factor is increased, the deceleration observed is higher

Boundary Layer Growth



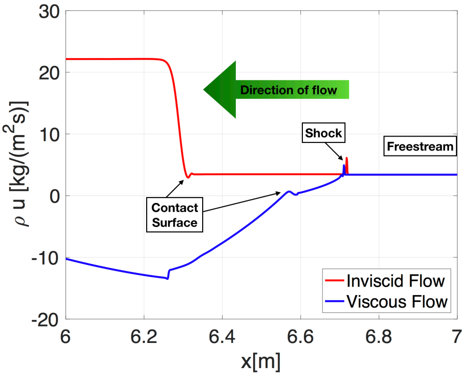
Simplified theoretical model is used to model the boundary layer. The deceleration observed with this model is very low. Hence, a scaling factor is used to decelerate the shock more in order to match the EAST deceleration profile.

Comparison of Flux values with the Inviscid Solution

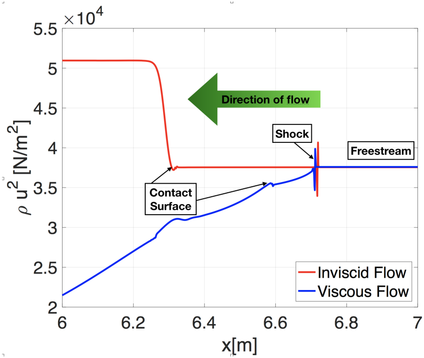
Based on the Rankine-Hugoniot conditions, we know that for a 1-D inviscid flow the mass flux is constant across a shock in a shock relative reference frame

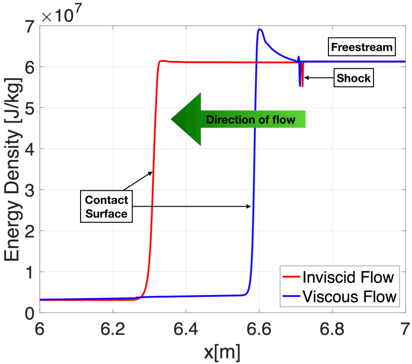
Initial Temperature	10,000 K
Scaling Factor	1000

The mass flux increases across the shock. The mass corresponding to the source term is lost into the boundary layer.



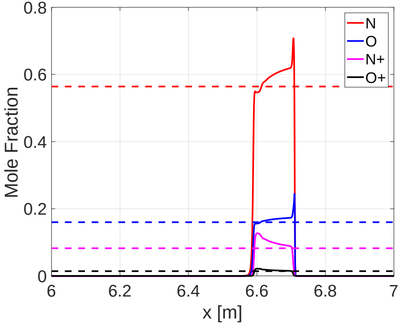
Comparison of Flux values with the Inviscid Solution

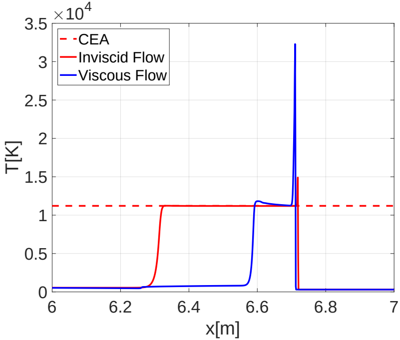




Momentum flux lower than inviscid value since shock speed is lower. Energy density decreases along the length of the shock tube and also the width of the shock is lesser since the contact surface decelerates at a lower rate than the shock.

Comparison with Equilibrium Conditions

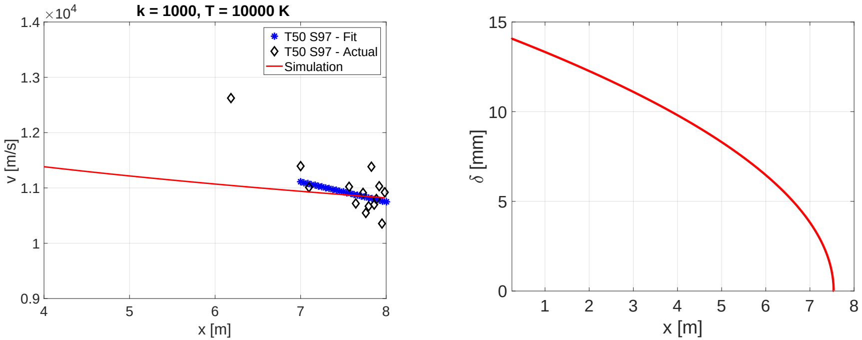




CEA used to obtain equilibrium solution

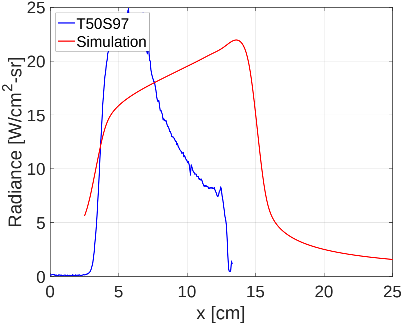
Temperature behind the shock shows an increasing trend and is above equilibrium. Similar to the trend observed in EAST.

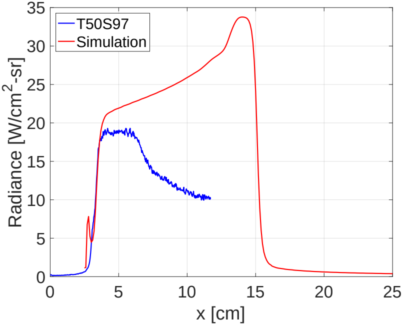
Comparison with EAST Data - Test 50 Shot 97



- Shock deceleration profile matches that of EAST
- The boundary layer thickness is about 14 mm which is higher than the value observed in experiments.
- This higher value of bl thickness is probably due to the fact that radiation losses are not considered in this work.

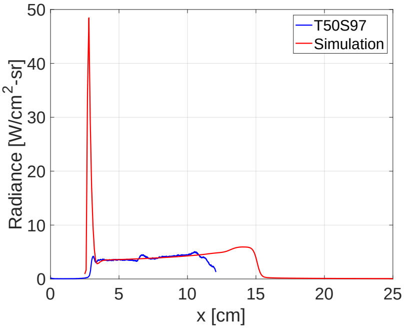
Comparison with EAST Data - Test 50 Shot 97

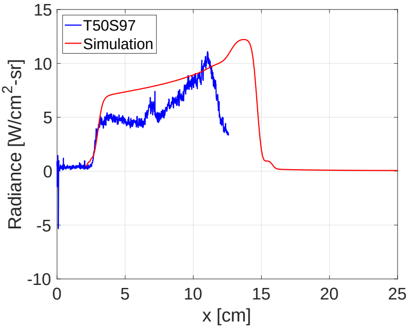




In the IR and Red region there is significant difference between the experiment and simulation. This may be attributed to the fact that the deceleration profile of the shot and simulations do not match exactly.

Comparison with EAST Data - Test 50 Shot 97





- The comparisons in the UV region show very good agreement quantitatively.
- In the VUV region, the results have similar trends and the experimental observations are close to the values obtained from the simulation.

Conclusions and Future Work

Conclusion

- Successfully demonstrated shock deceleration due to boundary layer growth in a quasi 1-D flow.
- Radiance obtained from simulations match well with the experiments for some wavelength region
- Deceleration profiles for various tests and shots of the EAST have been simulated and presented in the paper

Future Work

- Optimize the value of the scaling factor continuously as a function of shock location for better agreement with experiments
- Run the shock tube simulation for mars chemistry
- Include radiation losses in the model

Acknowledgements

Analytical Mechanics Associates Inc. for funding my summer internships when this work was done

Questions?