Shock Wave Interactions
A CFD Study of CUBRC LENS-XX Laminar Experiments

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Objectives

Primary

To predict surface distributions of pressure and heat flux using "standard" simulation model(s) for:

(a) Sharp 25° /55° double cone model

(b) Hollow cylinder-flare (30°) model

tested at laminar flow conditions in LENS-XX at CUBRC

Secondary

To understand/quantify sensitivity of predictions to uncertainties in freestream conditions

To understand/quantify the influence of physical models (thermochemical *vs.* chemical nonequilibrium) on flow predictions

Focus of this presentation is solely on the double cone model

Double Cone Model

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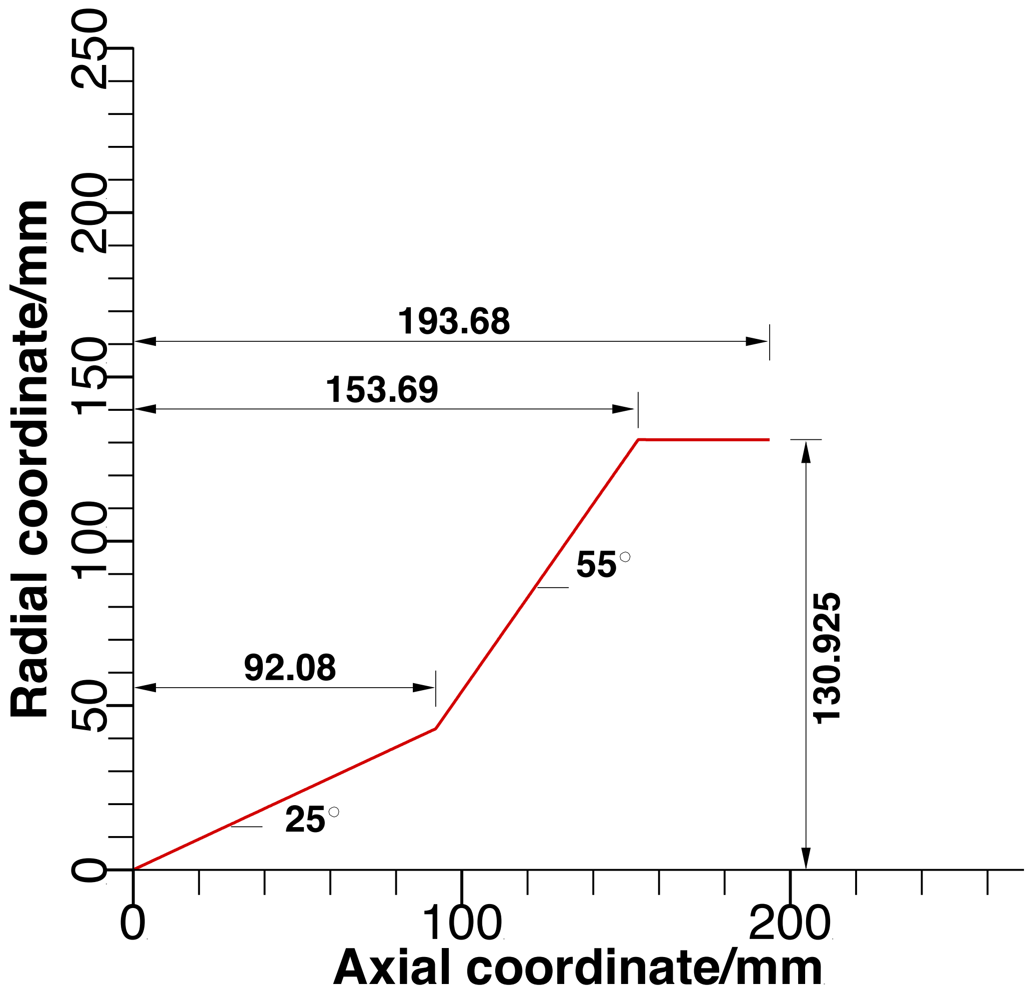

Cone-flare model has a sharp tip

Same model has been tested in LENS-I (reflected shock tunnel)

Modeling and Simulation

Simulation Tool

- v4.03.1 of *Dplr* (axisymmetric)

Physics

- 5-species air (N_2, O_2, NO, N, O) for all cases
- <u>2 Physical models</u>
  - Thermochemical nonequilibrium – TCNEQ
  - Chemical nonequilibrium - TEQ
- Thermodynamic properties of species: Lewis curve fits
  - For consistency with Cheetah
  - Typically would have used SHO/RR
- Momentum and energy transport properties: Gupta-Yos curve fits
- Mass transport: Self-consistent effective binary diffusion
- Chemistry: Park 90 mechanism and kinetics
- Wall model: Fully catalytic to atom recombination and T_w = 300 K

Numerics

- 1st-order accuracy in time and 2nd-order accuracy in space

Grid tailoring capability of *DPLR* exercised in all computations

Strategy

- **Establish grid requirements via the following studies:**
  - **Wall-normal grid resolution**
    - **Cell Reynolds number used the criterion**
    - **Final cell Re used is 0.1**
  - **Wall temperature sensitivity**
    - **Heating results insensitive to choice of wall temperature for high total enthalpy cases**
    - **At lowest total enthalpy, less than 1% change for wall temperatures beween 400 and 300 K**
  - **Grid convergence established by computing on grids that are 4x coarser and finer than nominal grid**
    - **Results reported on nominal grid only**
  - **2nd-order spatial accuracy found to be adequate for all axisymmetric computations**
    - **Some sensitivity seen in 3D computations, but 3D grids employed were coarser than nominal axisymmetric grid**

Freestream Velocity Uncertainty Line of Inquiry, I

- **Surface heating is proportional to the "enthalpy potential"**
  - **$q \propto H_0 - h_w$**
- **Total enthalpy is a conserved quantity across a normal shock**
  - **Inviscid flow is adiabatic**
- **Total enthalpy is a sum of flow kinetic energy and thermochemical enthalpy**

$$H_0(T,T_v) = \frac{1}{2}V^2 + \sum_{s=molecules} c_s \left\{ R_s T \left[3.5 + \left(\frac{\Theta_{v,s}}{T} \right) \frac{\exp\left(-\Theta_{v,s}/T_v\right)}{1-\exp\left(-\Theta_{v,s}/T_v\right)} \right] + \Delta_f H_s^o \right\} + \sum_{s=atoms} c_s \left[2.5 R_s T + \Delta_f H_s^o \right]$$

  - **If freestream is undissociated air, then no atomic contribution**

$$H_0(T_\infty,T_{v,\infty}) = \frac{1}{2}V_\infty^2 + \sum_{s=N_2,O_2} c_{s,\infty} \left\{ R_s T_\infty \left[3.5 + \left(\frac{\Theta_{v,s}}{T_\infty} \right) \frac{\exp\left(-\Theta_{v,s,\infty}/T_{v,\infty}\right)}{1-\exp\left(-\Theta_{v,s,\infty}/T_{v,\infty}\right)} \right] \right\}$$

Freestream kinetic energy is the dominant component – Velocity is the sensitivity variable

Freestream Velocity Uncertainty Line of Inquiry, II

- **Pitot pressure can be measured reasonably well – $P_0 \approx \rho_\infty V_\infty^2$**
  - **Cannot break this product without an independent measurement of velocity**

- ***Assume* uncertainty in given freestream velocity is ±x%, but P_0 is fixed**

$$V_\infty^{new} = f V_\infty^{old} \qquad f = 1 \pm x$$

- **Therefore,**

$$P_0^{new} = P_0^{old} \quad \Rightarrow \quad \rho_\infty^{new}\left(V_\infty^{new}\right)^2 = \rho_\infty^{old}\left(V_\infty^{old}\right)^2 \quad \Rightarrow \quad \rho_\infty^{new} = \frac{1}{f^2}\rho_\infty^{old}$$

- **Still have to specify T_∞**
  - **One way is to assume static pressure is also fixed (at nom.)**

$$p_\infty^{new} = p_\infty^{old} \quad \Rightarrow \quad \rho_\infty^{new}\left(\sum_{s=1}^{n_s} c_{s,\infty} R_s\right) T_\infty^{new} = \rho_\infty^{old} R T_\infty^{old} \quad \Rightarrow \quad T_\infty^{new} = f^2 T_\infty^{old}$$

Freestream enthalpy *will* change! => Freestream velocity and total enthalpy are synonymous

$$H_0(T_\infty^{new}) = f^2\left[\frac{1}{2}(V_\infty^{old})^2 + 3.5 R T_\infty^{old}\right] = f^2 H_0(T_\infty^{old})$$

Learning Cases – Cases from LENS-I Matrix

("Open" Validation Cases in AIAA 2013-2836)

	Run 90	Run 91	Run 80	Run 42
ρ_∞/g.m^{-3}	1.8342	1.5498	1.291	1.34
V_∞/km.s^{-1}	2.731	4.148	3.067	4.063
T_∞/K	190.1	729	166	303
$T_{v\infty}$/K	1001	773.1	2711	3085
Gas comp. (mass fractions)	O_2 = 0.9986 O = 0.0014	O_2 = 0.9389 O = 0.0611	N_2 = 0.9999 N = 0.0001	N_2 = 0.9973 N = 0.0027
H_0/MJ.kg^{-1}	3.99	10.26	5.28	9.17
Molecular (tr/rot)	4.3%	6.1%	3.3%	3.4%
Molecular(vib/el)	1.7%	0.3%	7.6%	5.5%
Atomic	0.5%	9.7%	0.1%	1.0%
Kin.energy	93.5%	83.9%	89.0%	90.1%

Freestream conditions from numerical simulations of nozzle flow

Double cone configuration has been extensively studied by Nompelis *et al*. (AIAA 2010-1283)

Unable to obtain a stable solution for Run 80 with TCNEQ model, but TEQ model is stable

Learning Case – Run 90 (O2/O Mixture)

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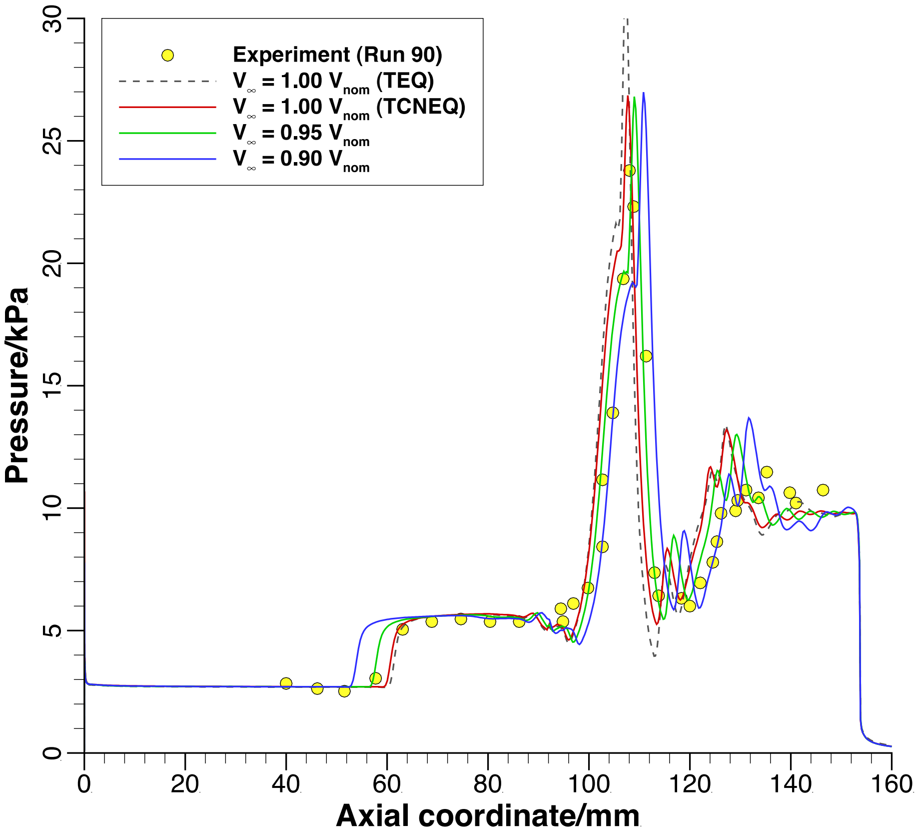
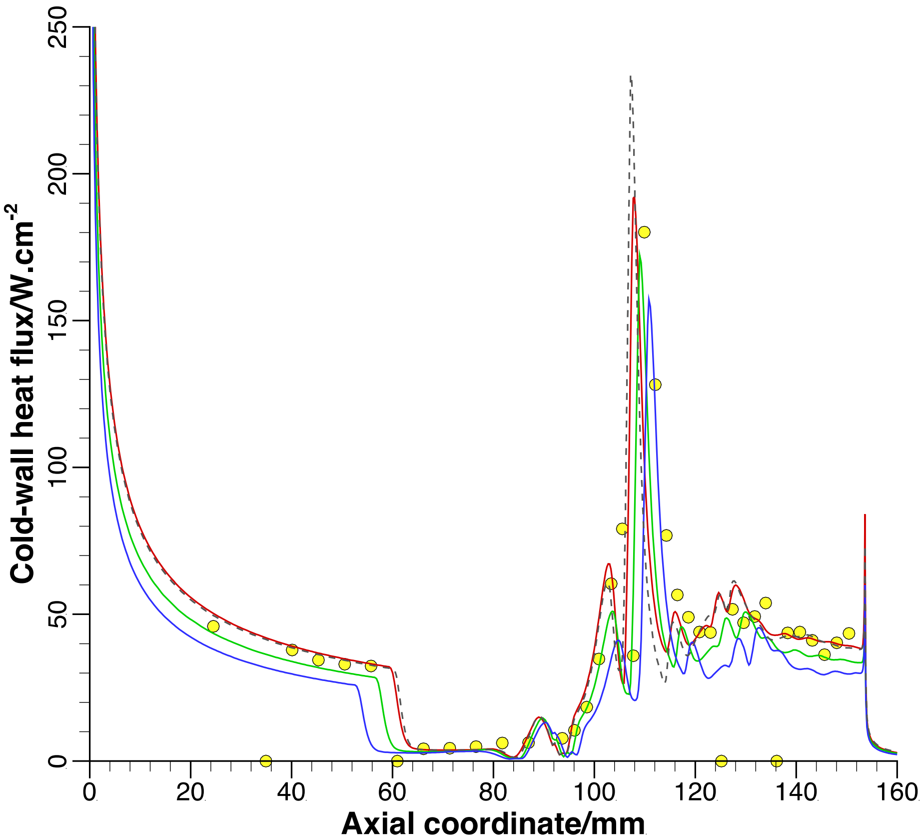
Pressure



Heat Flux



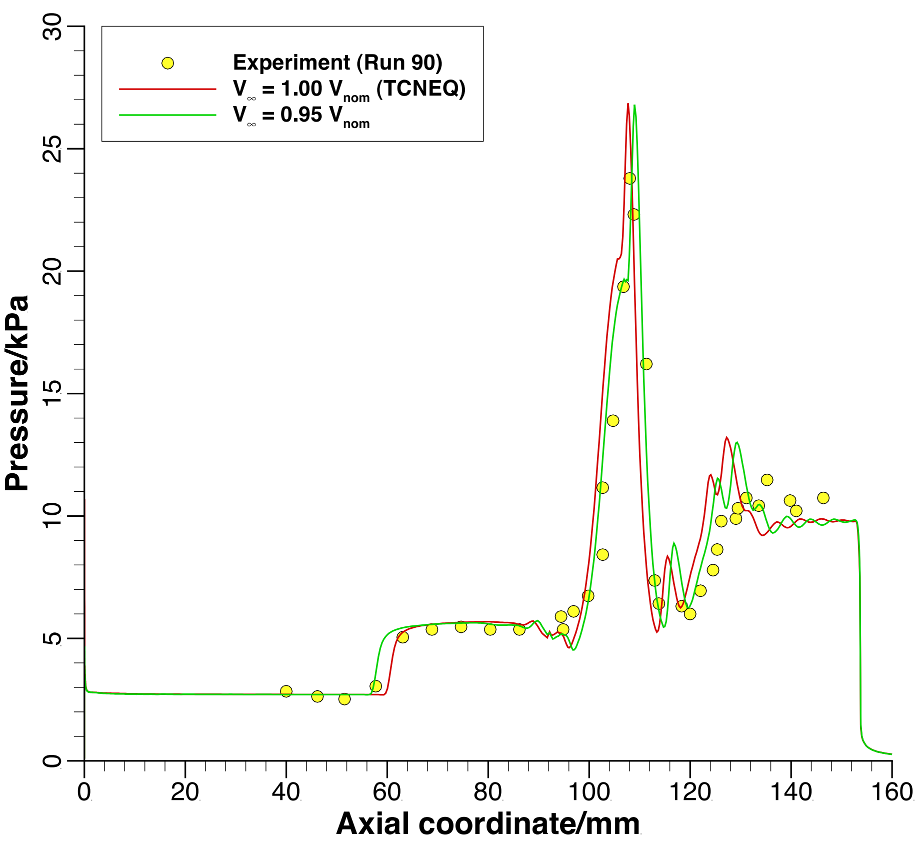
Predicted environments relatively insensitive to choice of TCNEQ or TEQ

Velocity has a bigger impact – lower velocity larger bubble size

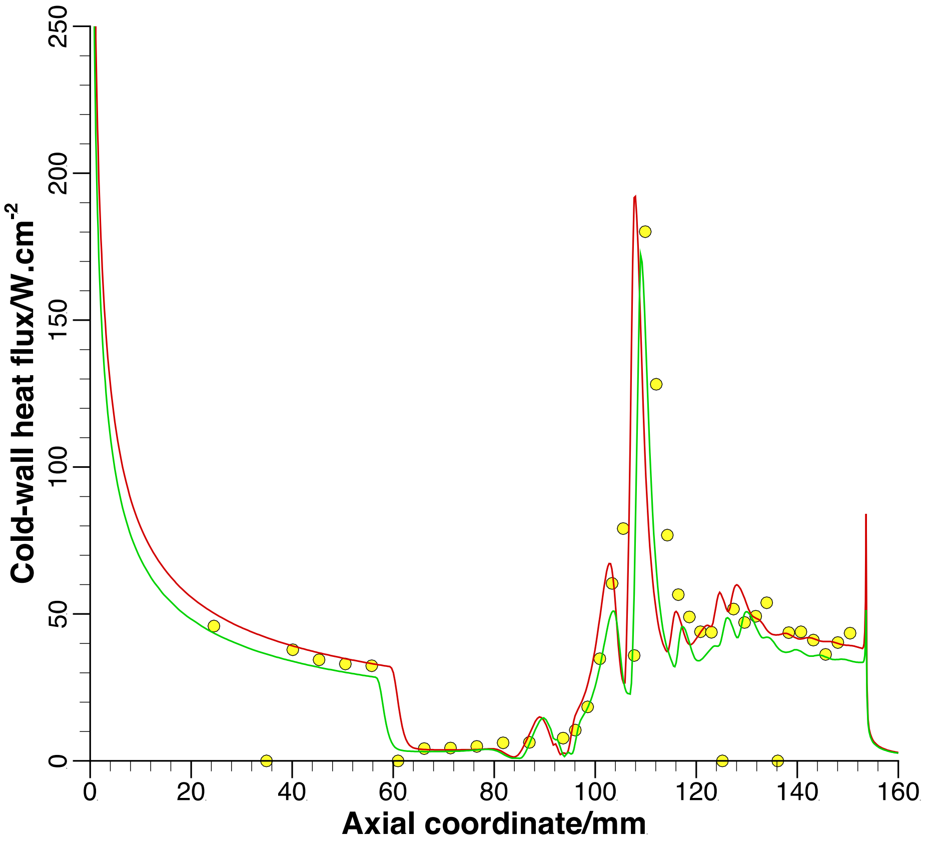
Velocity influence on the 55° cone is also large

Learning Case – Run 90 (O2/O Mixture)

Pressure



Heat Flux



If velocity is 95% of nominal, then better replication of pressure data

Error bars on experimental data not provided

Learning Case – Run 91 (O2/O Mixture)

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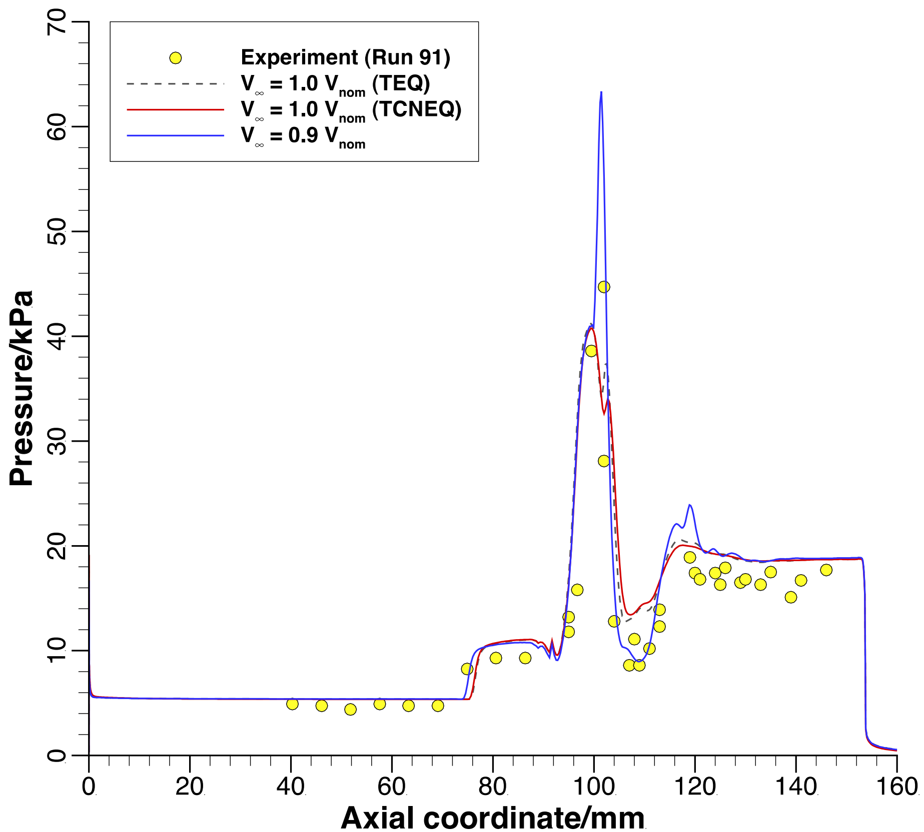
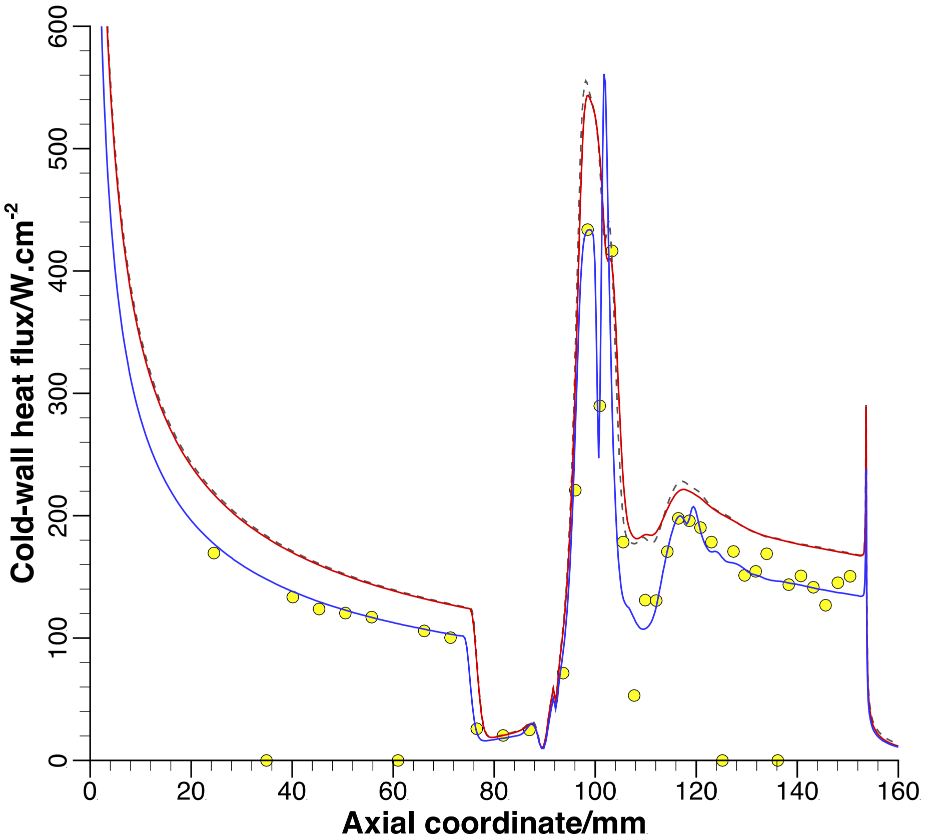
Pressure



Heat Flux



If velocity is 90% of nominal, then better replication of pressure data

The double peak characteristic post-impingement needs schlieren image for confirmation

Learning Case – Run 91 (O2/O Mixture)

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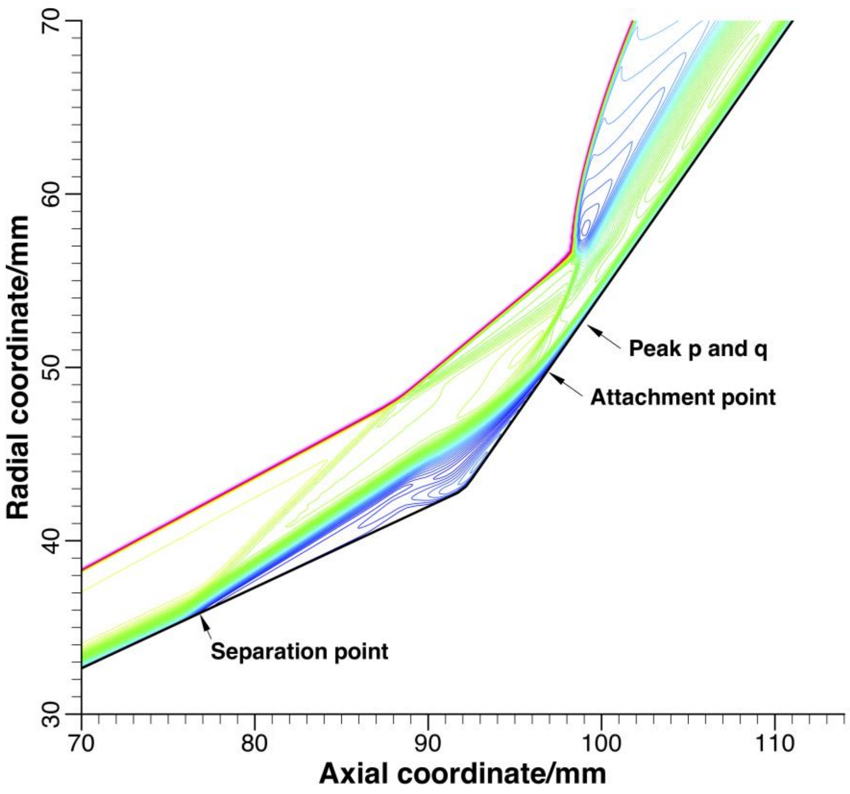
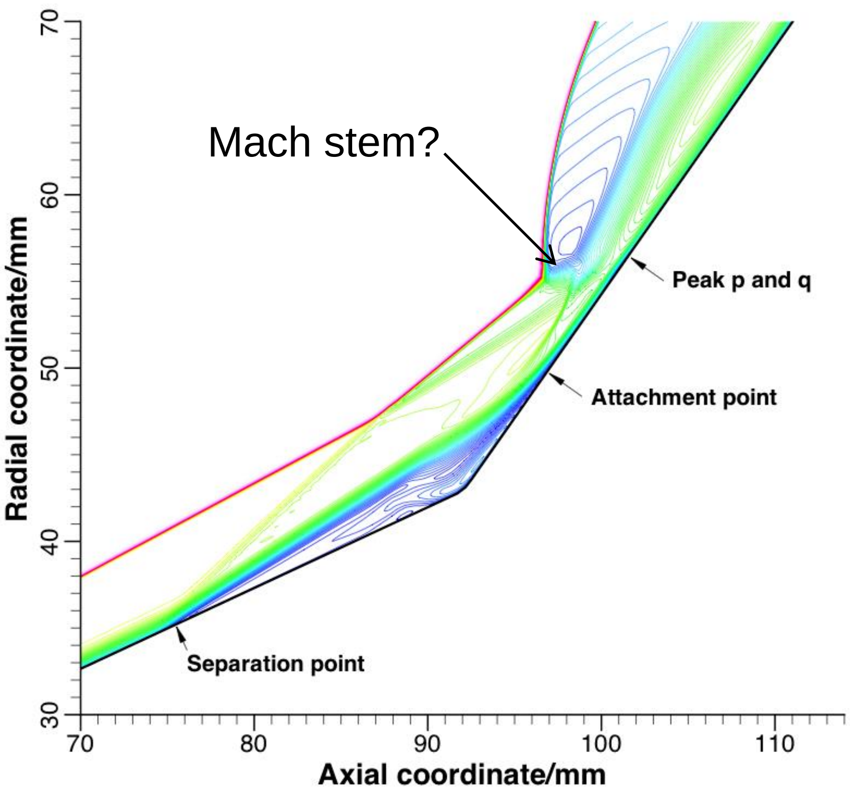
Nominal Velocity



90% Nominal Velocity



Velocity magnitude determines whether or not there is a Mach stem

A schlieren image for this case would be most helpful

From “Open” to “Blind” Validation Cases

- “Open” validation cases are from LENS-I
  - LENS-I is a reflected shock tunnel
- “Blind” validation cases are from LENS-XX
  - LENS-XX is an expansion tunnel

Still retain the freestream velocity uncertainty line of inquiry

“Blind” Validation Cases – LENS-XX Matrix

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	Case 1	Case 2	Case 6	Case 5	Case 3	Case 4
ρ_∞/g.m^{-3}	0.499	0.984	2.045	1.057	0.51	0.964
V_∞/km.s^{-1}	3.246	4.303	5.466	5.996	6.028	6.497
T_∞/K	175	389	573	523	521	652
P_0/kPa	5.1	17.5	59	36.8	18	39.5
H_0/MJ.kg^{-1}	5.44	9.65	15.23	18.51	18.7	21.77
Thermal	3.2%	4.1%	3.7%	2.8%	2.8%	3.0%
Kin.energy	96.8%	95.9%	96.3%	97.2%	97.2%	97.0%
M_∞	12.2	10.9	11.46	13.14	13.23	12.82
$Re_{u\infty}$ $\times 10^{-6}$/m^{-1}	0.14	0.19	0.39	0.23	0.11	0.2
λ_∞/mm	0.129	0.085	0.043	0.084	0.178	0.095
Kn_∞ $\times 10^3$	1.40	0.92	0.47	0.91	1.93	1.03

Freestream conditions from *CHEETAh* code (0D/Equilibrium)

Code calibrated to shock velocity and pressure measurements

Blind Study – Case 1 (Low Enthalpy)

Influence of Freestream Velocity

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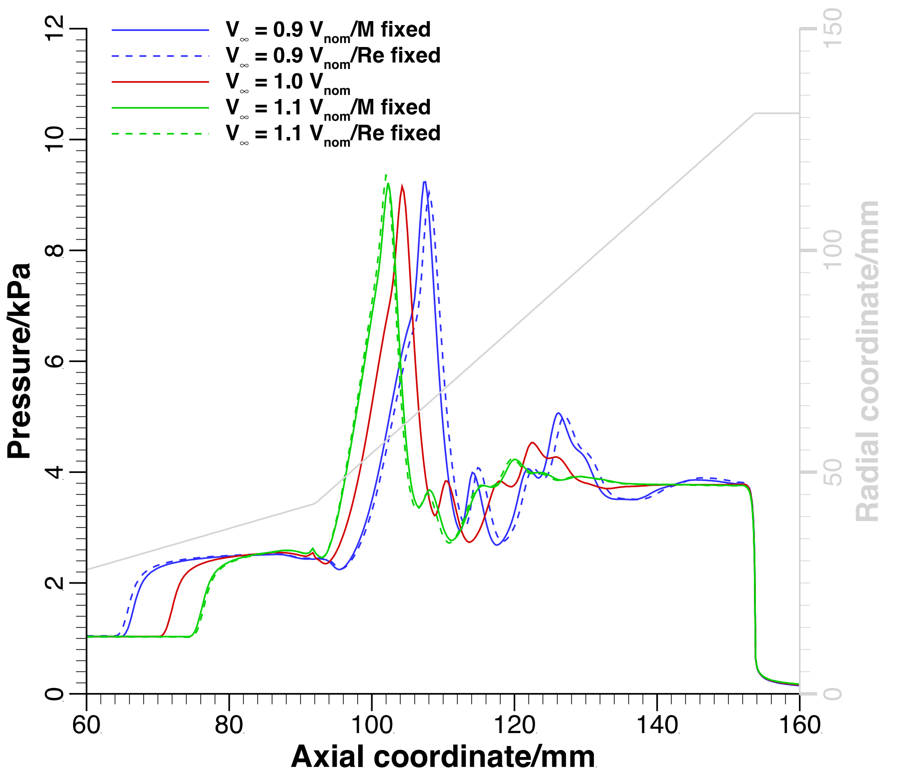
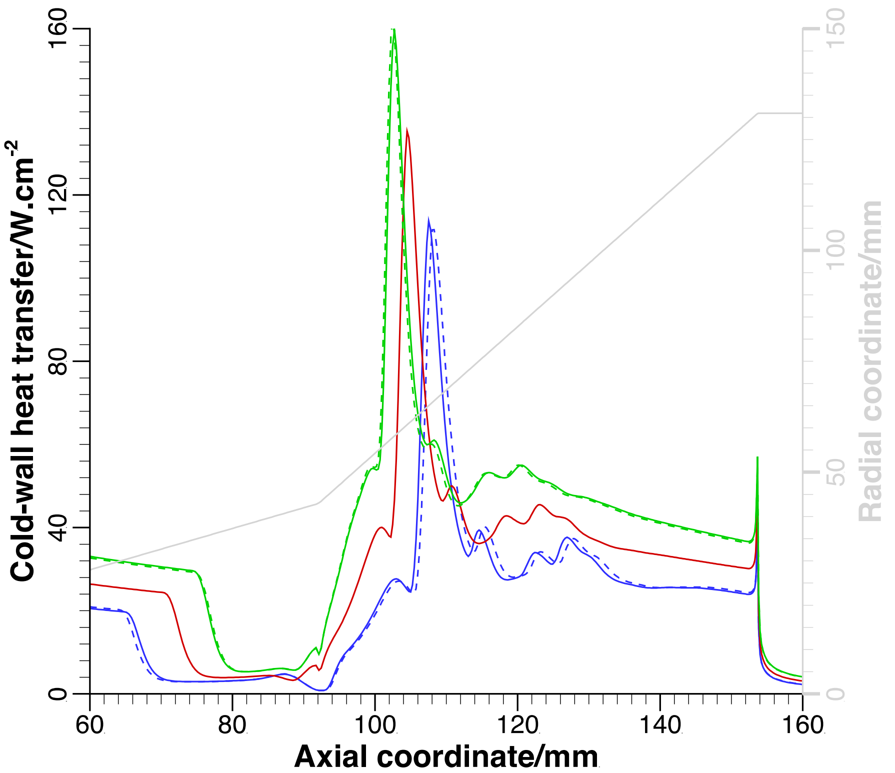
Pressure



Heat Flux



The test configuration is shown in light grey lines

T_∞ from "keep M fixed" or "keep Re fixed" idea has little influence on predictions

±10% variation in velocity at low enthalpy (5 MJ/kg) has more influence

Blind Study – Case 4 (High Enthalpy)

Influence of Freestream Velocity

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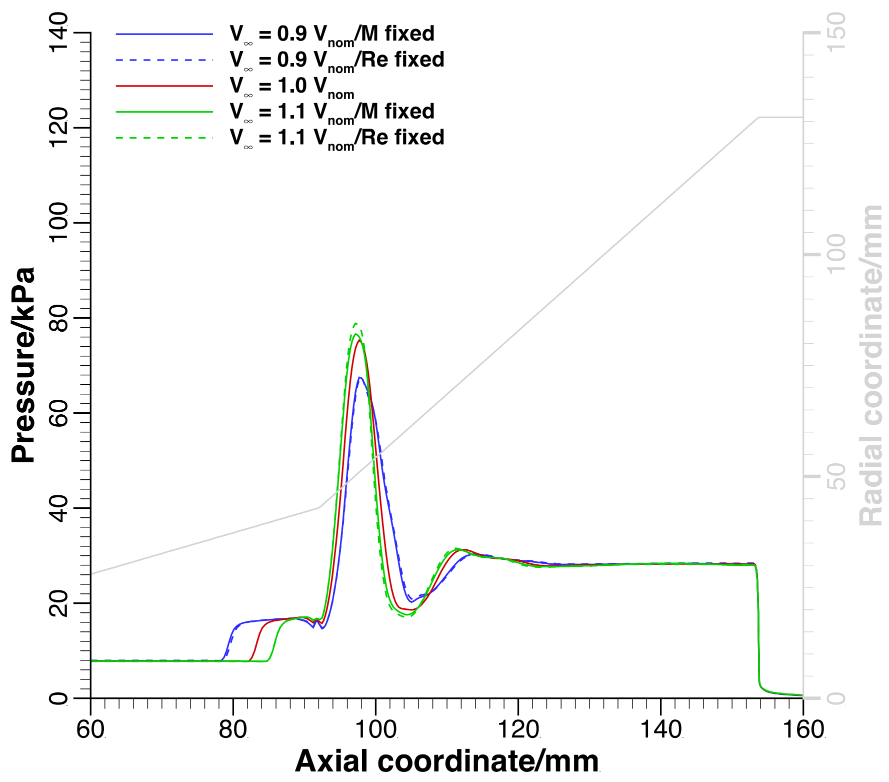
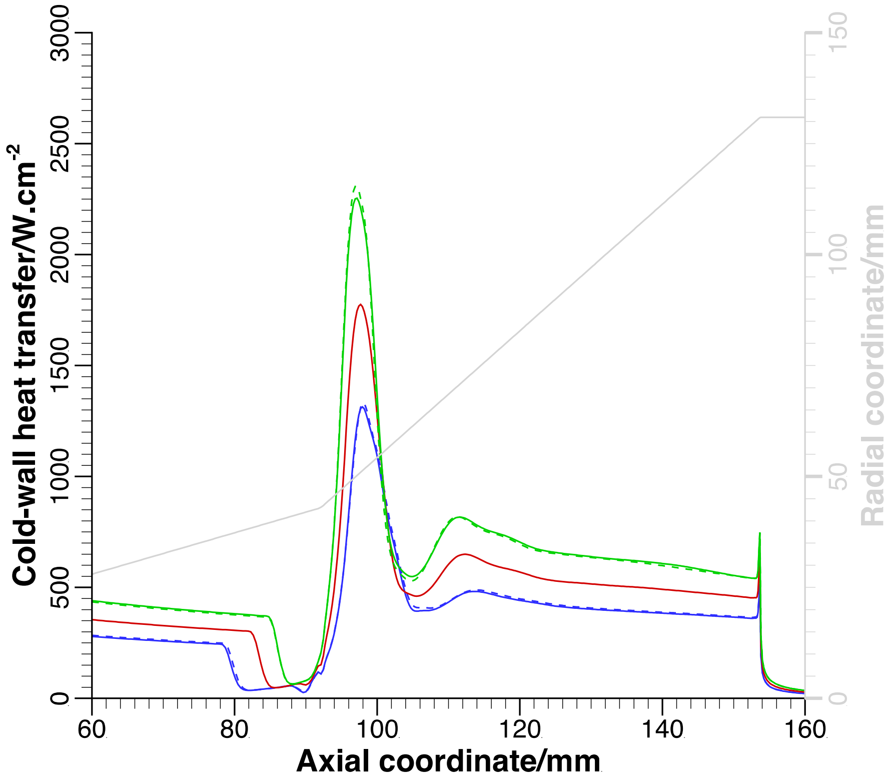
Pressure



Heat Flux



T_∞ from "keep M fixed" or "keep Re fixed" idea has little influence on predictions

±10% variation in velocity at high enthalpy (21.8 MJ/kg) has more influence

Blind Study – Cases 1 & 4

Influence of Angle of Attack

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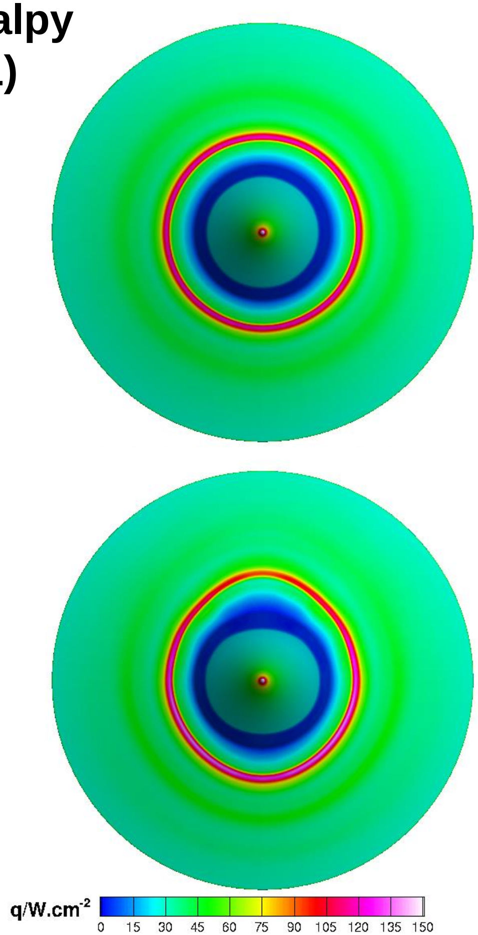
Low Enthalpy (Case 1)

$\alpha = 0°$

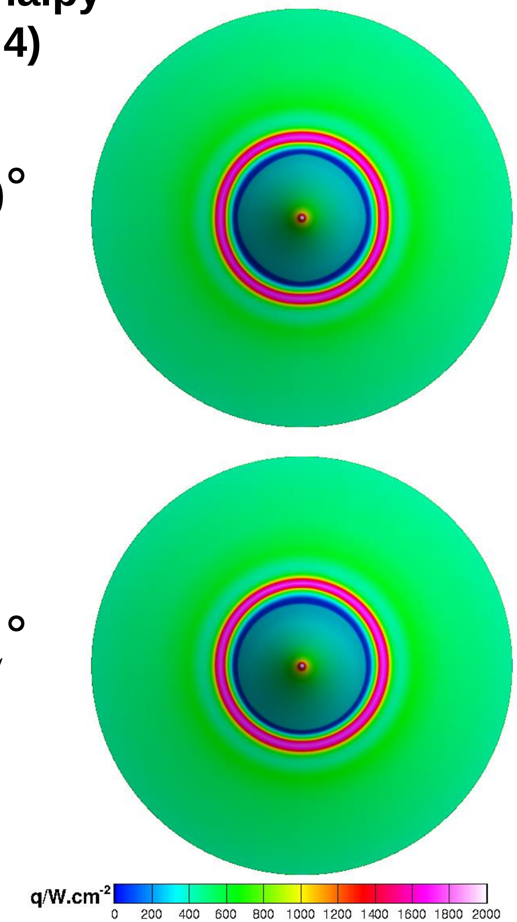
$\alpha = 2°$



High Enthalpy (Case 4)

$\alpha = 0°$

$\alpha = 2°$



Angle of attack influence is greatest for largest separation bubble size

Bubble size at 5 MJ/kg >> Bubble size at 21.8 MJ/kg

Blind Study – Case 1 (Low Enthalpy)

Influence of Gas Model

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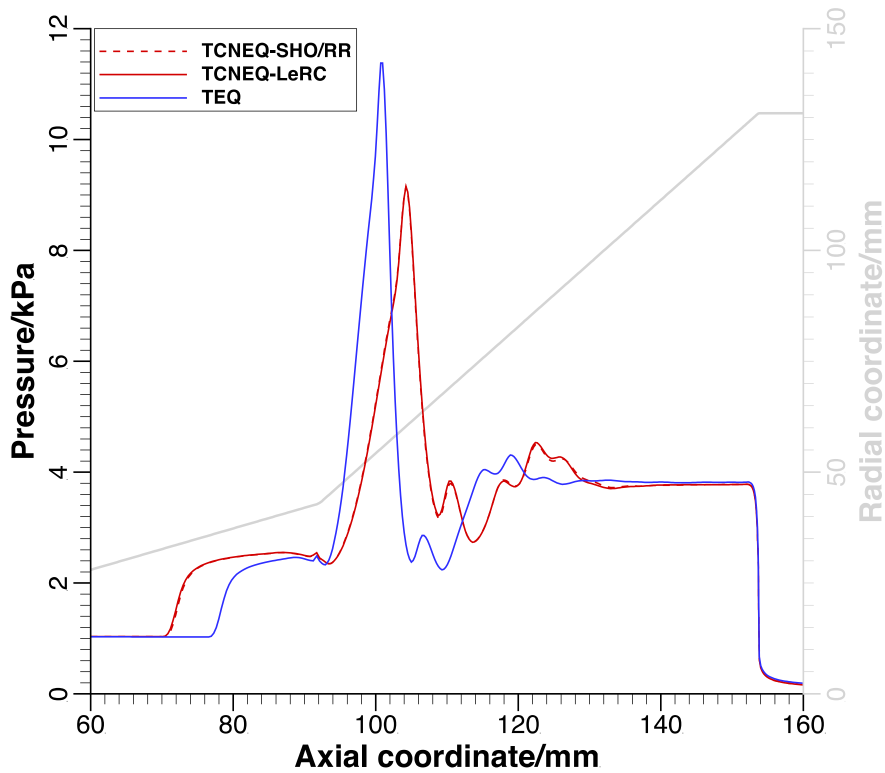
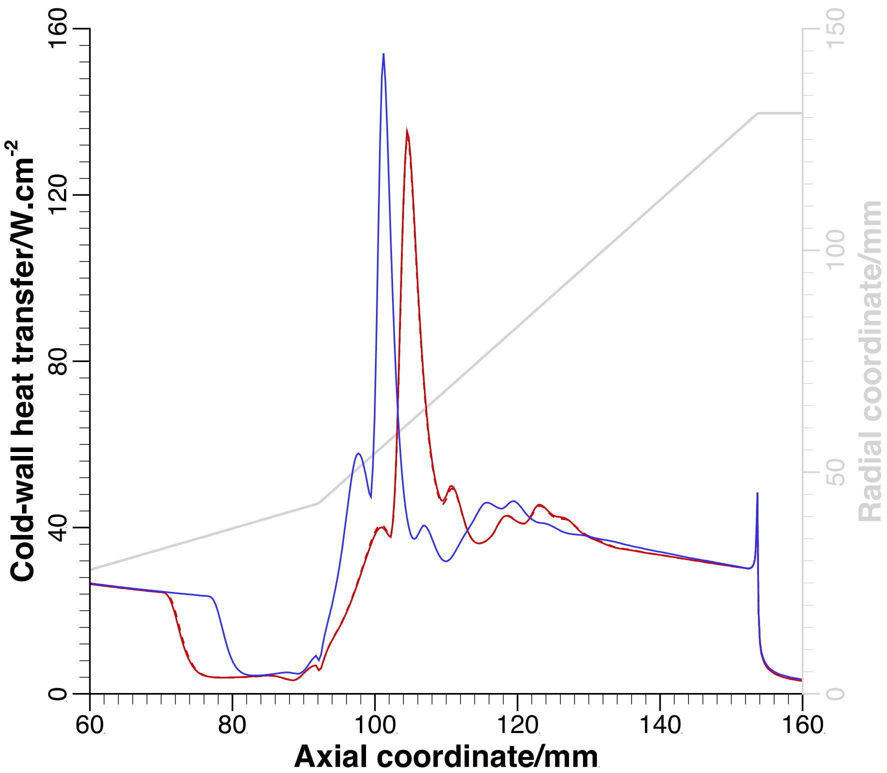
Pressure



Heat Flux



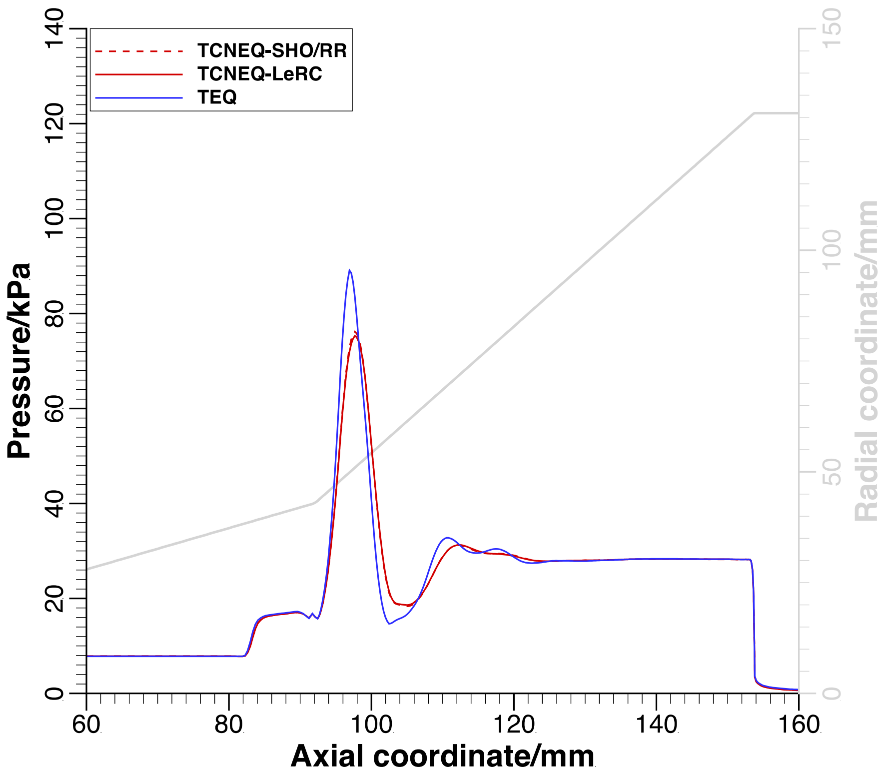
SHO/RR or LeRC fits for thermodynamic properties makes no difference

Thermal relaxation at low enthalpy (5 MJ/kg) has an enormous influence

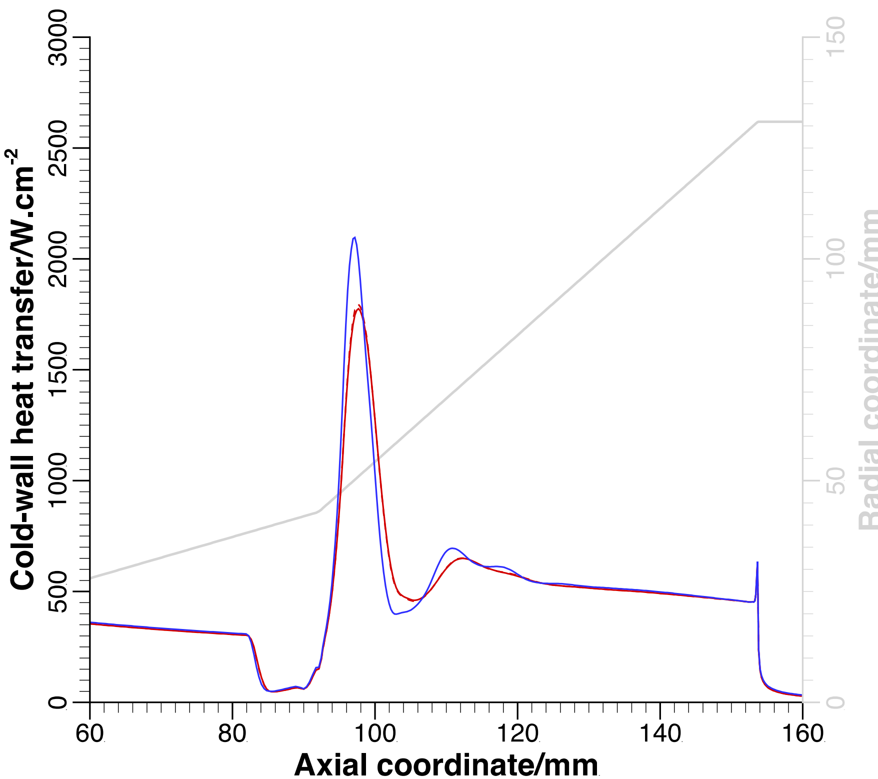
Blind Study – Case 4 (High Enthalpy)

Influence of Gas Model

Pressure



Heat Flux



SHO/RR or LeRC fits for thermodynamic properties makes no difference

Thermal relaxation at high enthalpy (21.8 MJ/kg) has smaller influence than in Case 1

Concluding Remarks

- **Accomplishments**
  - All cases computed for both configurations
    - The hollow cylinder-flare configuration has not received the same level of attention as the double cone configuration
  - Each case had something unique to offer, especially Case 2
    - Schlieren images for these cases would be most helpful
- **Things still left to do**
  - Study influence of transport properties
  - Complete grid convergence studies for the hollow cylinder-flare configuration
- **Lesson Learned and/or Open issues (in the view of the author)**
  - Since freestream velocity has the most influence on environments, would be preferable to have independent measurements of freestream velocity
    - Would also be preferable to work with the actual nozzle contour and perform 3D flow computations -> predicted freestream chemical state is a bonus
  - Need some cases from facility characterization as well to complete V&V story
    - Stag. measurements of heat flux *and* pitot pressure for either the 3.5-in cylinder or 1.25-in hemisphere