Shock Wave Interactions
A CFD Study of CUBRC LENS-II Turbulent Experiments

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June 20, 2014

AIAA Aviation and Aeronautics Forum and Exposition (AVIATION 2014)

Tech. Session FD-39. Comparison between CFD and Measurements in Hypervelocity Flows Part 2: Shockwave Turbulent Boundary Layer Interaction in High Reynolds Number Duplicating Mach 5–8 Flows

Acknowledgments

- **Michael Holden and Timothy Wadhams for the kind invitation**
- **Michael Wright and Michael Barnhardt of NASA Ames Research Center for encouragement of the work through NASA's ESM (formerly HEDL) program**
- **NASA Ames Research Center for funding this work via Contract NNA10DE12C to ERC, Inc.**

Objective(s)

Primary

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

- **(a) Sharp cone-flare (7° /40°) model**
- **(b) Hollow cylinder-flare (36°) model**

tested at turbulent flow conditions in LENS-II at CUBRC

Secondary

To explore transition (to turbulence) aspects of flow for these configurations

Focus of this presentation is solely on the sharp cone-flare model

Modeling & Computing Strategy

Modeling

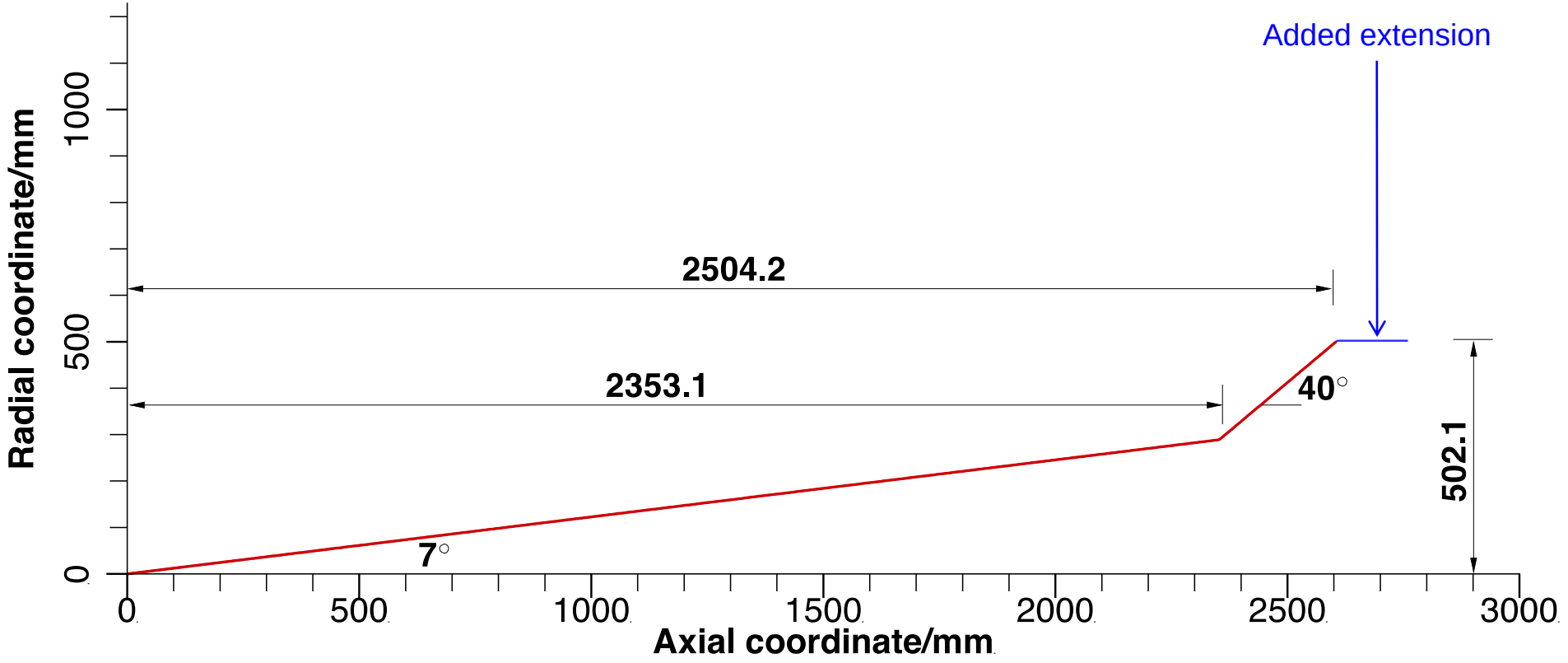
- **v4.03.1 of *Dplr***
  - **Ideal gas (γ=1.4) for all cases**
  - **Sutherland's law for viscosity of air**
  - **Constant Prandtl number = 0.71**
  - **Isothermal wall, T_w = 300 K**

Strategy

- **Perform laminar computations for cone alone (no flare)**
  - **Extract Re_θ from computed flow field using *Blayer***
    - **Edge detection method: 99.5% of freestream enthalpy**
  - **Use Re_θ (from laminar solution) to specify onset of transition**

- **Perform turbulent computations for full configuration**
  - **SST model with no compressibility correction**
  - **Dhawan-Narasimha model for transition (intermittency)**

Cone-Flare Model



Cone-flare model has a sharp tip

Sufficient run length to ensure natural transition ahead of flare (interaction region)

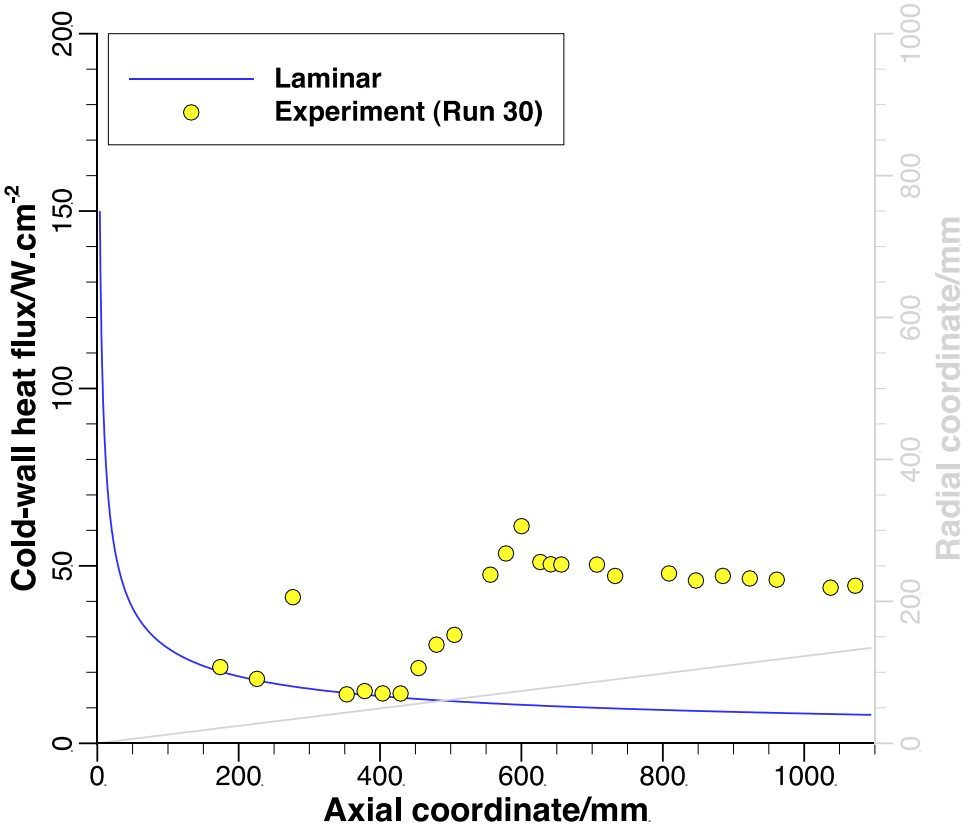
7° cone is identical to that of HIFiRE-1 configuration

HIFiRE-1 had a cylindrical section before the flare and the tip was blunt (2.5 mm radius)

Learning Case – HIFiRE-1/Run 30

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

Run #	43	30
	Mach 7	
ρ/g.m^{-3}	38	67
V/km.s^{-1}	2.20	2.17
T/K	250	227
Re x m 10^{-6}	3.7	9.8
L/m	***2.342***	?
H_0/MJ.kg^{-1}	2.65	2.58
h_w/H_0	0.11	0.12

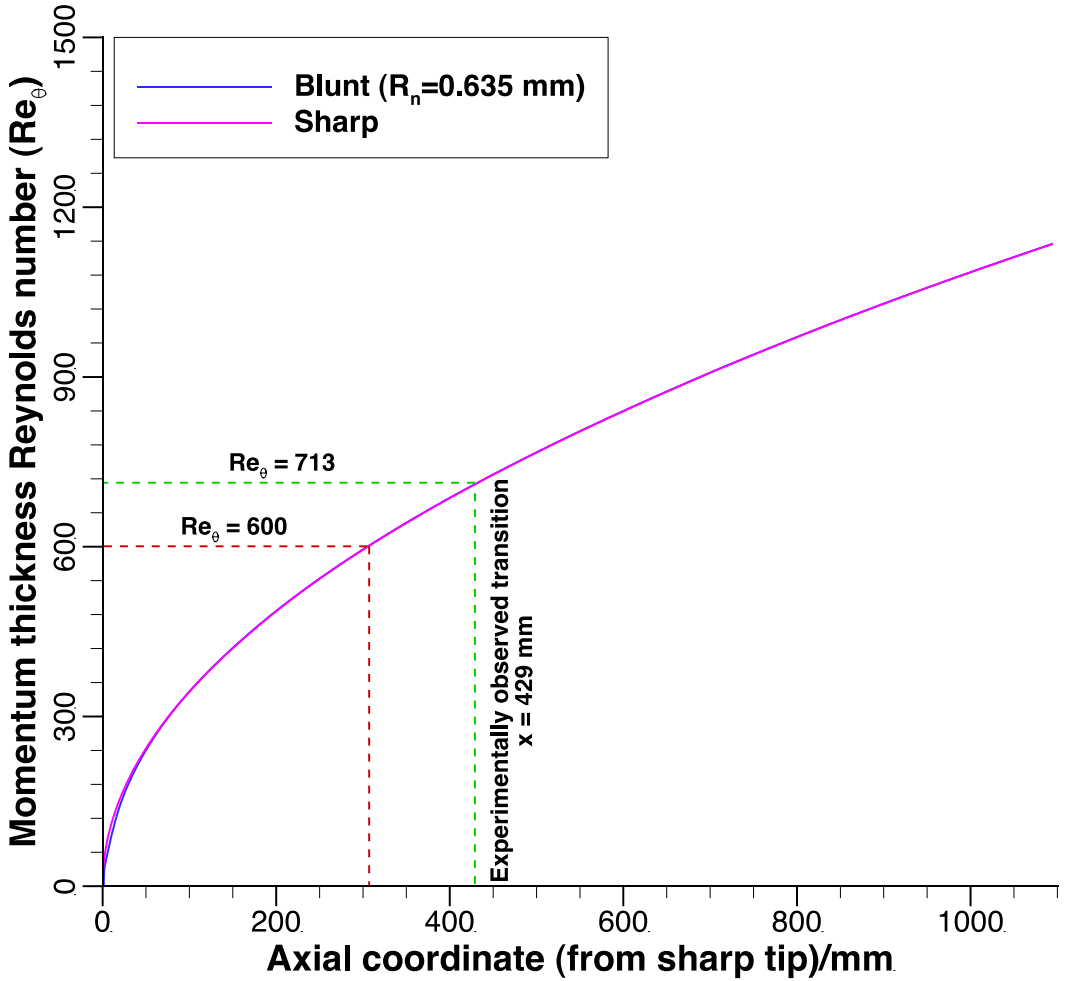


Run 43 of blind study matrix is comparable to Run 30 (HIFiRE-1)

Comparison of laminar results with experimental data shows transition location at 429 mm

Extract Re_θ at x = 429 mm from laminar flow solution

Transition Location (Run 30)

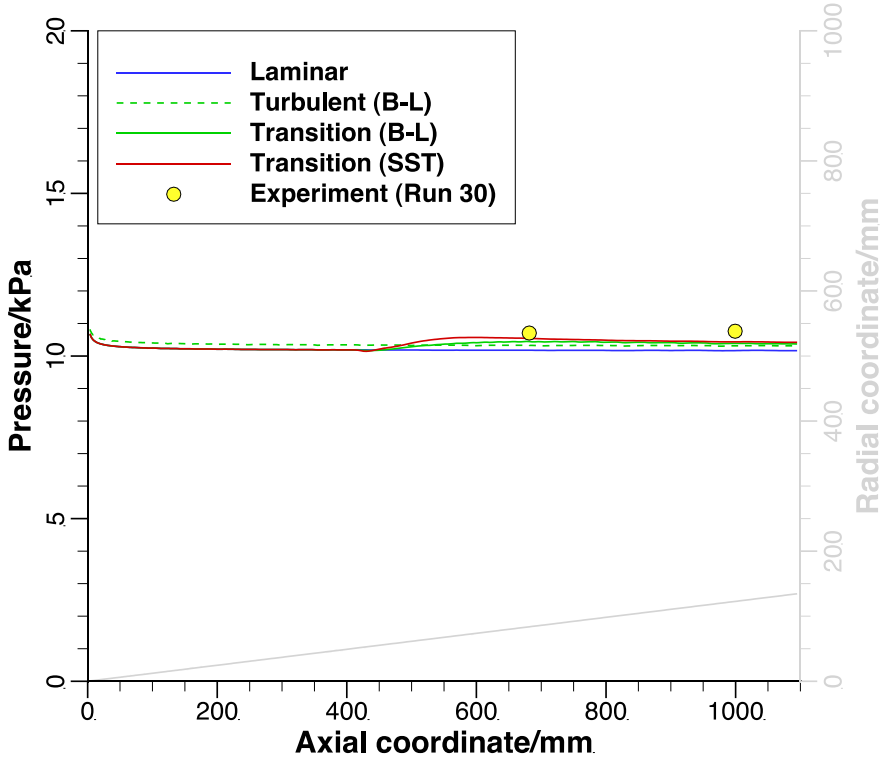


Re_θ at x = 429 mm is ≈700 – preferred location for Baldwin-Lomax model

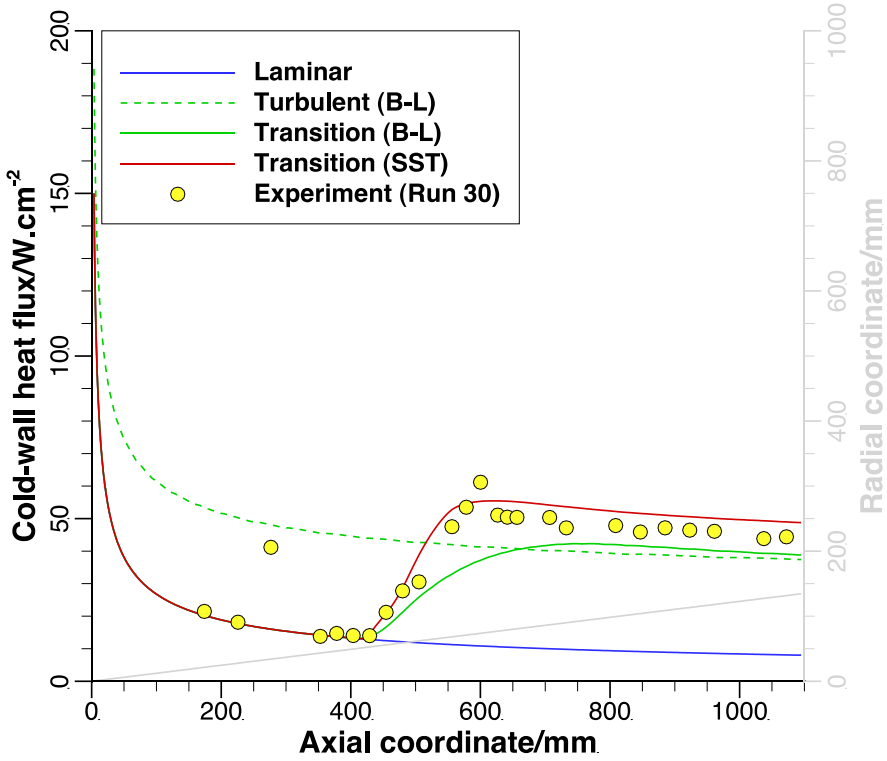
Re_θ = 600 occurs at x = 310 mm – preferred location for SST model

Turbulent Flow Computations – Run 30 (HIFiRe-1)

Pressure



Heat Flux



SST model (without compressibility) provides best agreement with experimental data

Input transition locations for B-L and SST models are different!!!

Blind Study Test Matrix for Cone-Flare Geometry

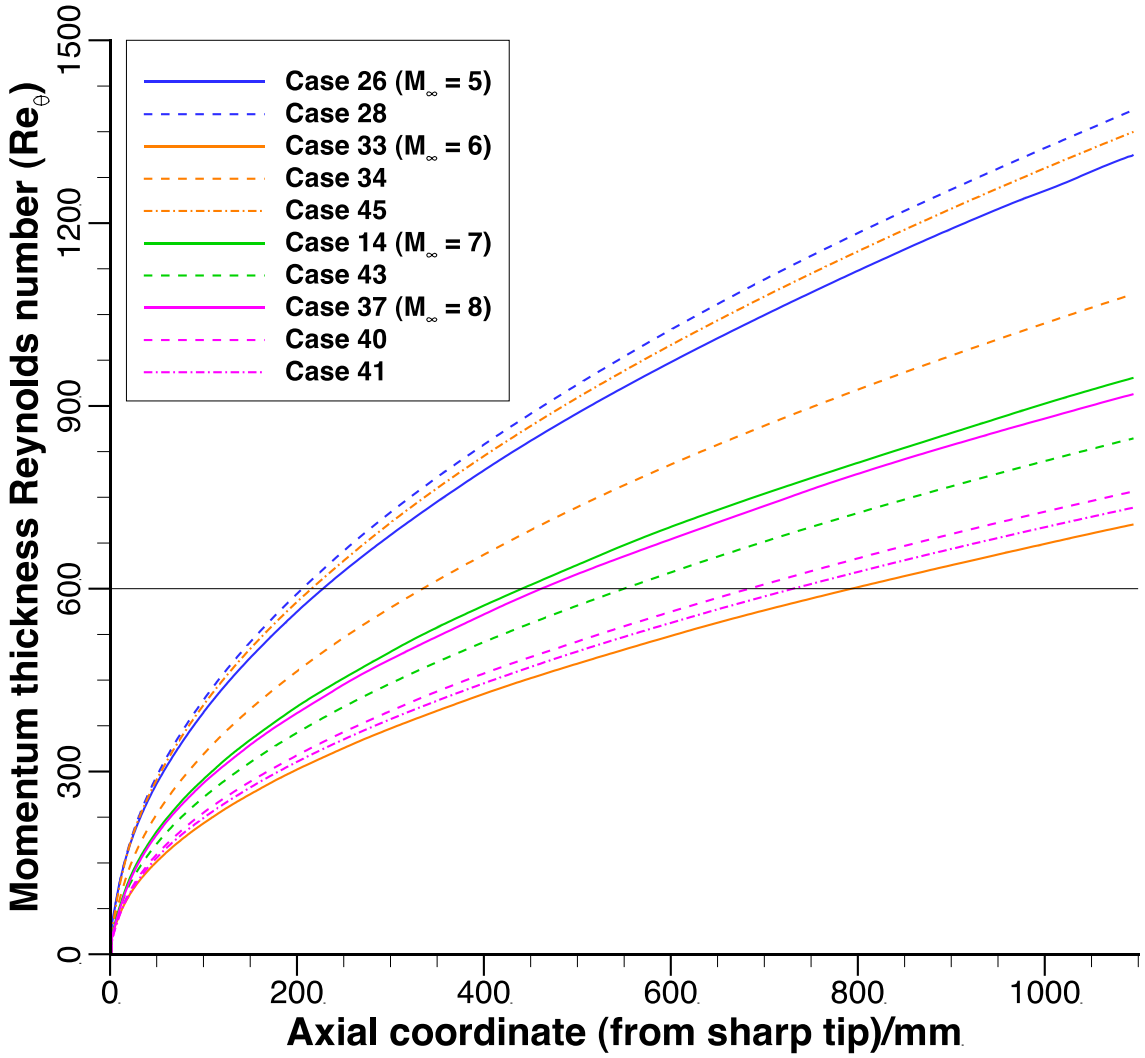
Run #	26	28	33	34	45	14	43	37	40	41
	Mach 5		Mach 6			Mach 7		Mach 8		
ρ/g.m^{-3}	284	141.7	73.7	71.12	111.3	57.21	37.88	43.7	24.22	23.55
V_1/km.s^{-1}	0.89	1.48	0.93	1.58	1.85	1.18	2.20	1.28	1.75	2.10
T/K	76	220	56	170	244	67	250	60	118	167
Re x m 10^{-6}	49	14.5	18.5	9.7	13.1	15.0	5.2	14.0	5.2	4.4
L/m	2.408	2.407	2.395	2.422	***2.809***	2.440	***2.342***	2.393	2.404	2.403
H_0/MJ.kg^{-1}	0.47	1.31	0.49	1.41	1.96	0.76	2.65	0.88	1.64	2.37
h_w/H_0	0.64	0.23	0.62	0.21	0.15	0.40	0.11	0.34	0.18	0.13

Wall enthalpy comparable to total enthalpy => sensitivity to wall temperature

Cases 45 & 43: Inferred characteristic length at variance with cone axial length of 2.353 m

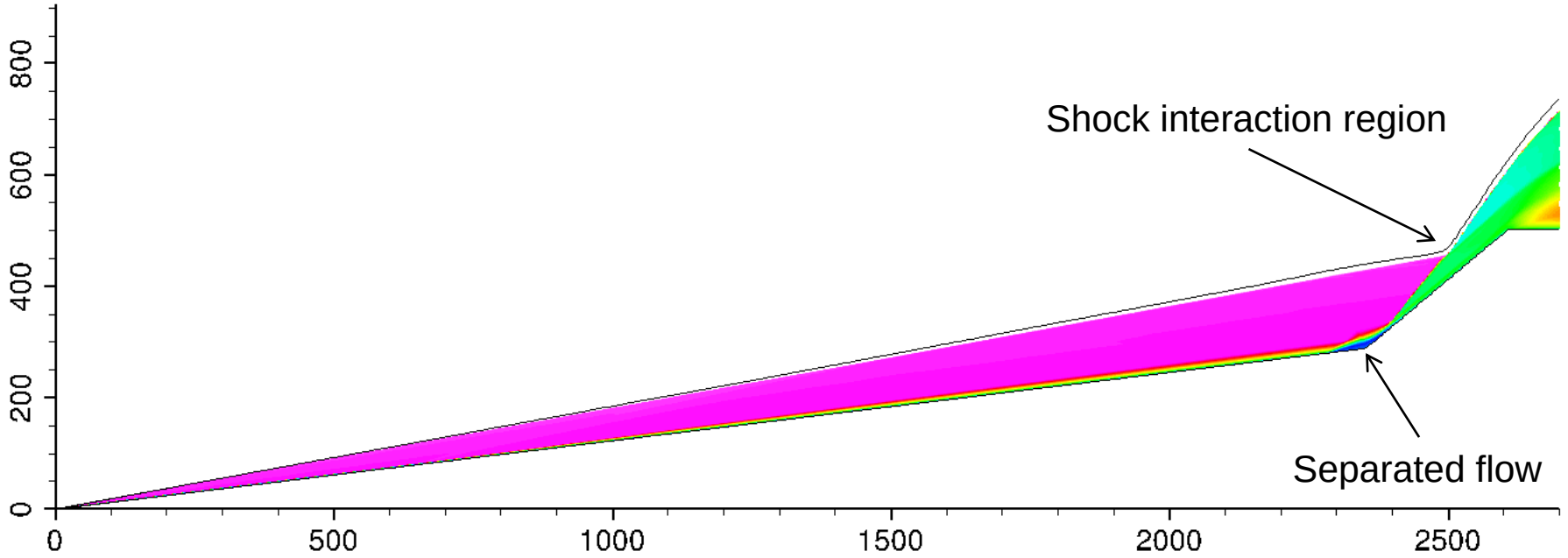
Real-gas effects, if any, probably limited to change in γ, i.e., no chemistry

Transition Locations for Blind Study Matrix



Locations corresponding to Re_θ = 600 used for *all* blind study cases (since SST used)

Sample Result: Run 37 (Mach 7)

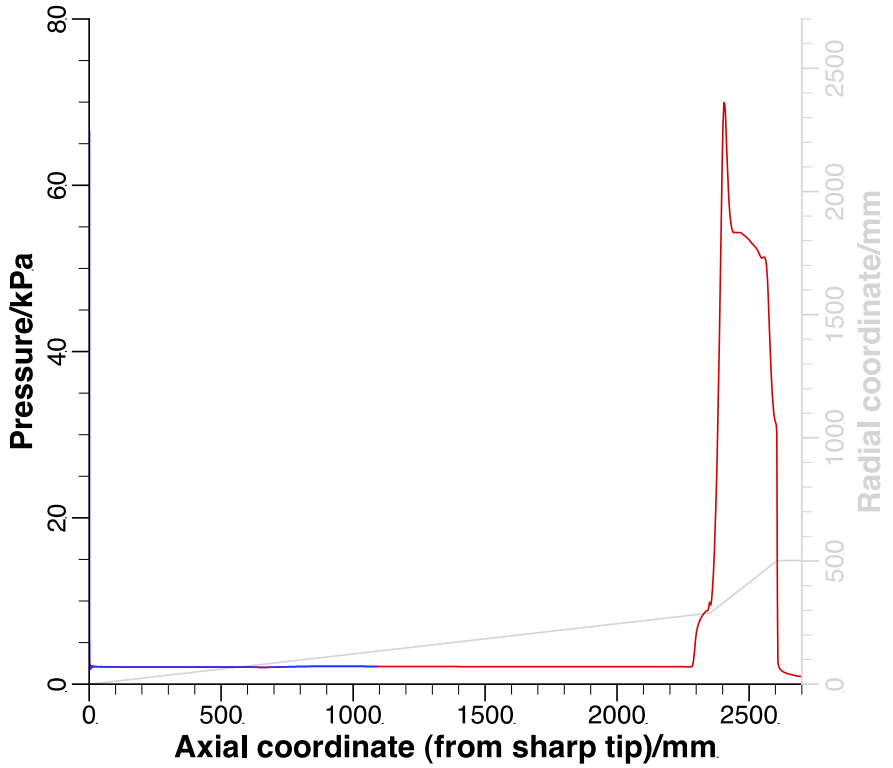


Grid tailored to outer shock including the shock interaction region

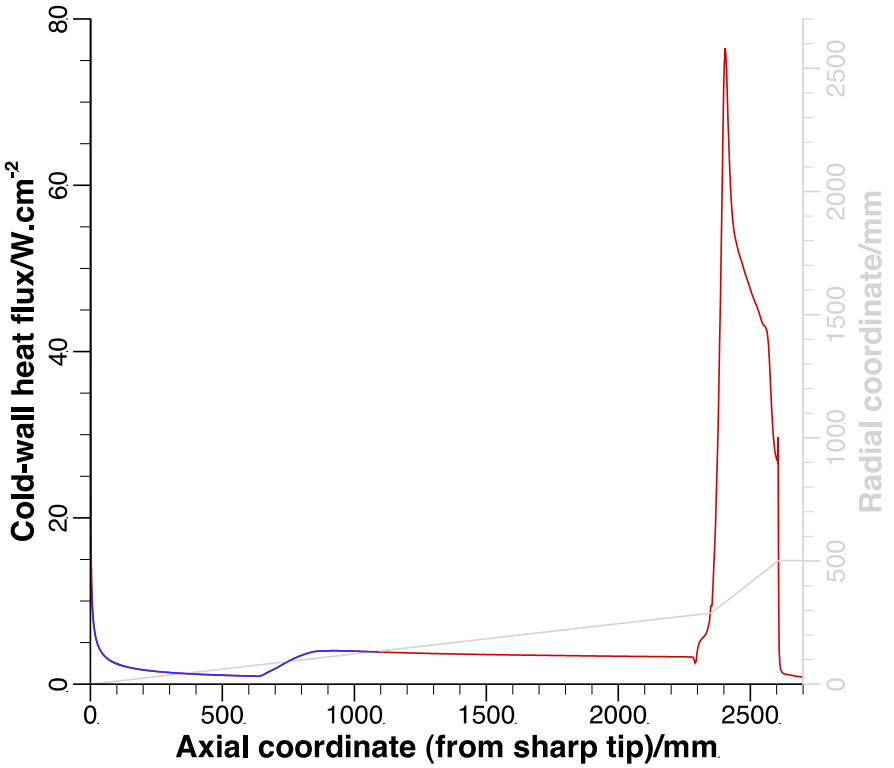
Separated flow seen at the foot of the flare

Sample Result: Run 37 (Global View)

Pressure



Heat Flux

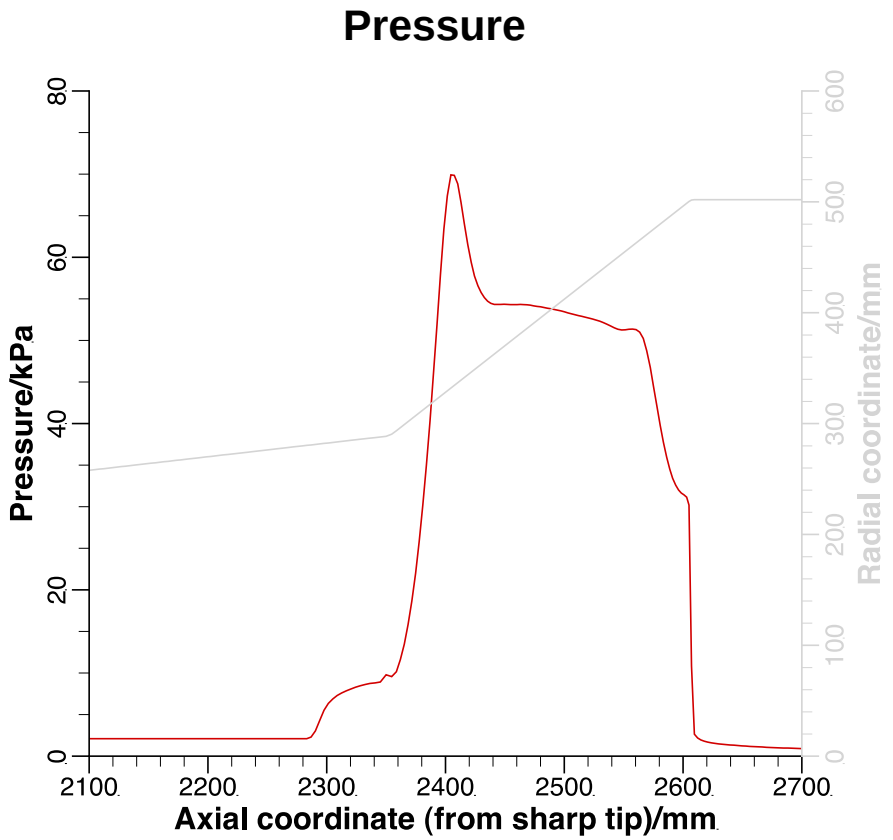


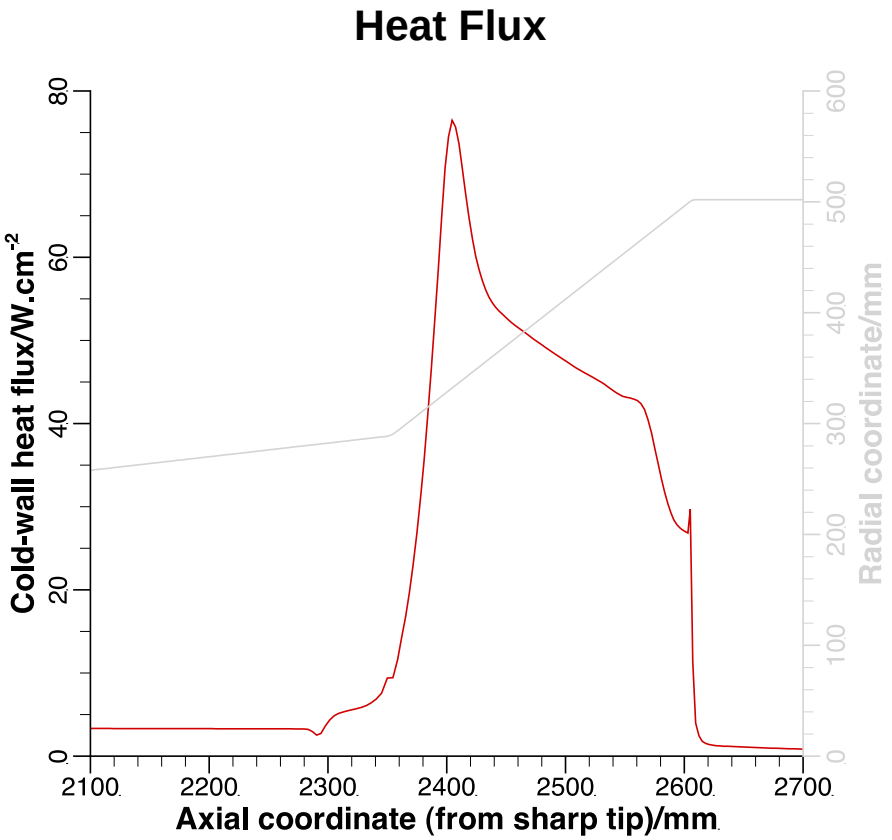
Only SST computations performed for full configuration

Transition location at $Re_\theta = 600$

No laminar or Baldwin-Lomax turbulent solution for full configuration!!!

Sample Result: Run 37 (Local View)





Only SST computations performed for full configuration

Transition location at $Re_\theta = 600$

No laminar or Baldwin-Lomax turbulent solution for full configuration!!!

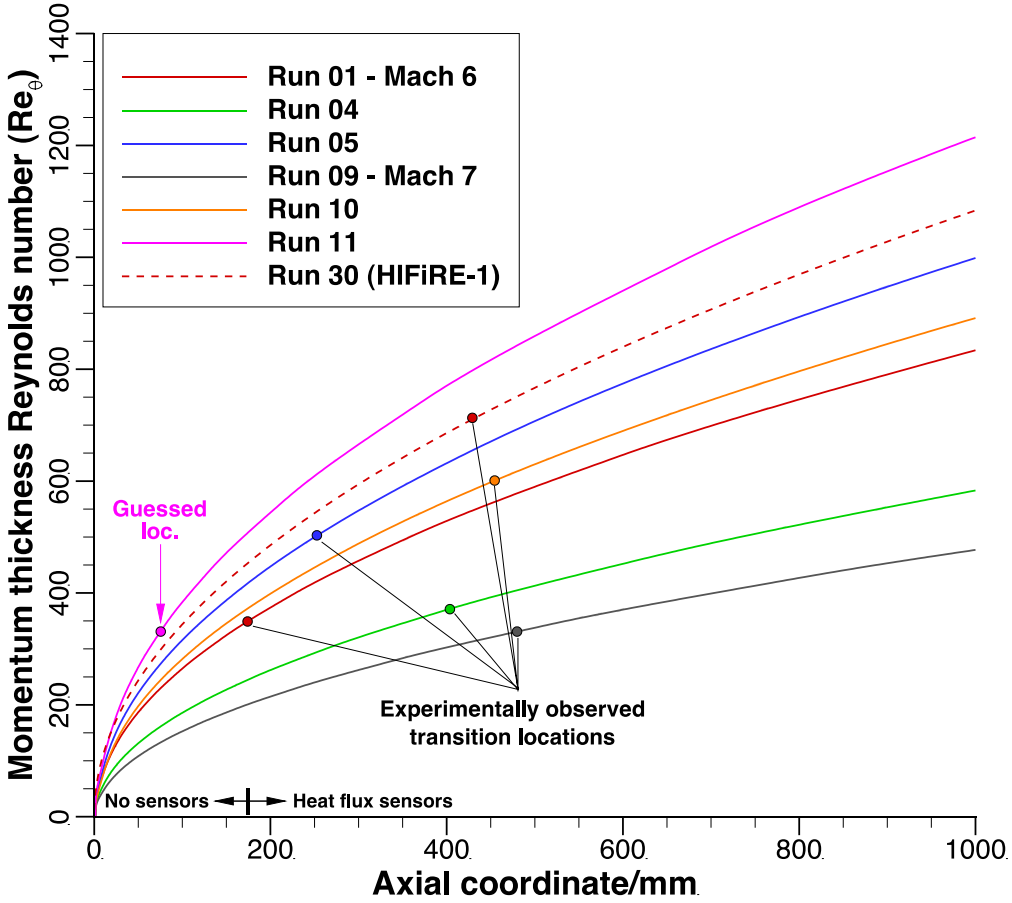
How Good is the Re_θ = 600 Transition Criterion?

- **Answer: Good only for one HIFiRE-1 case, but not applicable across all cases!!**

- **Additional cases from AIAA 2013-2836**
  - **Experimentally determined transition locations available for some cases**
    - **For Runs 1, 4, 5, 9, and 10 transition location available**
    - **For Run 11, flow transitioned before first sensor location (174 mm)**
  - **These additional cases have been computed as well**

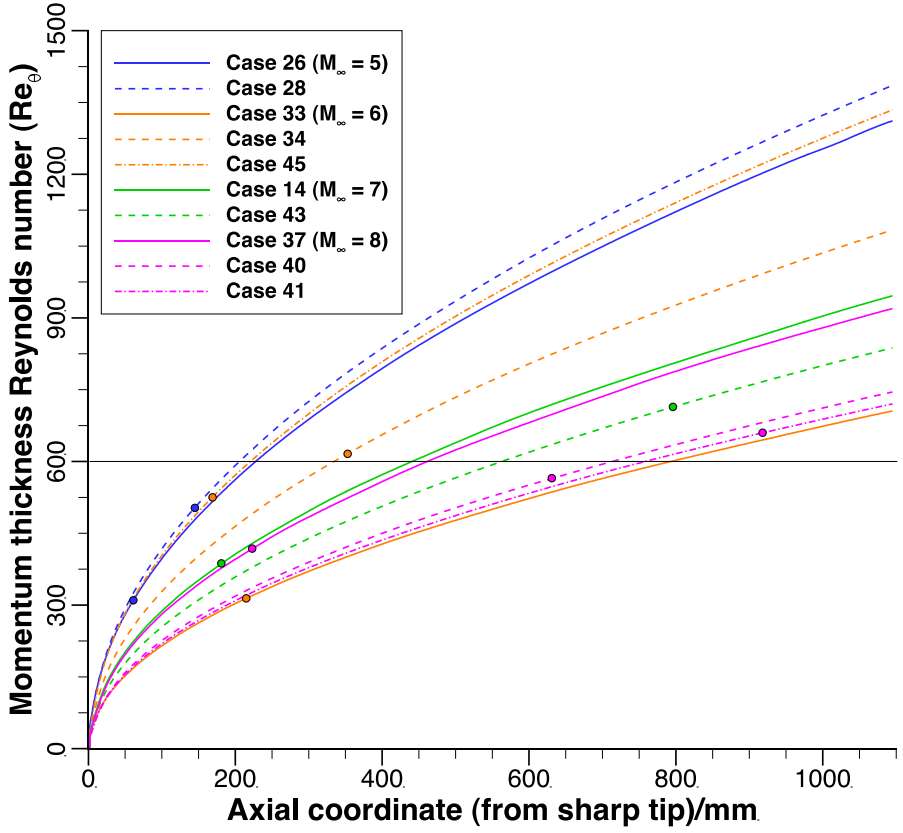
- **Results from additional calculations can be used to construct a model to make predictions of onset of transition (at least for the cone-flare geometry)**
  - **Details will be in the written paper**
  - **Applicability to the cylinder-flare configuration remains to be seen**

x_{tr} vs Re_θ from Additional Computations



	Run #	1	4	5	9	10	11	30
Expt.	x_{tr}/mm	174	404	253	480	454	?	429
CFD	Re_θ	349	372	503	331	617	?	713

Transition Onset Predictions for Blind Study Cases



- $Re_\theta \neq 600$ in all cases
- In most cases, transition occurs earlier
- Cases have not been recomputed with new onset locations

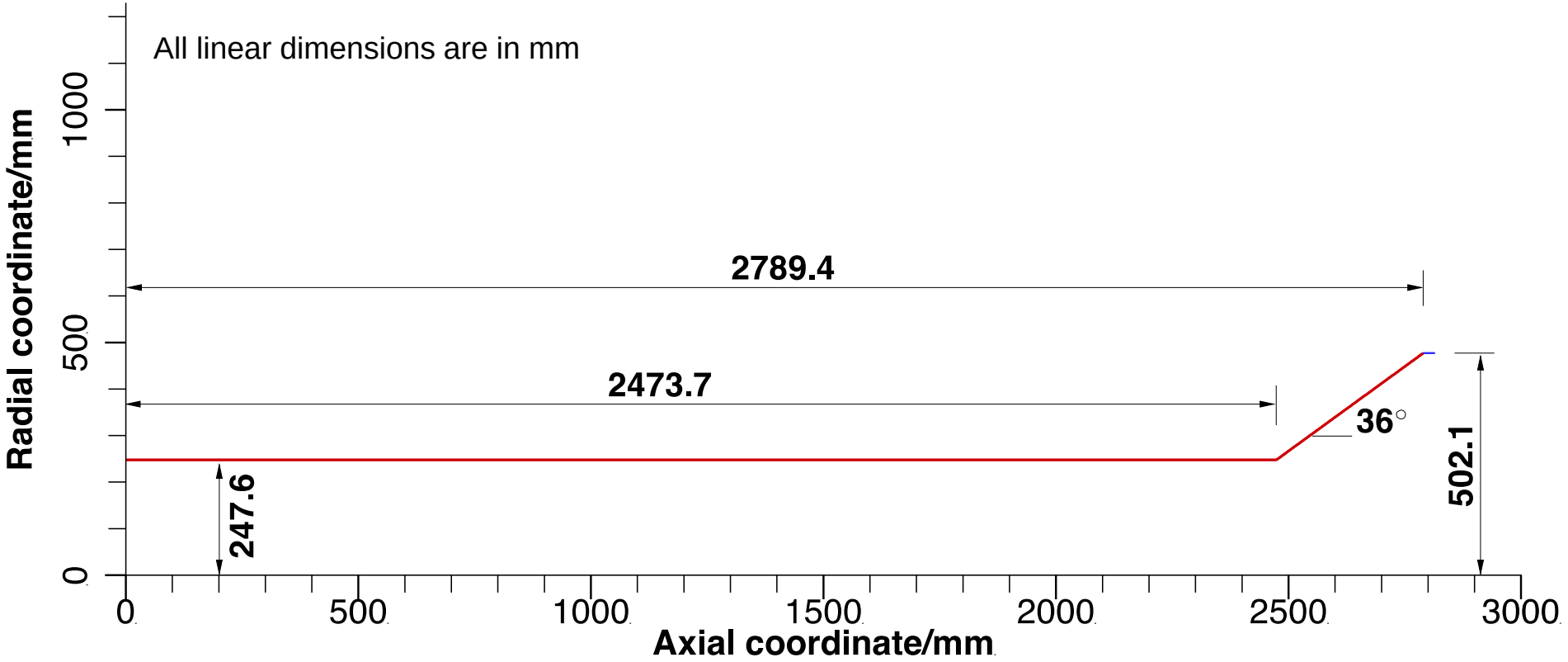
Run #	26	28	33	34	45	14	43	37	40	41
	Mach 5		Mach 6			Mach 7		Mach 8		
x_{tr}/mm	61	145	215	169	353	181	796	223	631	918

Concluding Remarks

- **Accomplishments**
  - All cases computed for both configurations
  - Transition imposed at $Re_\theta = 600$ for all cases
    - Unfortunately this criterion is solely for the HIFiRE-1 case
  - An attempt made to predict transition onset for the 7° sharp cone
    - Cases have not been recomputed with predicted onset locations
- **Things still left to do**
  - Recompute all cases with predicted onset locations
  - Reconcile differences between SST and B-L for transition onset
  - Grid convergence and wall temperature sensitivity studies
  - Choice of turbulence models such as Spalart-Allmaras, Lag, …
    - Can be a collaborative effort with *Overflow* especially since flow medium is ideal gas (γ = constant)
  - Real-gas effects, esp. at Mach 7 or 8
    - Most likely to be purely a variable γ effect, but …
- **Open issue (in the view of the author)**
  - 3D vs Axisymmetric, but 3D is resource intensive

Backup

Hollow Cylinder-Flare Model



Cone-flare model has a sharp tip

7° cone is identical to that of HIFiRe-1 Configuration

HIFiRE-1 had a cylindrical section before the flare and the tip was blunt (2.5 mm radius)

Test Matrix for Cone-Flare Geometry

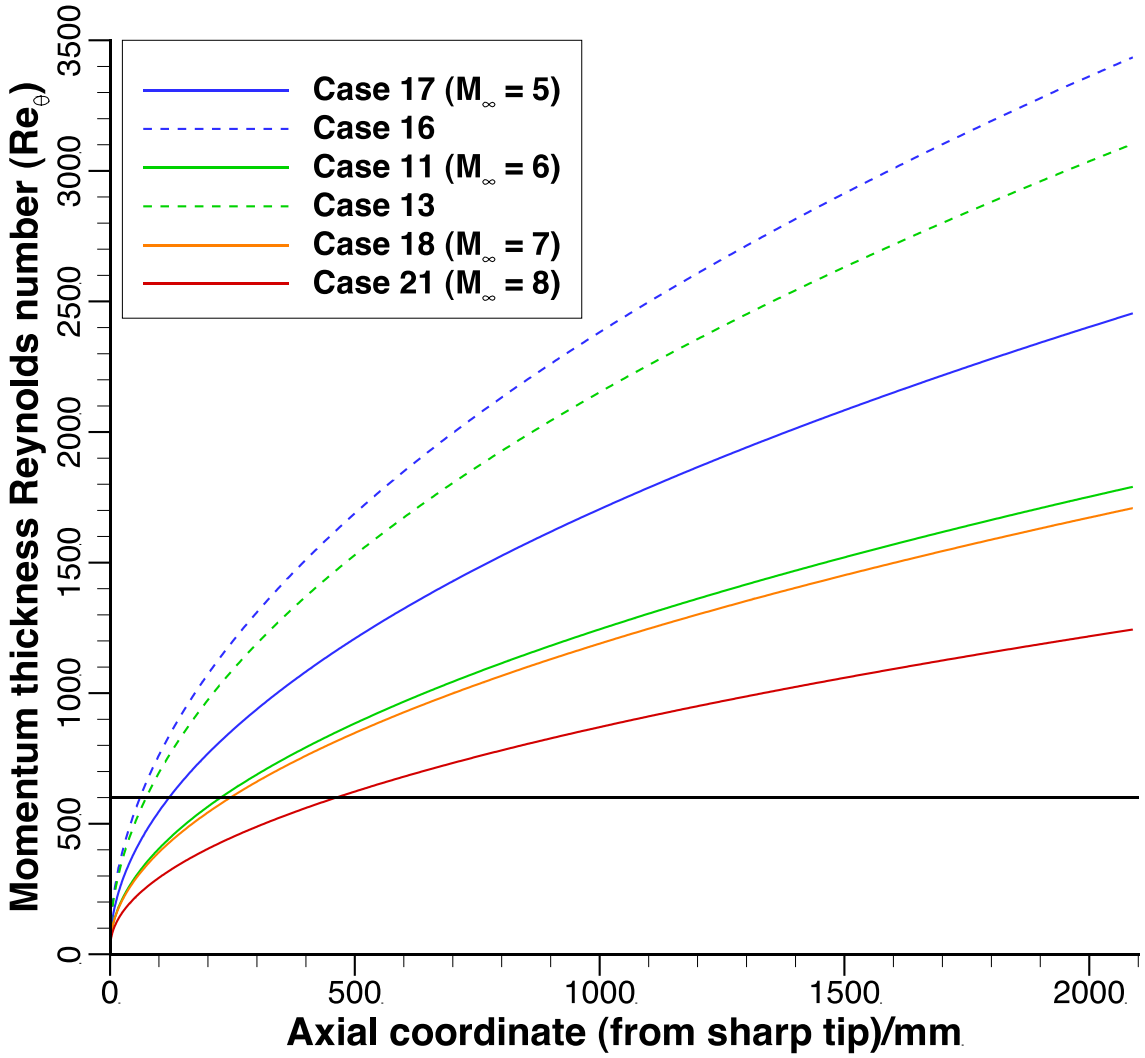
Case	17	16	11	13	18	21
	Mach 5		Mach 6		Mach 7	Mach 8
ρ/g.m^{-3}	109	213	52.6	158	45.9	23.1
V/m.s^{-1}	1.46	1.45	1.70	1.68	2.09	2.17
T/K	214	212	202	193	224	184
Re x m 10^{-6}	11.3	22.2	6.7	20.5	6.6	4.1
L/m	***2.858***	***2.846***	2.596	2.596	2.590	2.590
H_0/MJ.kg^{-1}	1.27	1.26	1.64	1.59	2.41	2.53
h_w/H_0	0.24	0.24	0.18	0.19	0.13	0.12

Wall enthalpy comparable to total enthalpy => sensitivity to wall temperature?

Inferred characteristic length for Cases 16 & 17 differs from the others

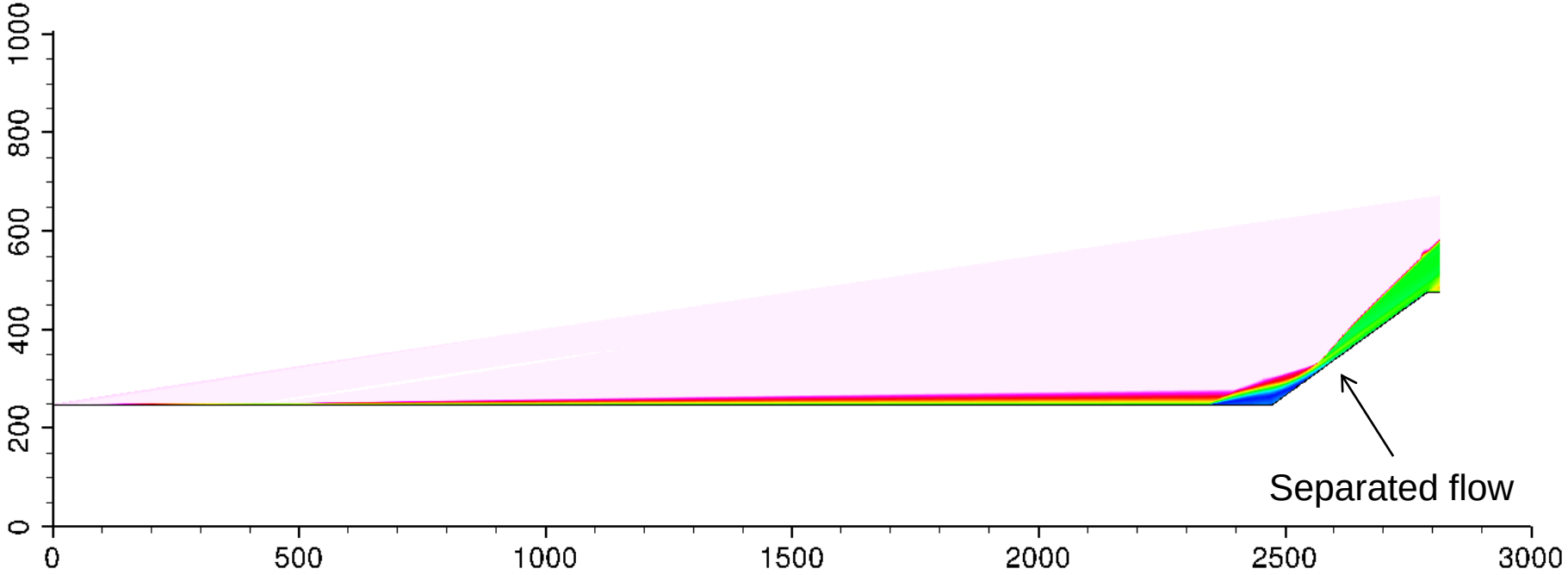
Real-gas effects probably limited to change in γ

Transition Locations for Blind Study Matrix



Locations corresponding to Re_θ = 600 used for *all* blind study cases (since SST used)

Sample Result: Run 18 (Mach 7)

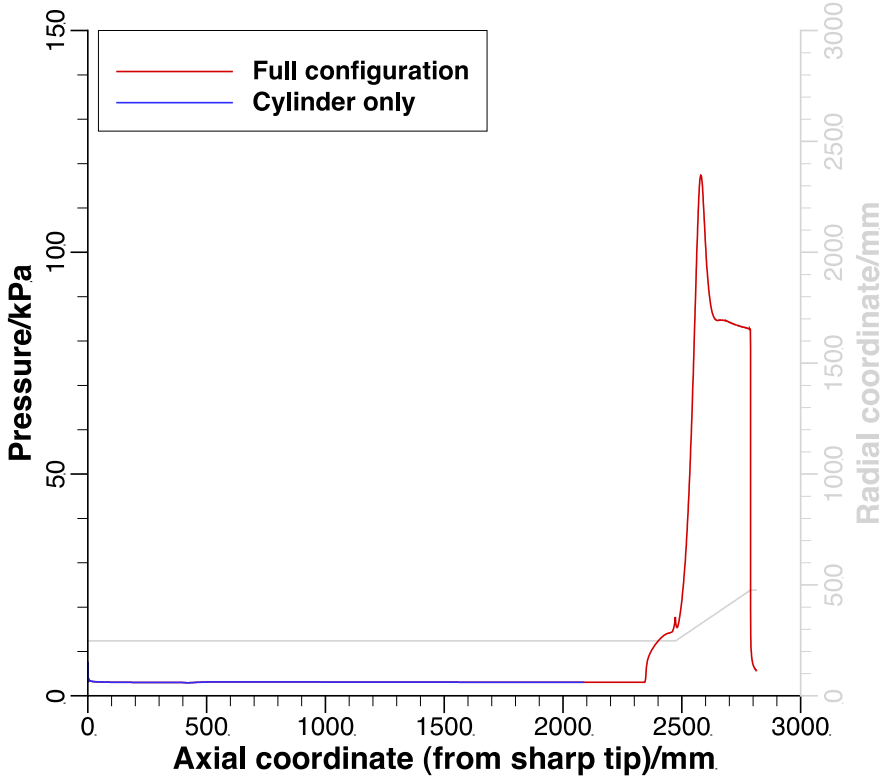


LE shock and flare shock do not interact

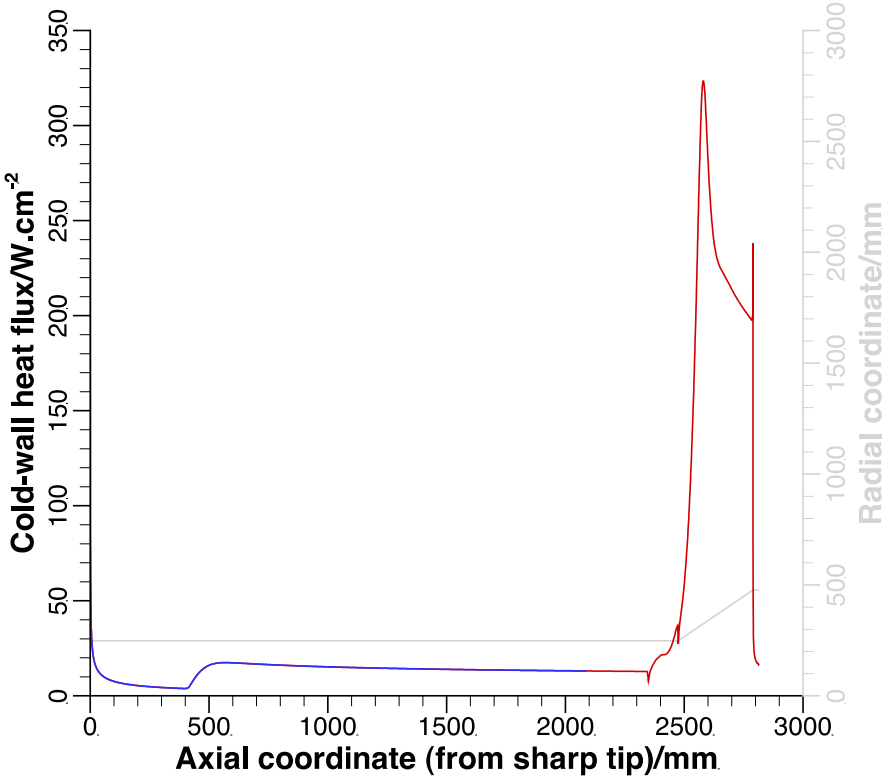
Separated flow seen at the foot of the flare

Sample Result: Run 18 (Global View)

Pressure



Heat Flux

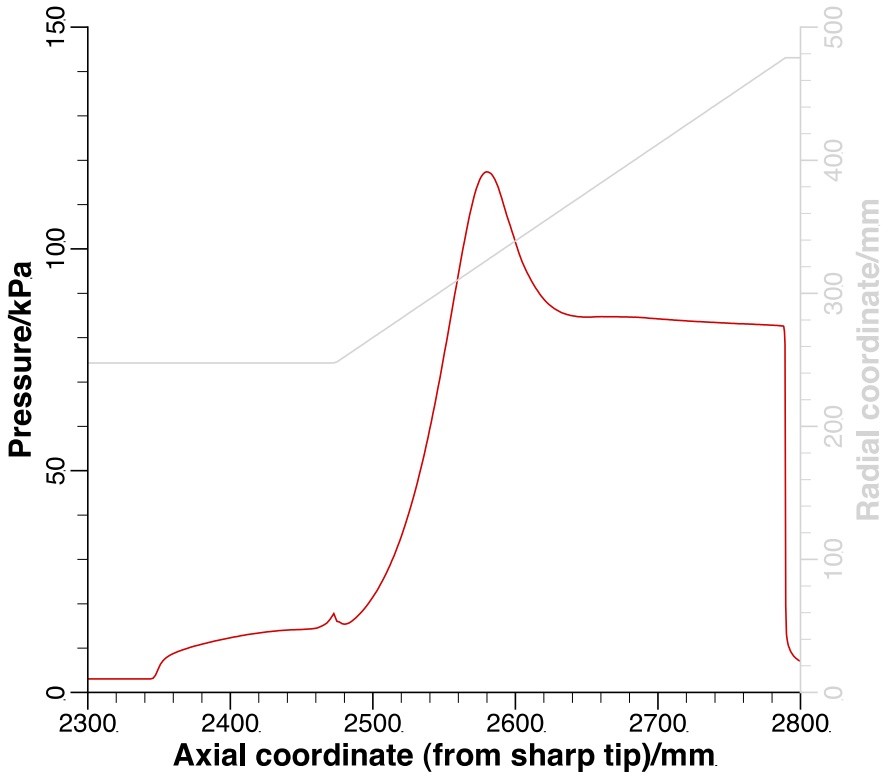


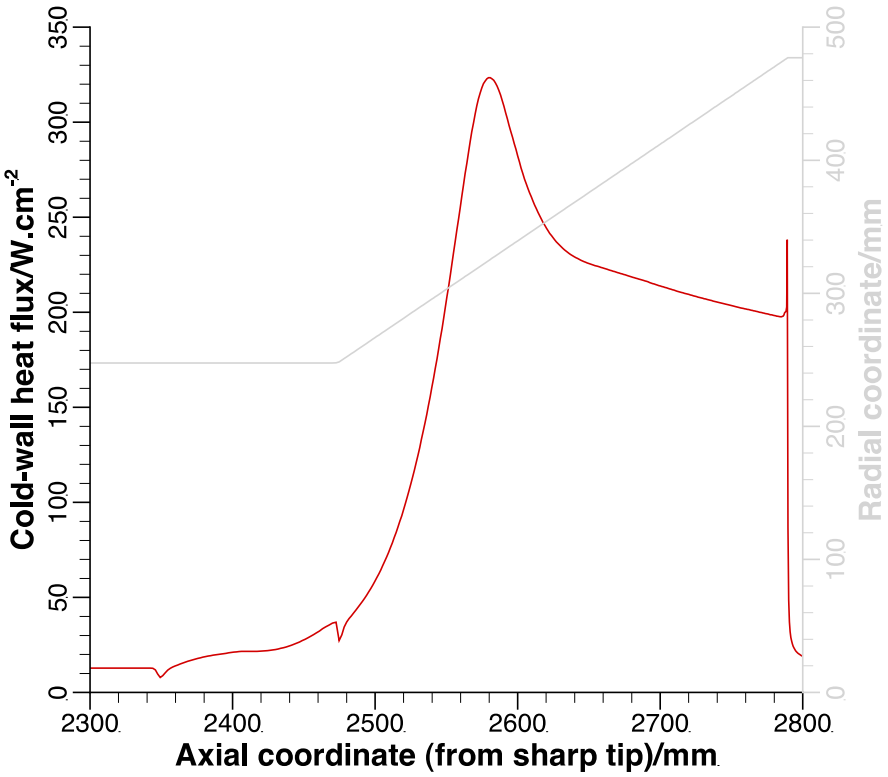
Only SST computations performed for full configuration

Transition location at $Re_\theta = 600$

No laminar or Baldwin-Lomax turbulent solution!!!

Sample Result: Run 18 (Local View)





Only SST computations performed for full configuration

Transition location at $Re_\theta = 600$

No laminar or Baldwin-Lomax turbulent solution!!!