Investigation of supersonic and hypersonic laminar shock/boundary-layer interactions

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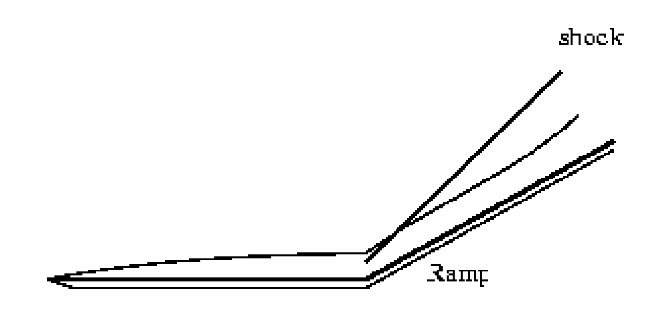
Outline of Presentation

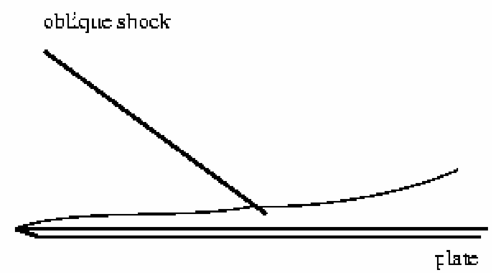
- Background and Motivation
- Configuration and Numerical Methods
- Range of Test Cases & Experimental Data
- Results: M = 2.0 and M = 7.73
- Correlations of All Test Cases
- Conclusions

Background and Motivation

- SBLI study: the effect on surface heating rates;
- Experiment: high heat fluxes in the re-attachment area, e.g. ramp flow (Smith, 1993);
- 2D CFD modelling: failed to predict the separation length and the peak heat flux, possibly due to transition.

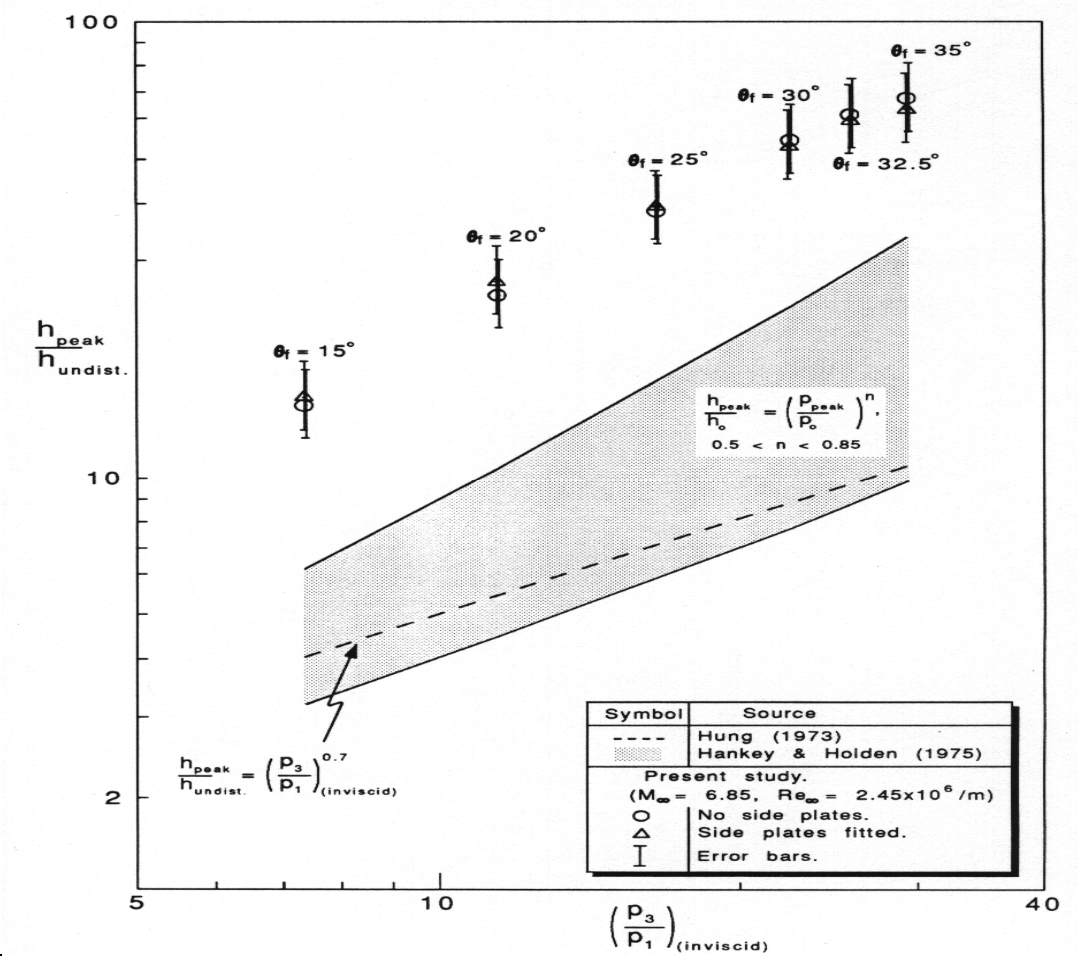


Ramp flow



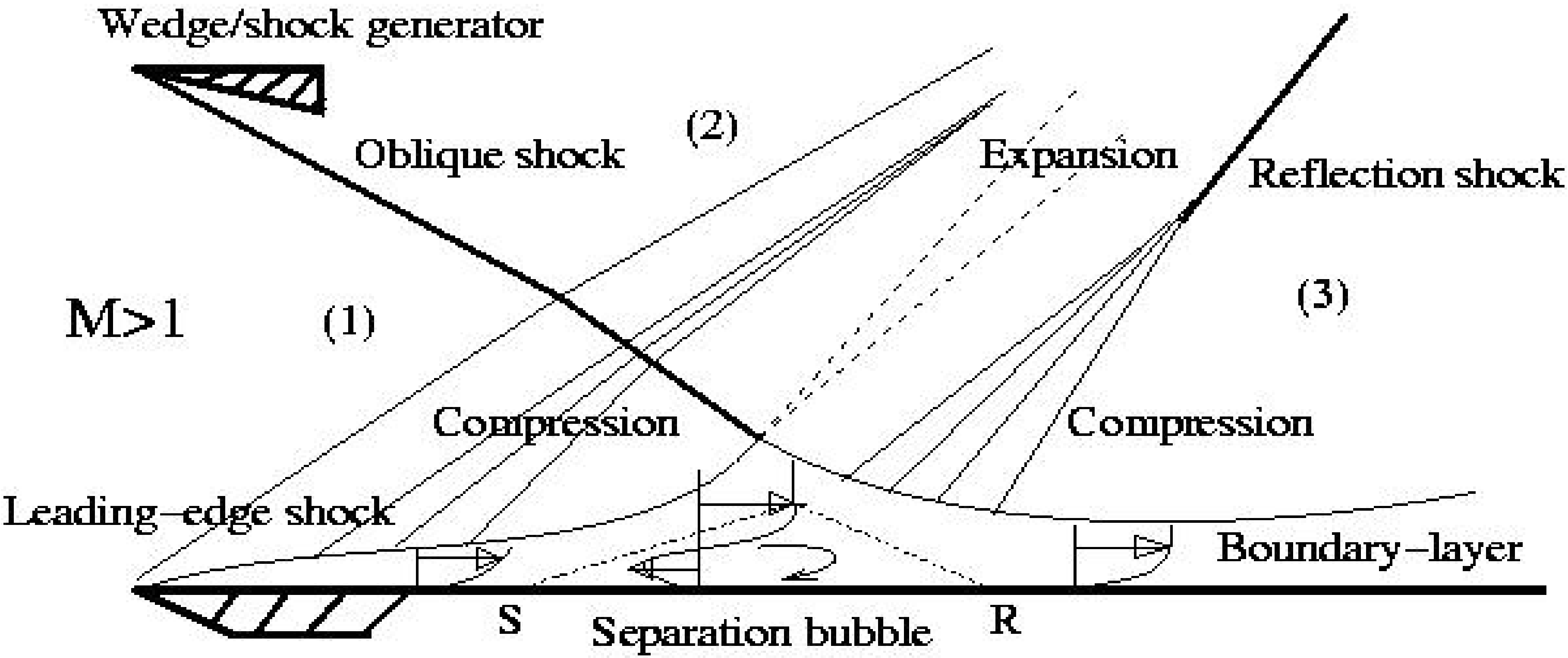
Oblique shock/bl interaction

Comparison of Peak Reattachment Heating with Laminar Interference Heating Correlations



Compression ramp experiments, M = 6.85 (Smith, 1993)

Schematic of flow configuration



Numerical methods

- Compressible, unsteady 3-D Navier-Stokes code;
- Grid transformation for complex geometries;
- 3-stage explicit Runge-Kutta for time advancement;
- 4th-order central finite difference scheme;
- Entropy splitting for Euler terms and Laplacian form for viscous terms;
- Stable high-order boundary treatment;
- TVD/ACM for shock capturing.

For details, see Sandham et al., JCP 178, 307-22, 2002

Range of Test Cases

Case	Symbols	Mach number, M_∞	Reynolds number, $R_{e_{x_o}}$	Overall p. ratio (p_3/p_1)
1	Δ	7.87	1.48×10^6	5.41
2	∇	7.73	0.46×10^6	1.56; 3.08; 5.56
3	$\triangleright$	6.85	0.78×10^6	11.00
4	$\triangleleft$	6.85	0.25×10^6	2.68; 4.56; 7.33; 11.08
5	$\diamond$	4.50	0.30×10^6	1.74; 2.91; 4.43
6	$\circ$	2.00	0.30×10^6	1.25; 1.40; 1.63; 1.86

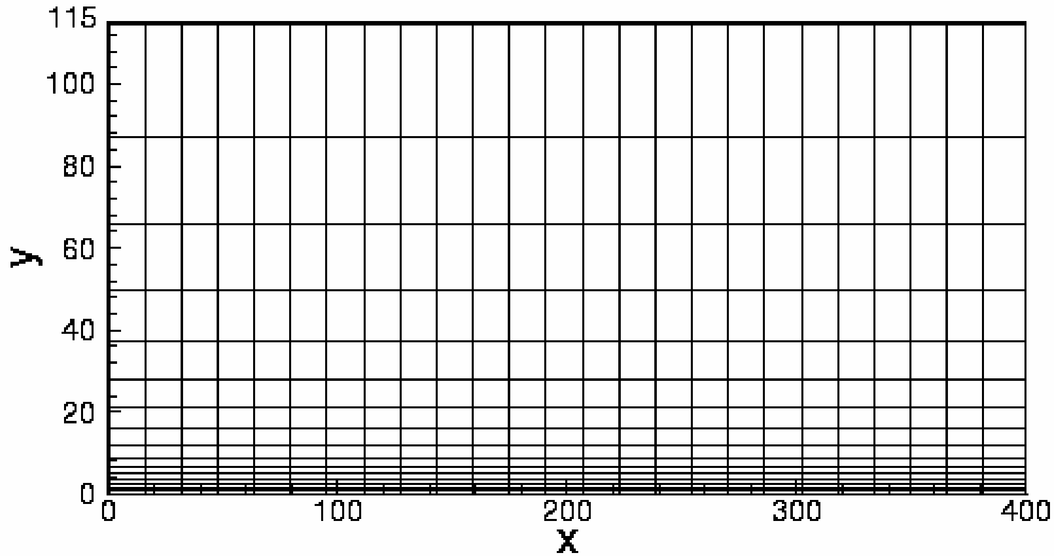
Reynolds numbers are based on the length from the leading edge to the shock impingement point in the absence of boundary-layer, x_0

Simulation of case 6: Supersonic M = 2.0 inflow

- Previous studies: experiments by Hakinnen et al. (1959); computations by Katzer (1989), Wasistho (1998)
- $p_3/p_1 = 1.25, 1.40, 1.65, 1.86$;
- Baseline grid: 151x128;
- Boundary Conditions:

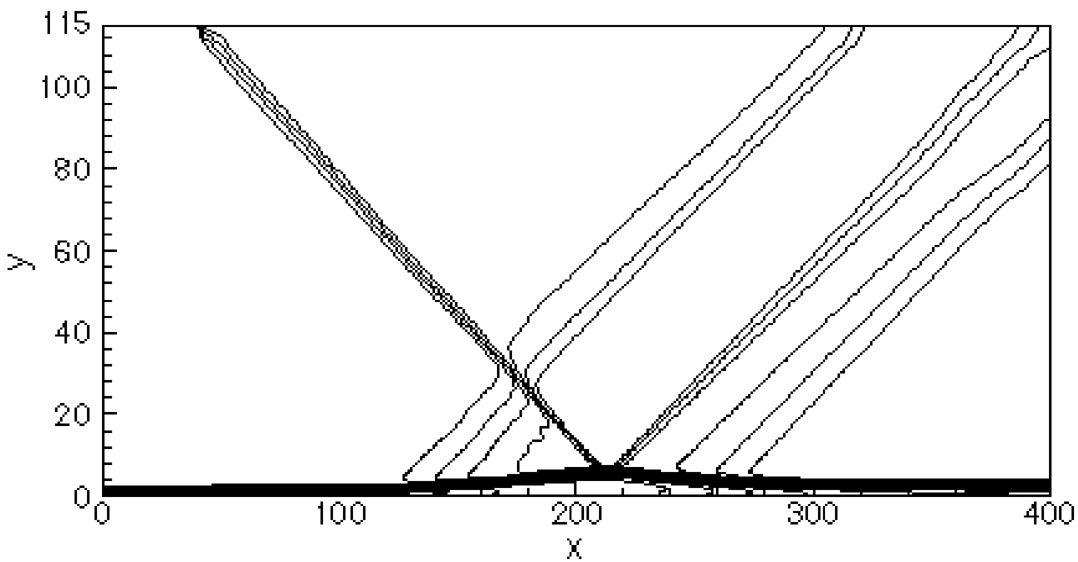
  - Inflow: prescribed velocity and temperature b.l. profiles

  - Wall: non-slip, adiabatic;



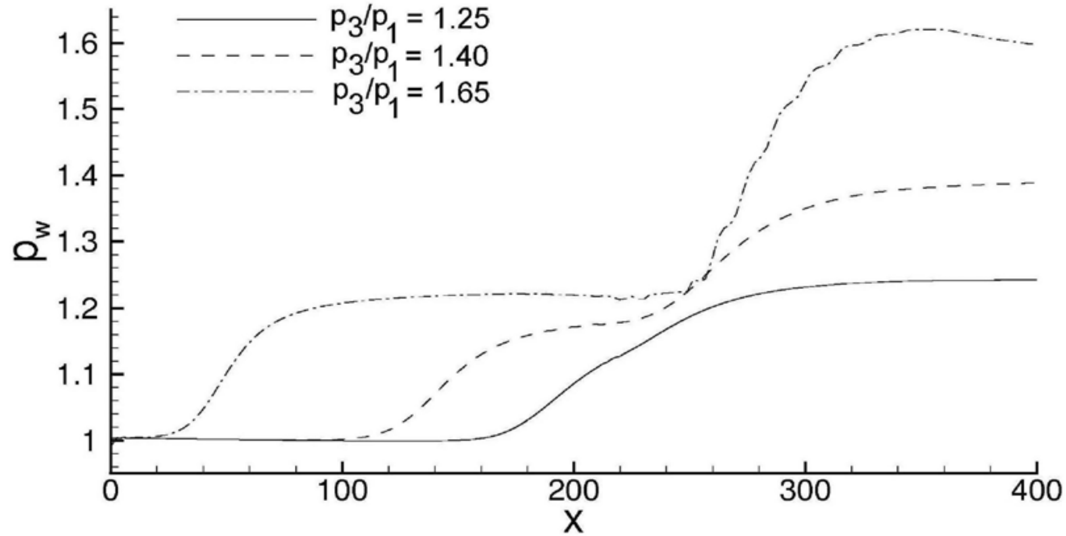
Domain: 400 x 115 based on inlet displacement thickness;

Grids: 151 x 128 (uniform in x and stretched in y)

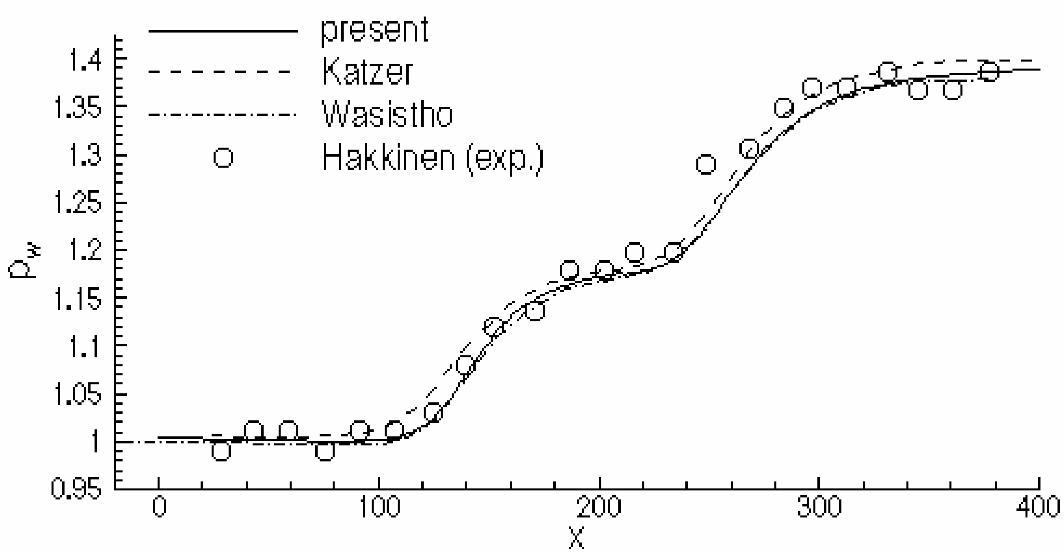


Case 6, M = 2.0, p_3/p_1 = 1.40

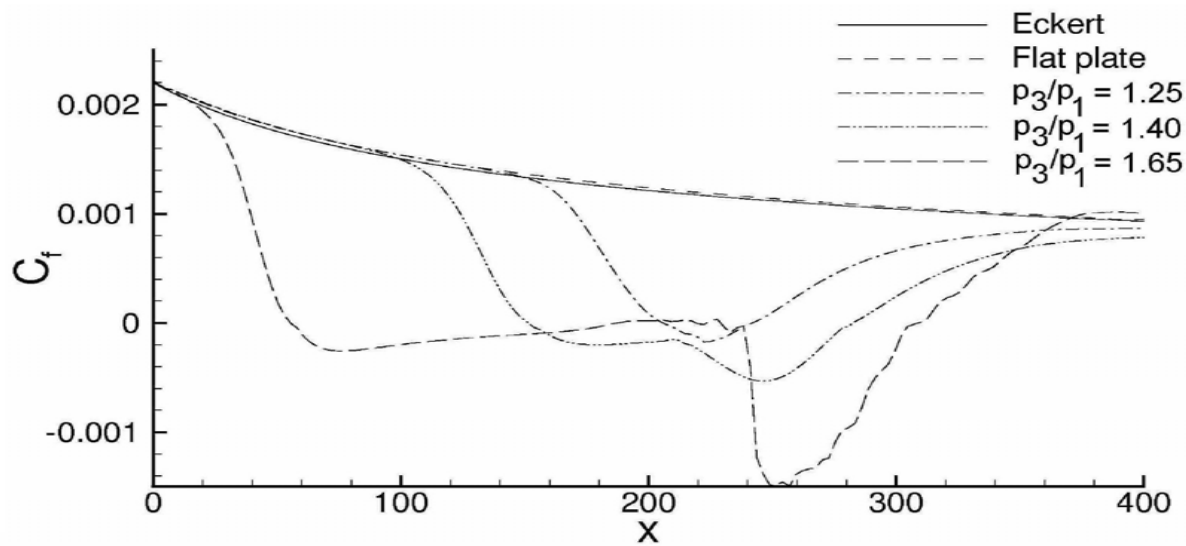
Density contours



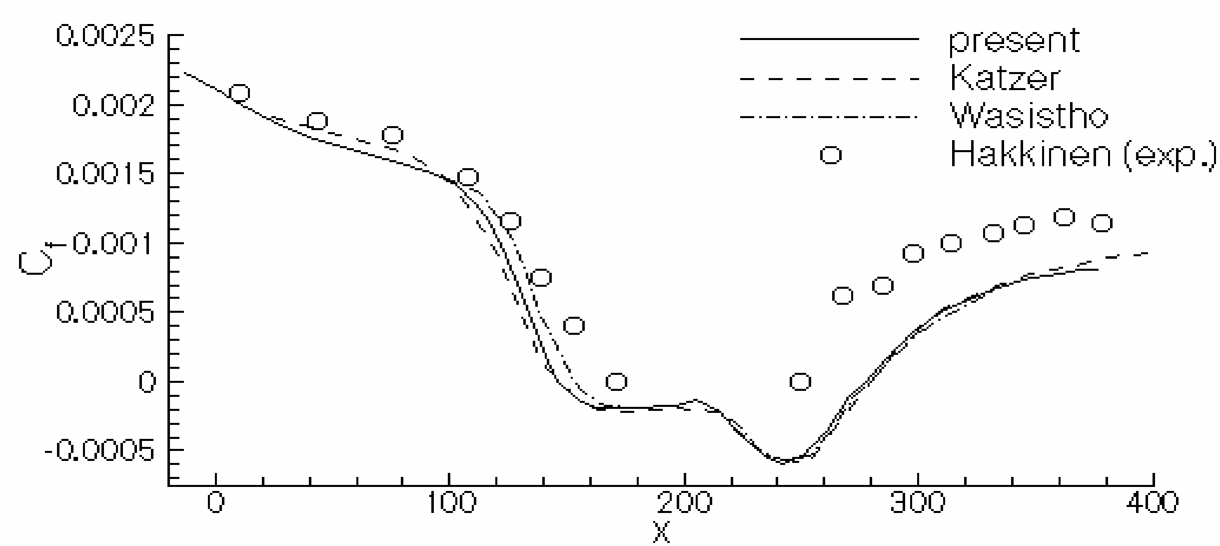
Case 6, M = 2.0
Wall pressure distributions



Case 6, M = 2.0, p_3/p_1 = 1.40
Wall pressure distribution



Case 6, M = 2.0
Skin friction distributions



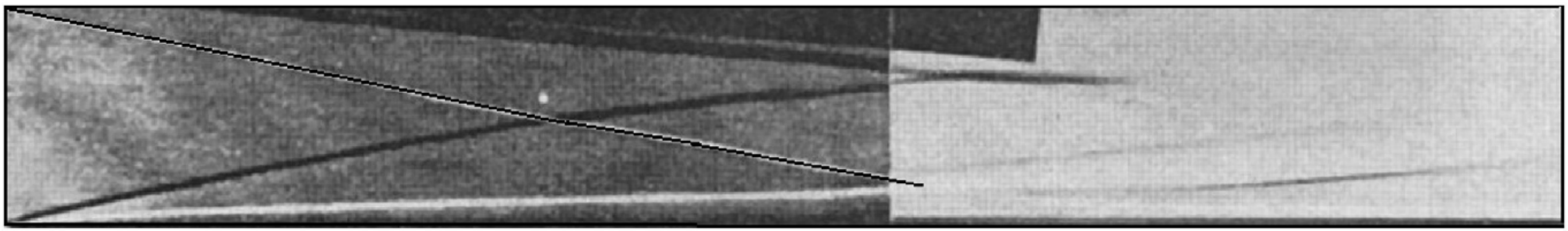
Case 6, M = 2.0, p_3/p_1 = 1.40
Skin friction distribution

Simulation of case 2: Hypersonic M = 7.73 inflow

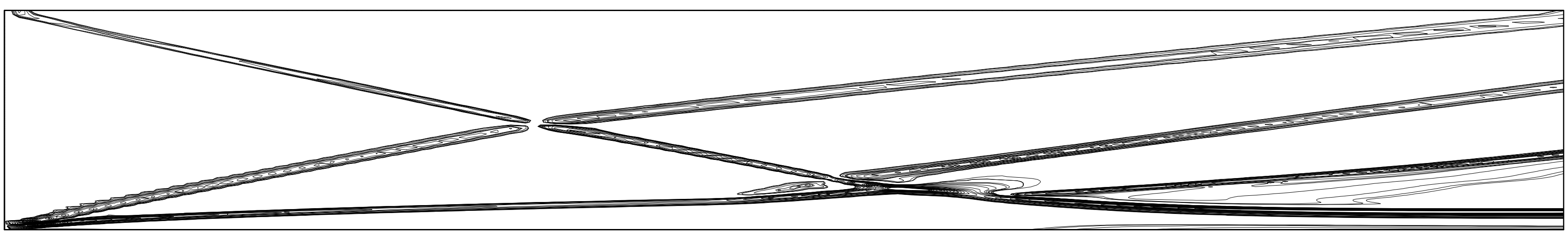
- Based on experimental studies of Kaufman and Johnson, NASA TN D-7835 (1974)
- p_3/p_1 = 1.56, 3.08, 5.56;
- Computational domain conforms to experiments
- Baseline grid: 128x192;
- Boundary Conditions:
  - Inflow: normalised quantities based on freestream
  - Wall: non-slip, isothermal;

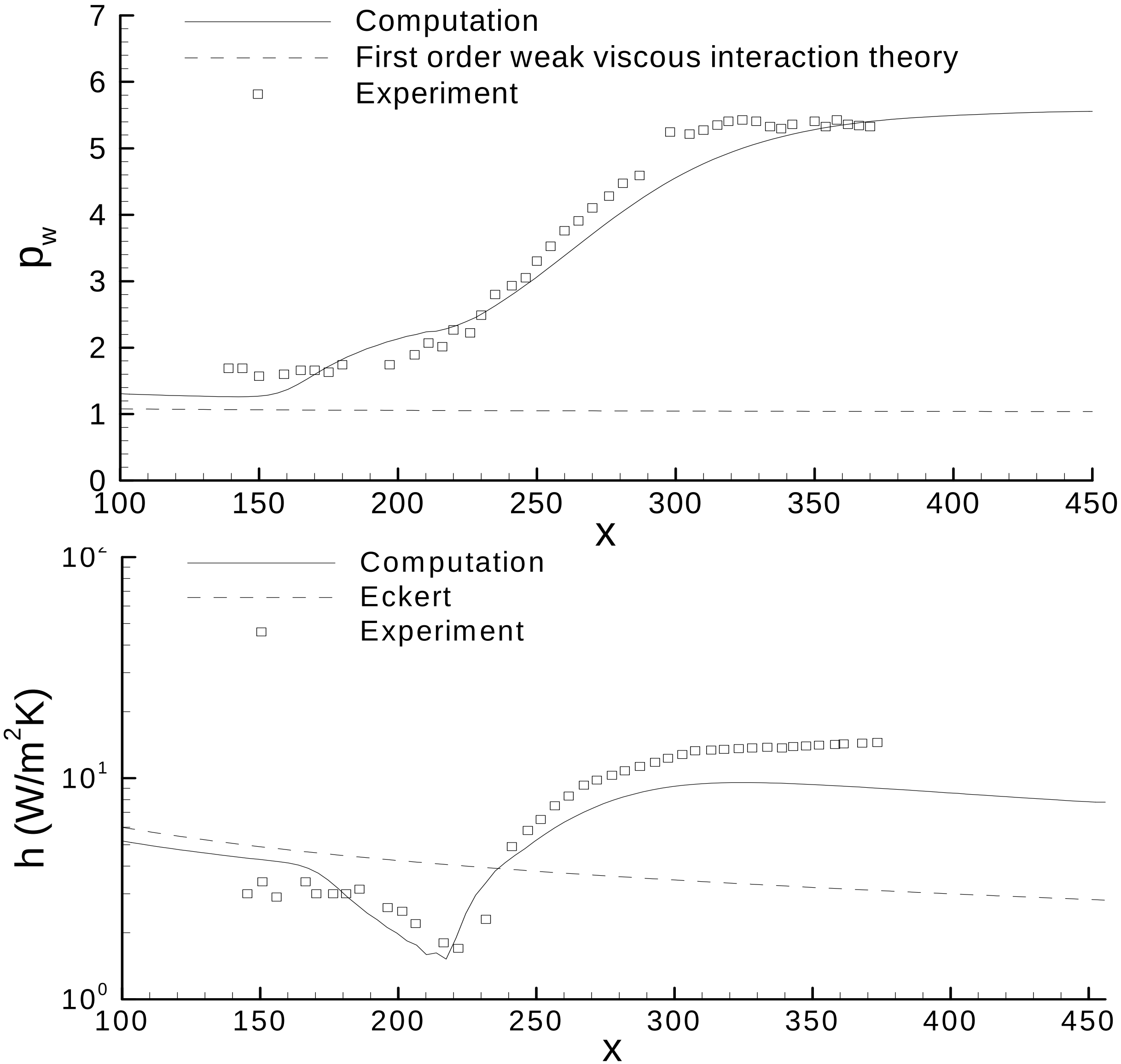
Case 2, M = 7.73, $\beta = 11.08^0$, $p_3/p_1 = 5.56$

Schlieren: density gradients



Simulation: density gradients

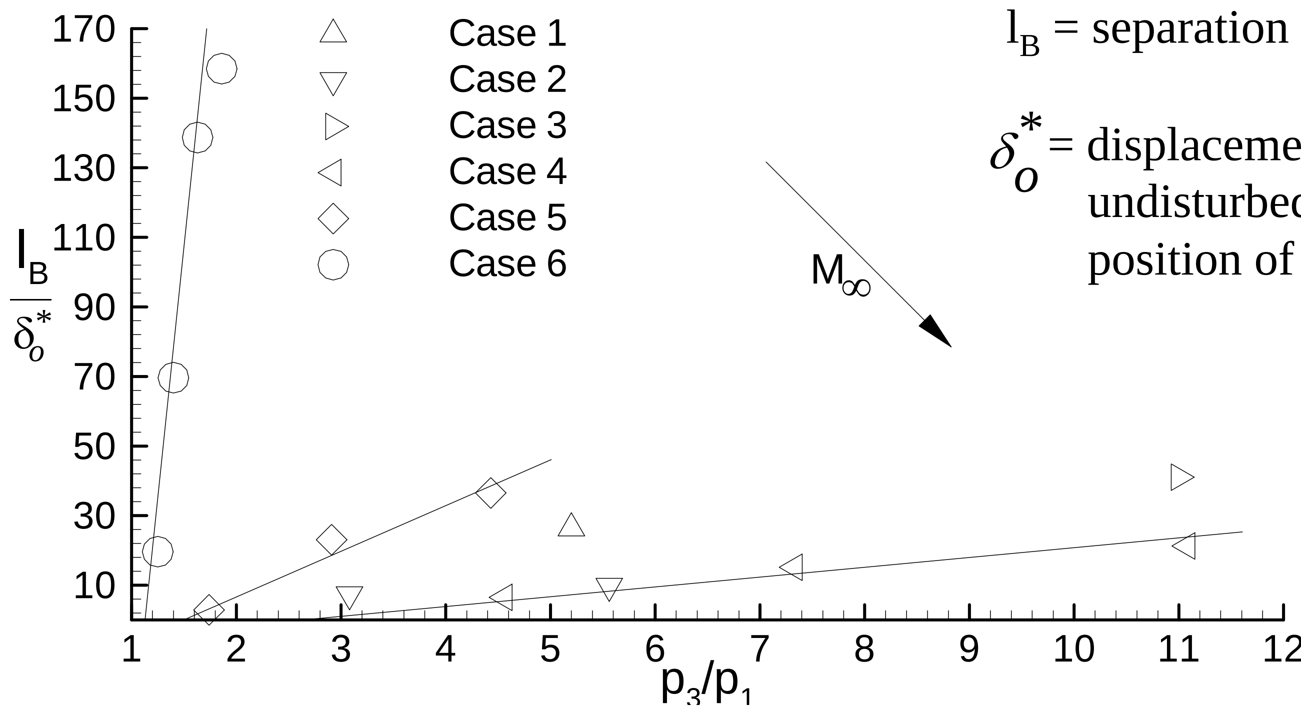




Case 2, M = 7.73, $p_3/p_1 = 5.56$

Wall pressure and heating distributions

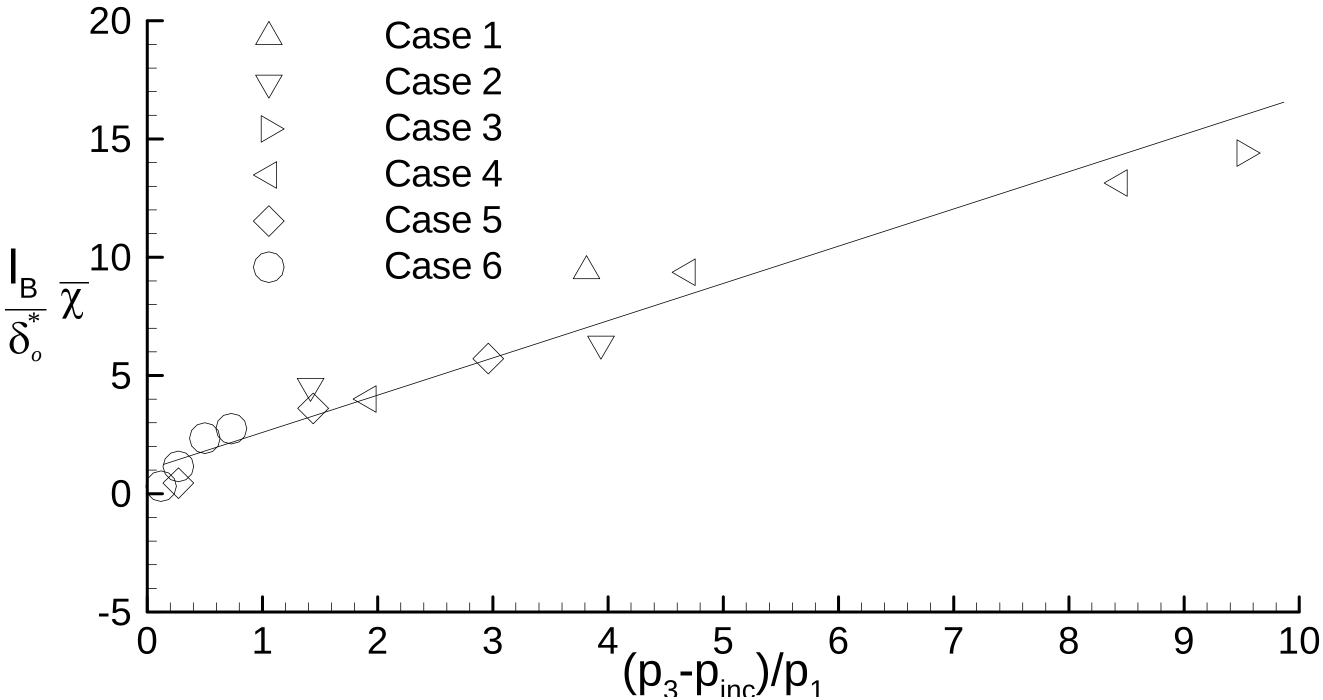
Correlations: Influence of the Mach number and Shock Strength



l_B = separation bubble length

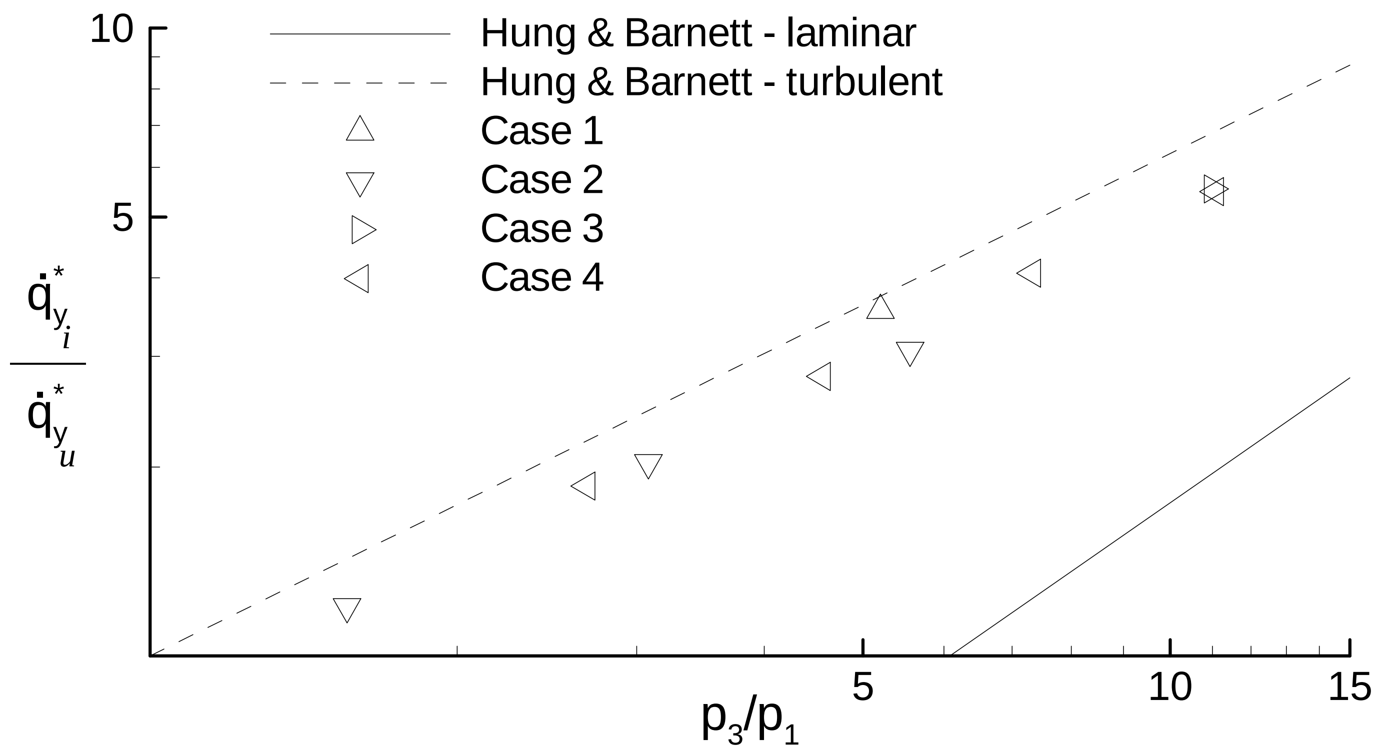
δ_o^* = displacement thickness of an undisturbed boundary-layer at the position of impingement point, x_o

Correlations: Separation bubble length



$$\overline{\chi} = \frac{M_\infty^3}{\sqrt{R_{e_{xo}}}}\sqrt{C}$$

Correlations: Peak heating



Conclusions and Future Work

- At M = 2.0 experiment and simulations agree fairly well;
- At M = 7.73 agreement between experiment and simulations is relatively poor;
- 2-D and 3-D laminar SBLI simulations have so far failed to resolve the discrepancies with experimental data;
- It is possible that the interactions undergo transition;
- 3-D unsteady simulations to investigate boundary-layer instability are underway and will be reported later.