Space Launch System (SLS) Small Protuberance Aerodynamic Heating Methodology

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Background

- In the Constellation Thermal Environments 5 (TE5) data book a small protuberance criteria was included to facilitate estimation of enhanced heating on small (≤ 0.5 inch) protuberances such as bolt heads, small steps, or other small discontinuities
- The criteria was based on breaking the vehicle up into several axial zones, calculating a representative boundary layer displacement thickness at the start of the zone (a conservative approximation for the zone), and generating plots based on the following relation:

$$\frac{q_{\text{max}} - q_{\text{fp}}}{q_{\text{fp}}} = \frac{1}{2}\left\{\frac{h}{wF}\left(1 - \frac{\delta^*}{h}\right) - 2.5 + \left[6.25 + \frac{5h}{wF}\left(1 + \frac{\delta^*}{h}\right) + \left(\frac{h}{wF}\right)^2\left(1 - \frac{\delta^*}{h}\right)^2\right]^{1/2}\right\}$$

- This relation (Polak, 1974, derived from Jaeck, 1966) gives the peak of the enhanced heating, relative to a local flat-plate value, in terms of the protuberance height (h), width (w), boundary layer displacement thickness (δ^*). The factor F is a function of Mach number and specific heat ratio.

Background

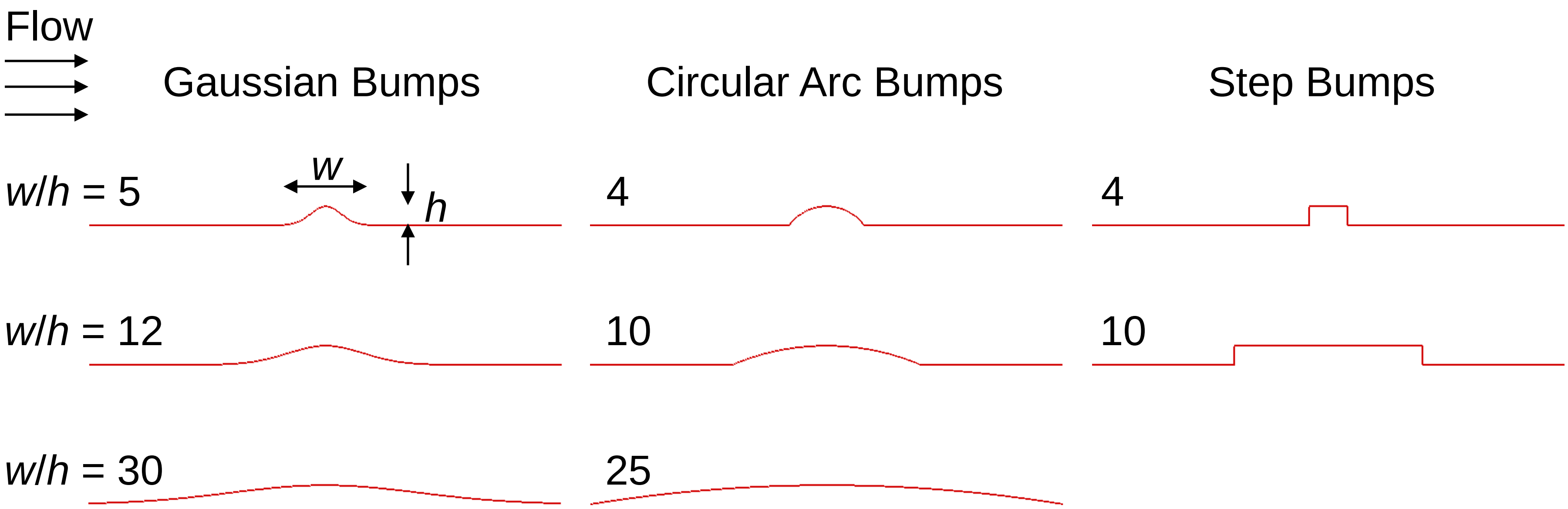
- However, with further investigation of the background of this relation, we realized there were issues with the way we had implemented it:
  - w = two-dimensional (2-D) streamwise width, not spanwise width
  - δ/δ^* = 2.91 (Blasius solution for incompressible laminar boundary layer) had been assumed. A representative value of δ/δ^* for a turbulent incompressible boundary layer would be roughly 8, though compressibility typically reduces that value.
- The intended range of applicability for the relation was limited: it was derived from laminar small disturbance theory, and empirically modified for turbulent flow. It was designed for relatively “long” 2-D protuberances, in comparison to both the protuberance height ($h/w \leq 0.1$) and the boundary layer thickness [$(h/w)(\delta/w) \leq 0.005$]
- In contrast, in the rocket world, we often have relatively “short” protuberances, in comparison to both h and δ (e.g., a bolt head near the aft end of the vehicle)

Approach

- As a first step to revising our methodology, we have sought to parametrically investigate this issue using 2-D Reynolds-Averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD)
  - This CFD methodology has obvious limitations, but it has the advantage of being very economical for a parametric study
  - Additionally, though RANS will be challenged by flow separation, it will at least calculate the normal boundary layer flow with good accuracy
- The overall approach of the effort was:
  - Run a flat plate turbulent compressible boundary layer using Loci-CHEM, using a Space Launch System (SLS) relevant trajectory. Calculations were run at Mach 2, 3 and 4. Flat plate length was 3000in, on the order of the length of the SLS Block I vehicle. Turbulence model: SST. Both Wilcox and Sarkar compressibility corrections were tested.
  - Boundary layer profiles were extracted at various axial locations, and used as prescribed inflow boundary conditions to dedicated 2-D simulations of small protuberances
  - Three different types of protuberances have been investigated thus far…

Geometries Studied

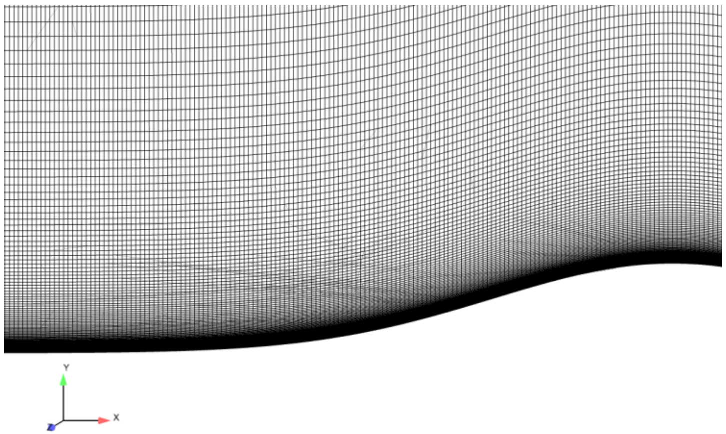
- Three basic types of 2-D protuberances studied thus far:



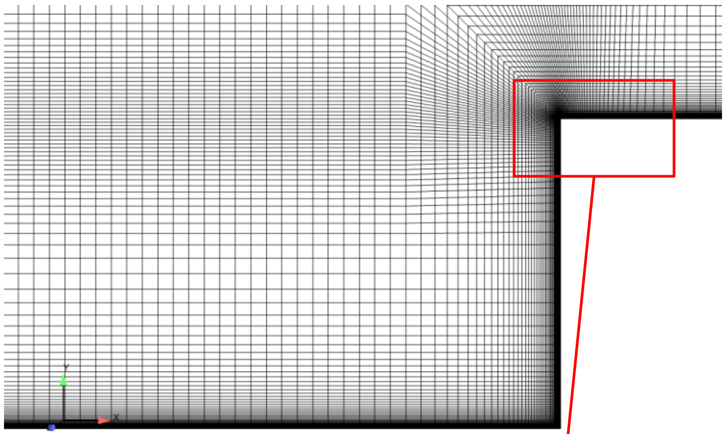
- Three groups of *w*/*h* ratios: 4–5, 10–12, and 25–30
- Three values of *h*: 0.5, 0.2 and 0.08 inches
- Wall-normal grid spacing: 1e-4 inches ($y^+ = 0.1$–0.2)
- Streamwise grid spacing: 0.01 inches, better near sharp corners
- Note: *w* for Gaussian is based on y=0.01*h*

Protuberance CFD Grids

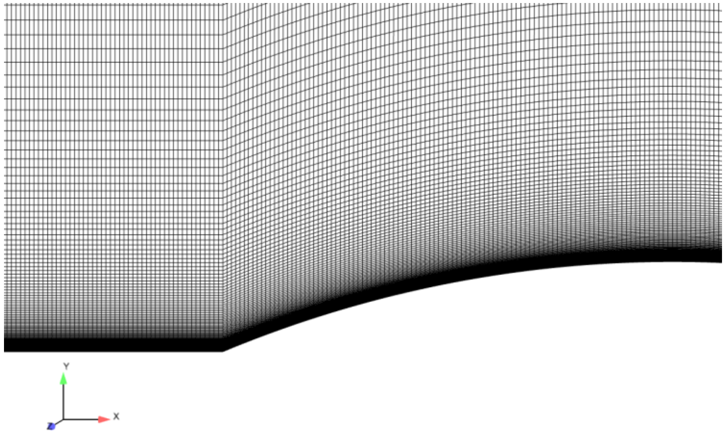
Grid in Vicinity of Gaussian Profile



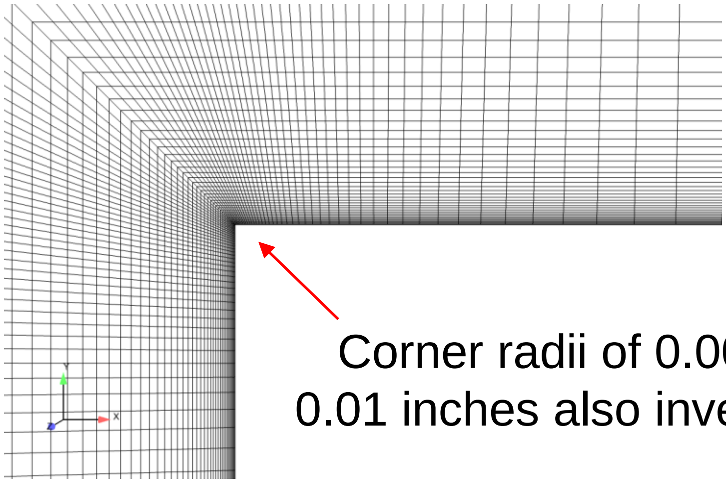
Grid in Vicinity of Front Step Face



Grid in Vicinity of Circular Arc Profile



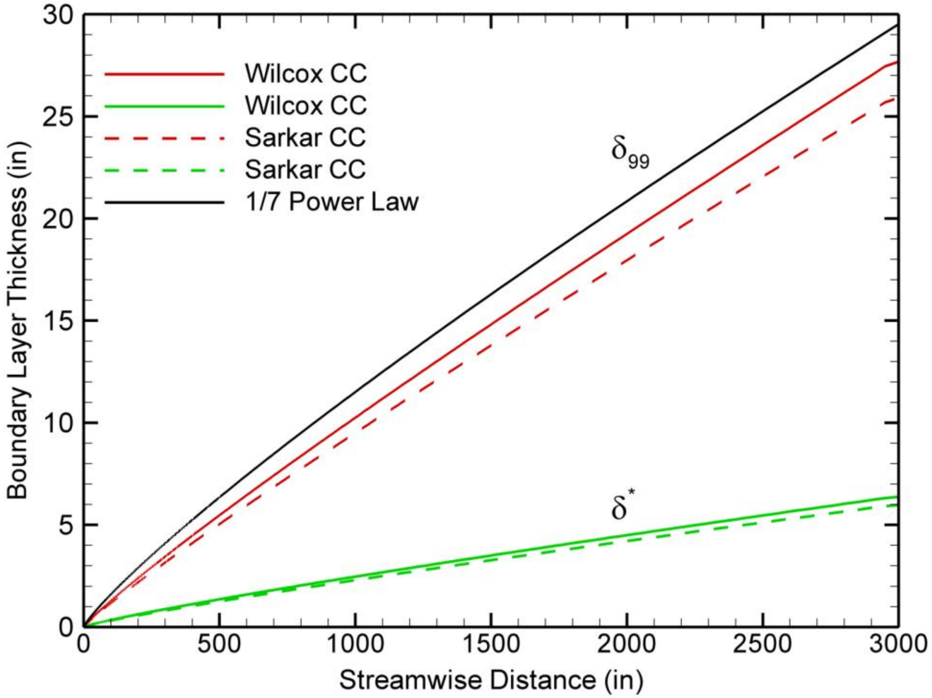
Grid in Vicinity of Front Step Face Top Corner



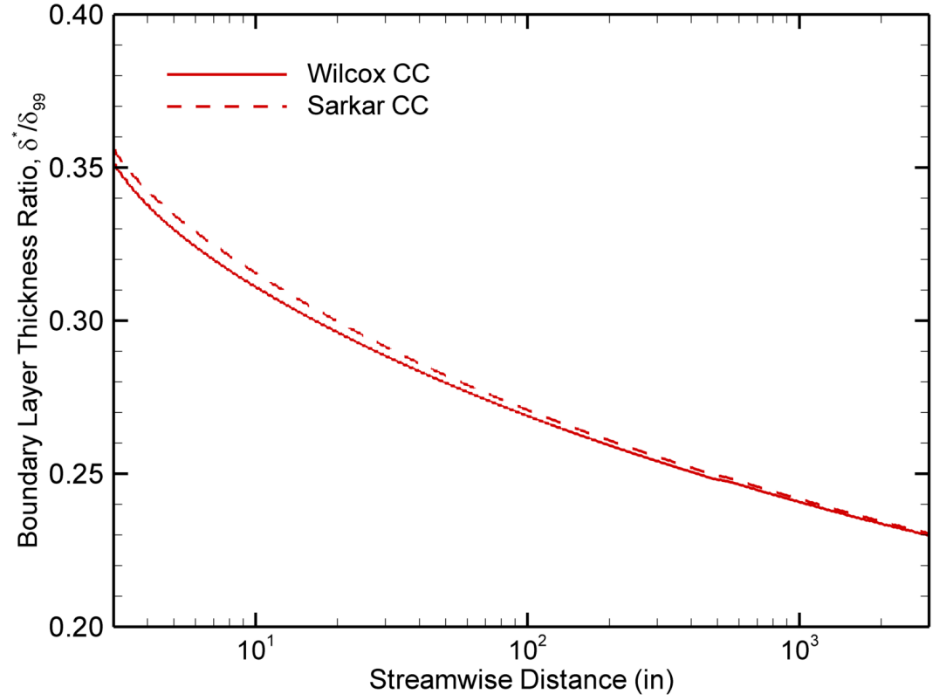
Corner radii of 0.001 and 0.01 inches also investigated

Flat Plate Boundary Layer Thicknesses at Mach 3

Boundary Layer Thicknesses



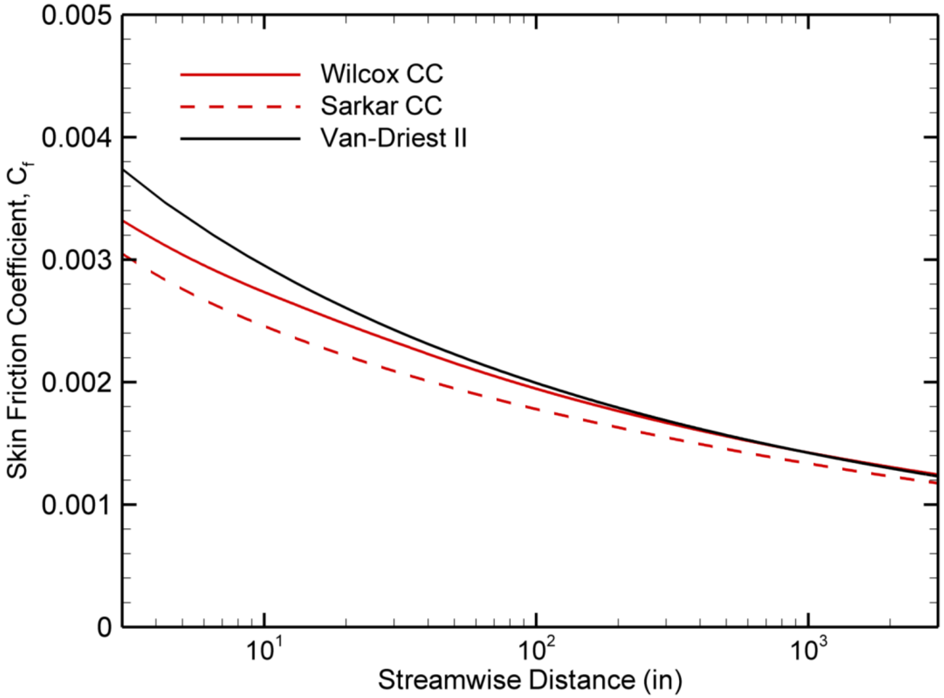
Boundary Layer Thickness Ratio



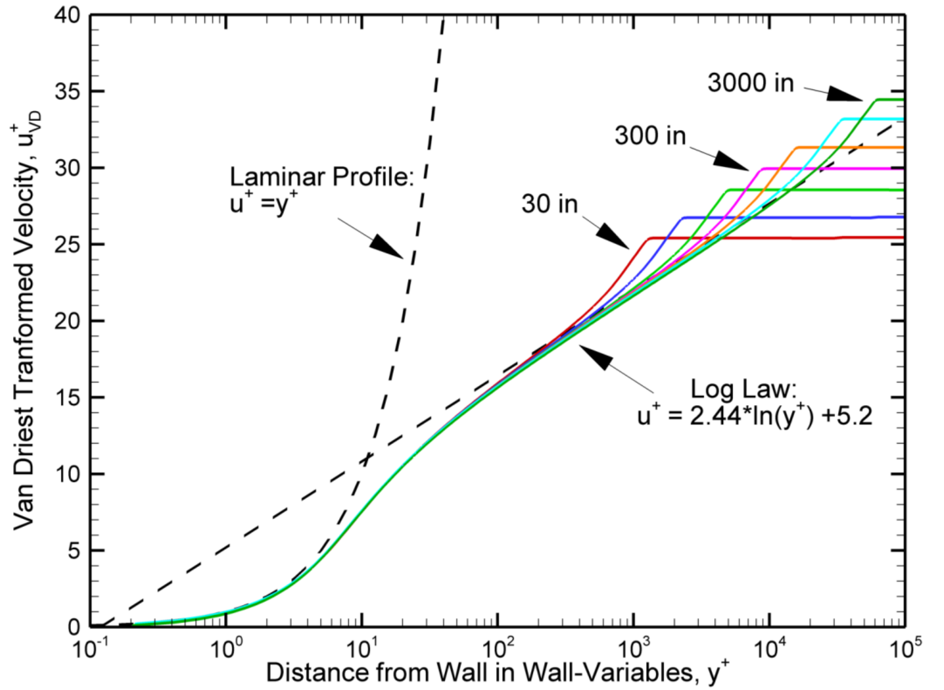
- Boundary layer grows to nearly 30 inches in thickness
- Profiles extracted at 30, 60, 150, 300, 600, 1500 and 3000 inches from Wilcox CC solution
- Profiles extracted at 10, 20, 30, 50, 100, 200, 300, 500, 1000, 1300, 1600 and 2000 inches from Sarkar CC solution
- For much of the flat plate, the ratio $\delta_{99}/\delta^* \approx 4$

Flat Plate Boundary Layer Characteristics at Mach 3

Skin Friction Coefficient



Boundary Layer Profiles (Wilcox CC)



- Both compressibility corrections agree well with the Van-Driest II prediction over much of the flat plate (Wilcox is a little better)
- Velocity profiles are shown using the Van Driest transformed velocity (to account for density variations)
- Transformed profiles are in good agreement with expected log law and wake profile

Mach Number Contours – Gaussian Profile

w/*h* = 30 | *w*/*h* = 12 | *w*/*h* = 5

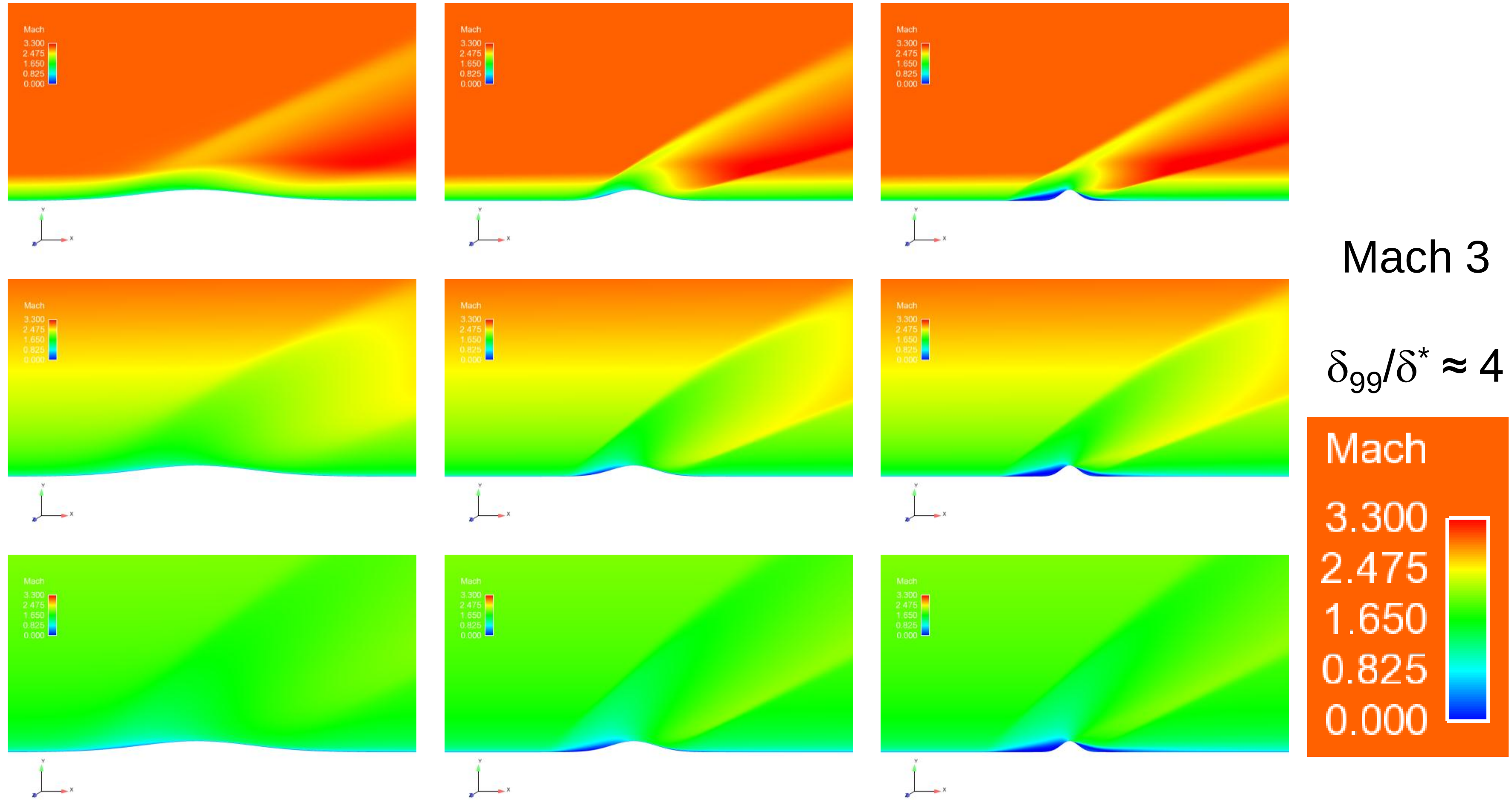
$h/\delta^* = 1.4$

$h/\delta^* = 0.22$

$h/\delta^* = 0.031$

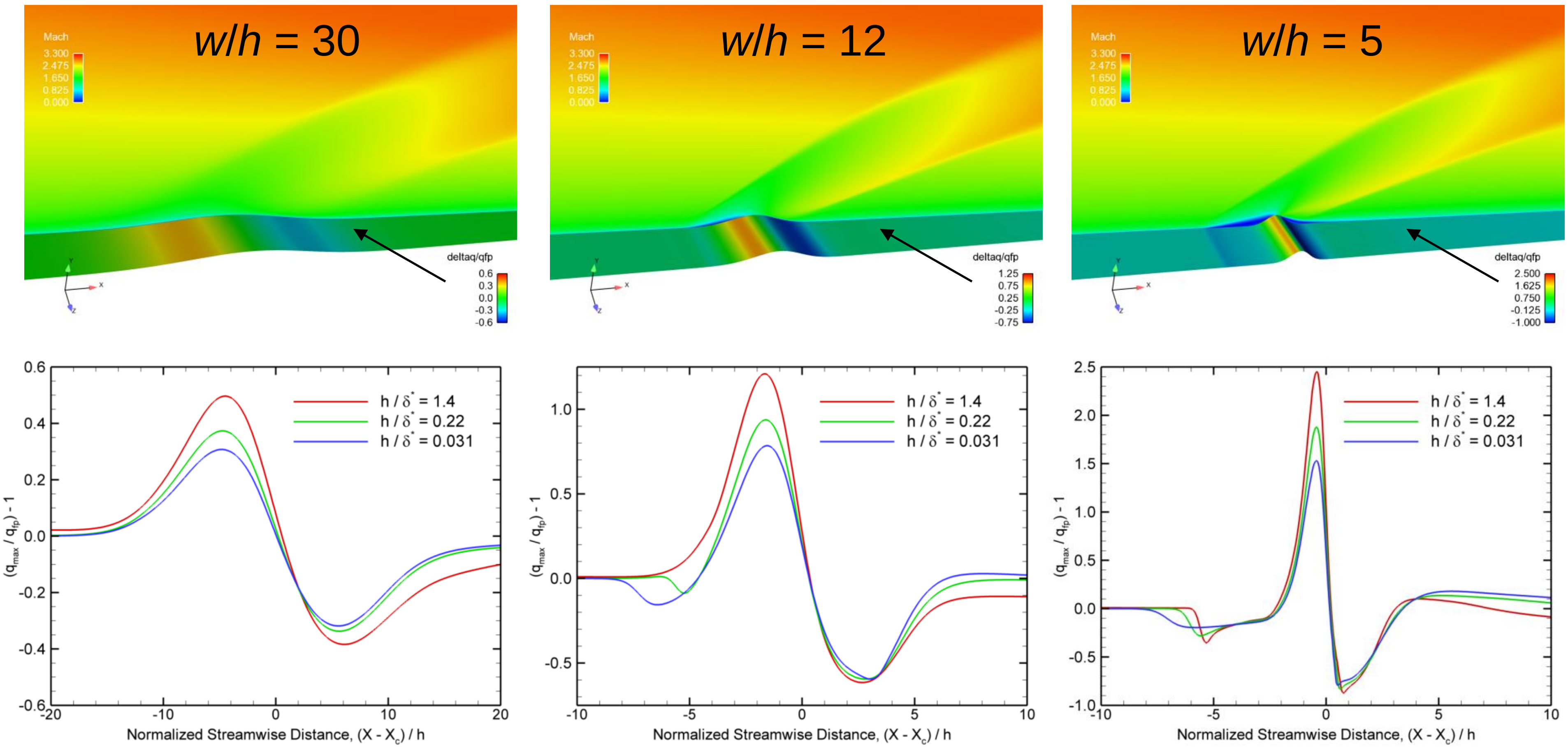
Mach 3

$\delta_{99}/\delta^* \approx 4$



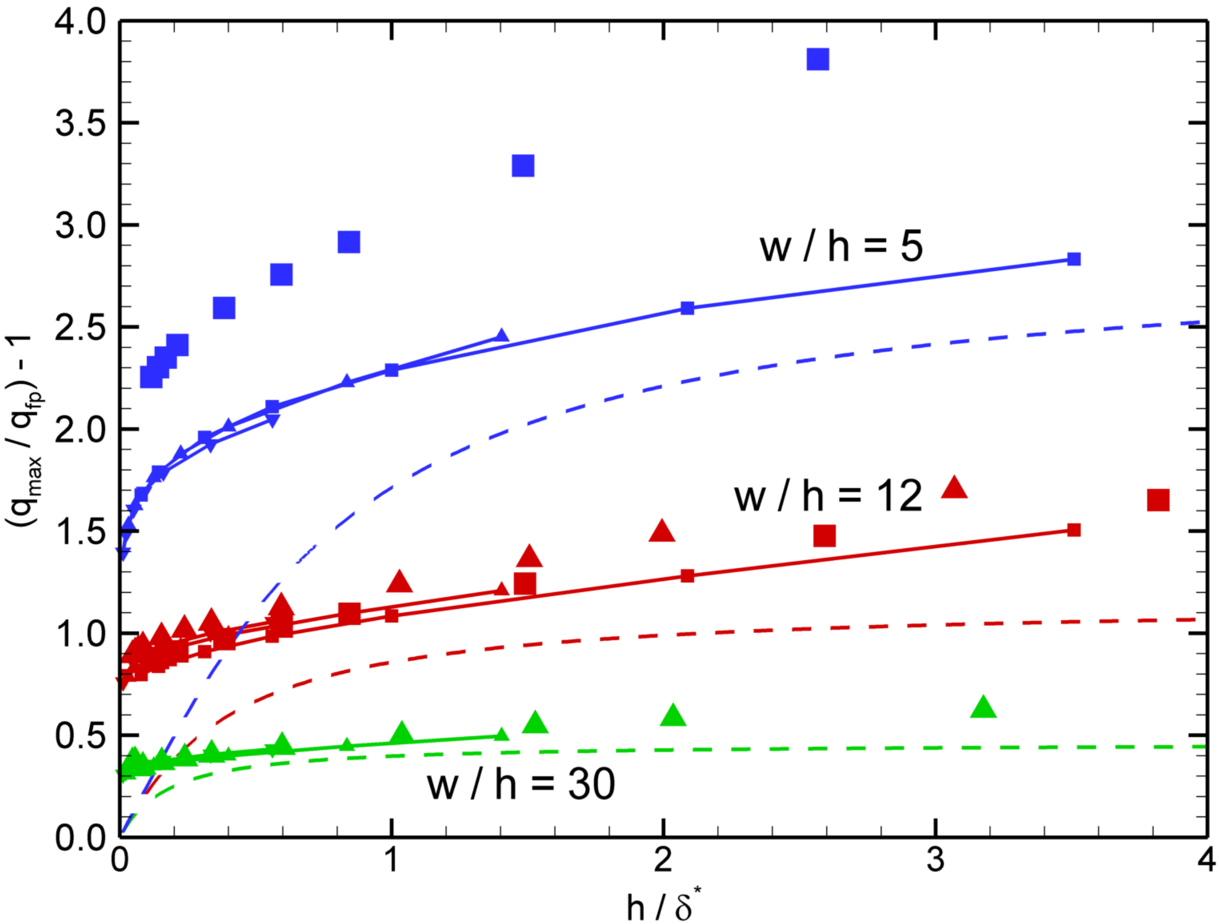
- Case in upper left corner is most like the flow scenario the original relation was intended for
- As h/δ^* shrinks, and/or w/h shrinks, more flow separation becomes evident in the CFD results

Heating Augmentation – Gaussian Profile



- Note that the images in the upper panel are at conditions of Mach 3, $h/\delta^* = 0.22$
- Heating amplification increases with *w*/*h* as well as h/δ^*

Maximum Heating Augmentation – Gaussian Profile



Mach 3

$\delta_{99}/\delta^* \approx 4$

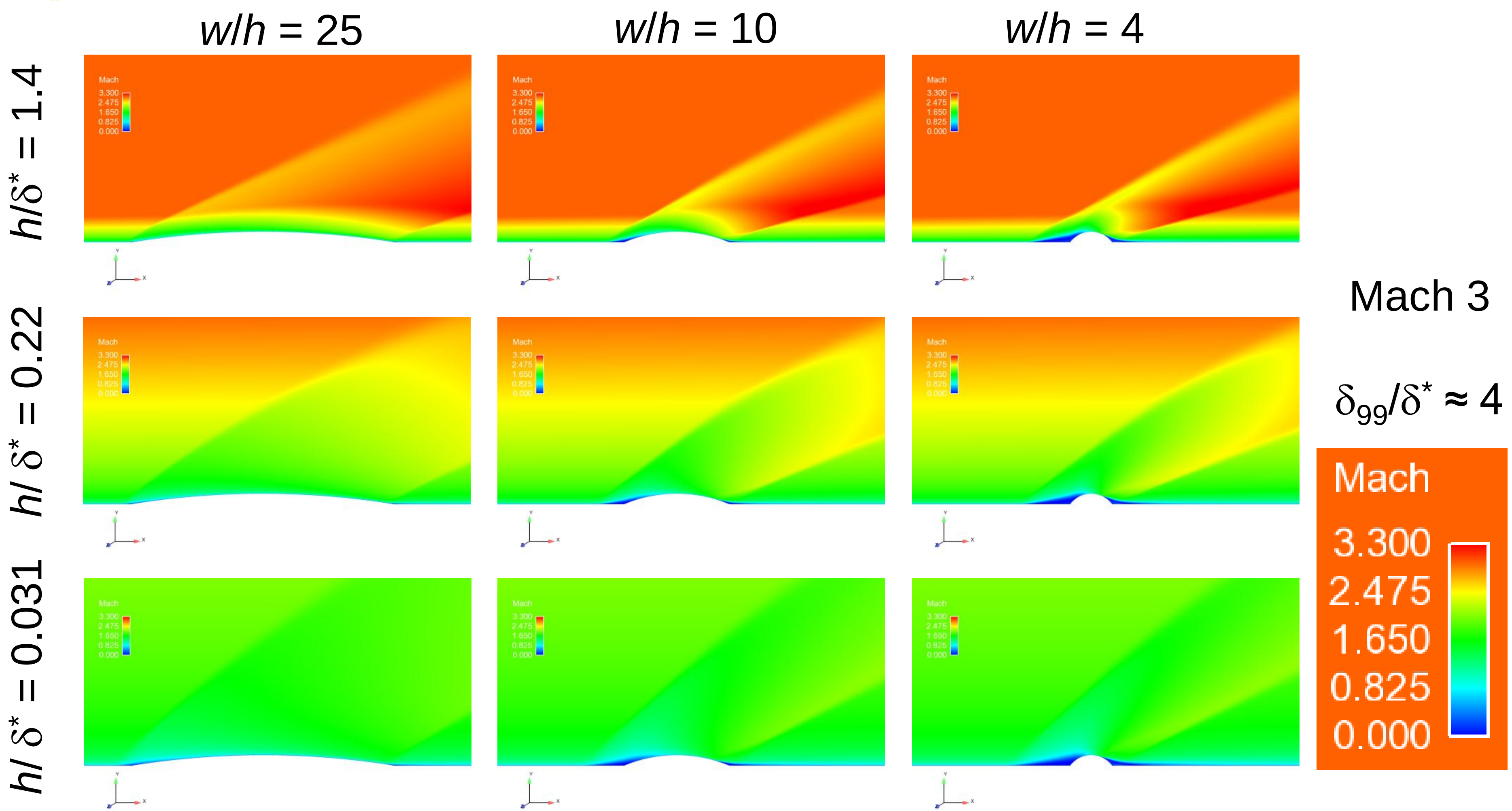
Wilcox CC =
lines and small symbols

Sarkar CC =
large symbols

h = 0.5 in = squares (■)
h = 0.2 in = delta (▲)
h = 0.08 in = grad (▼)

- Good collapse of CFD results with *w*/*h*
- Heating augmentation is strong function of *w*/*h* as well as h/δ^*
- Note differences between Wilcox and Sarkar CC results (partially related to δ^* and q_{fp})

Mach Number Contours – Circular Arc Profile



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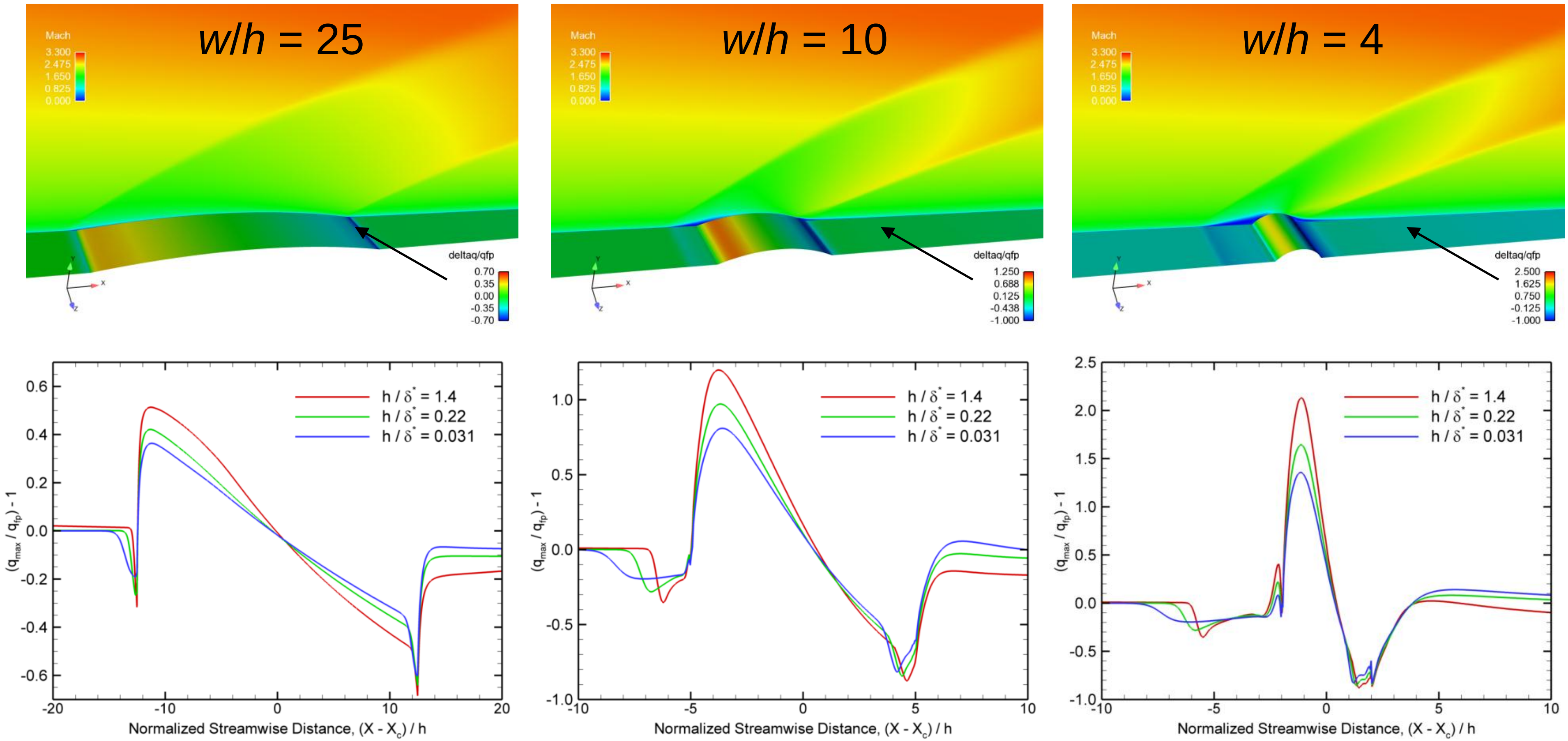

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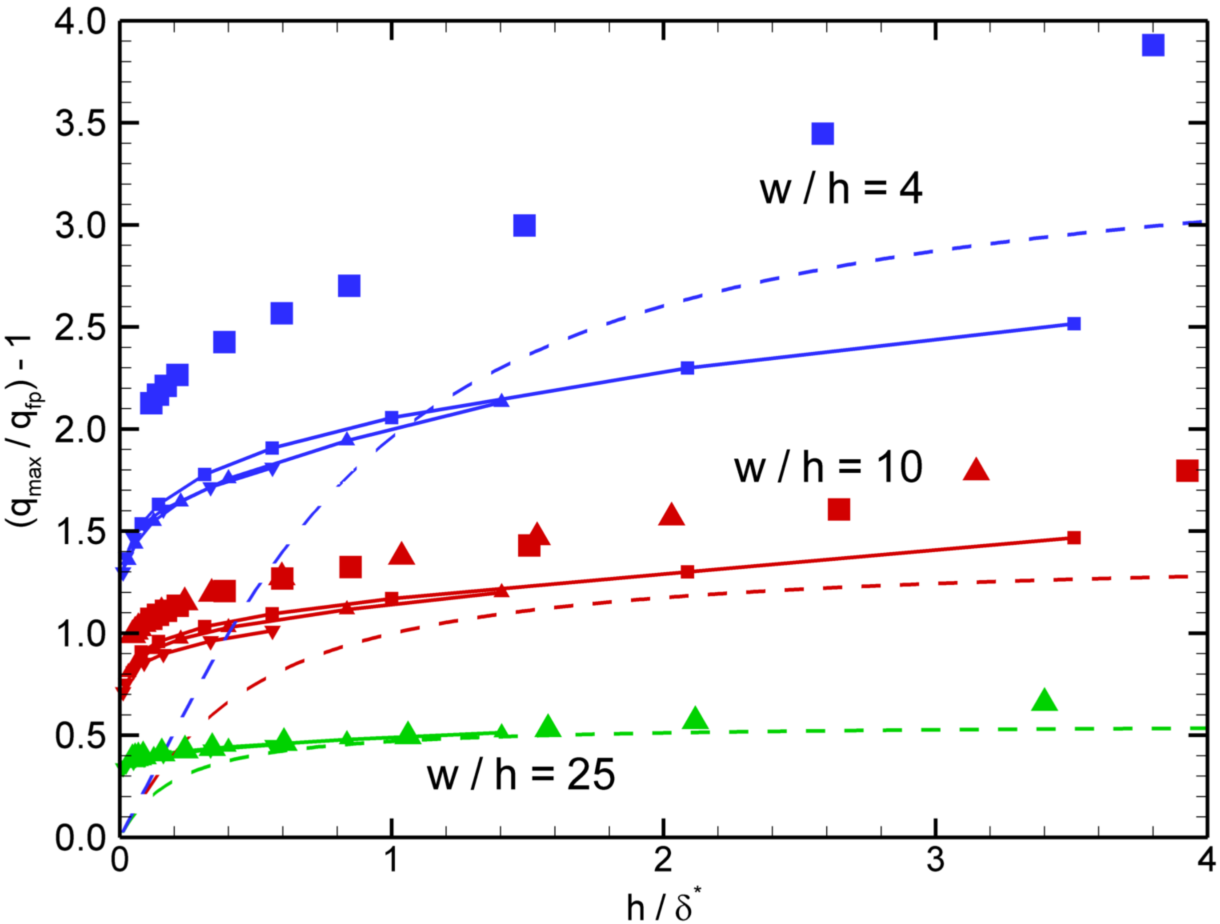

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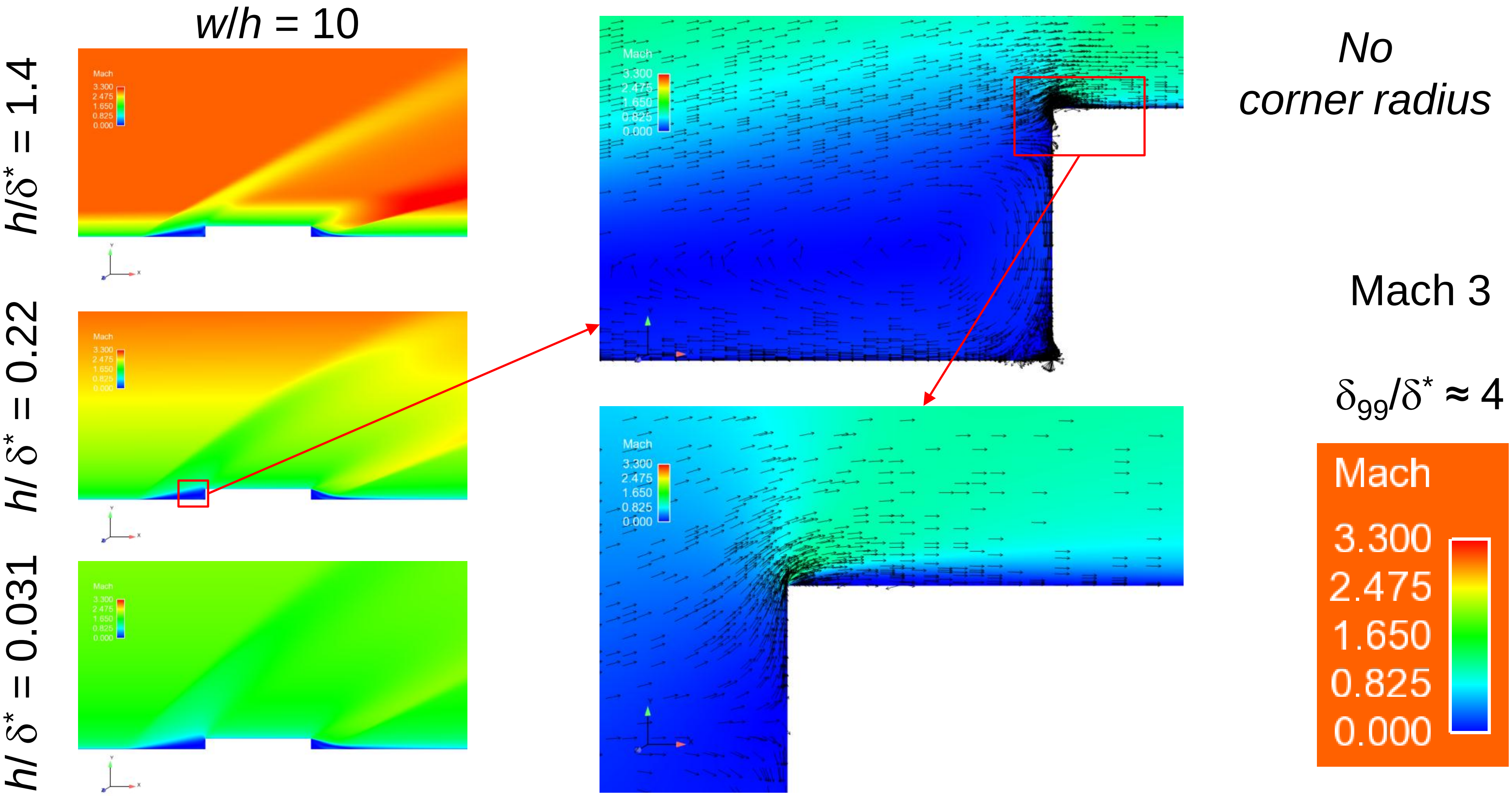
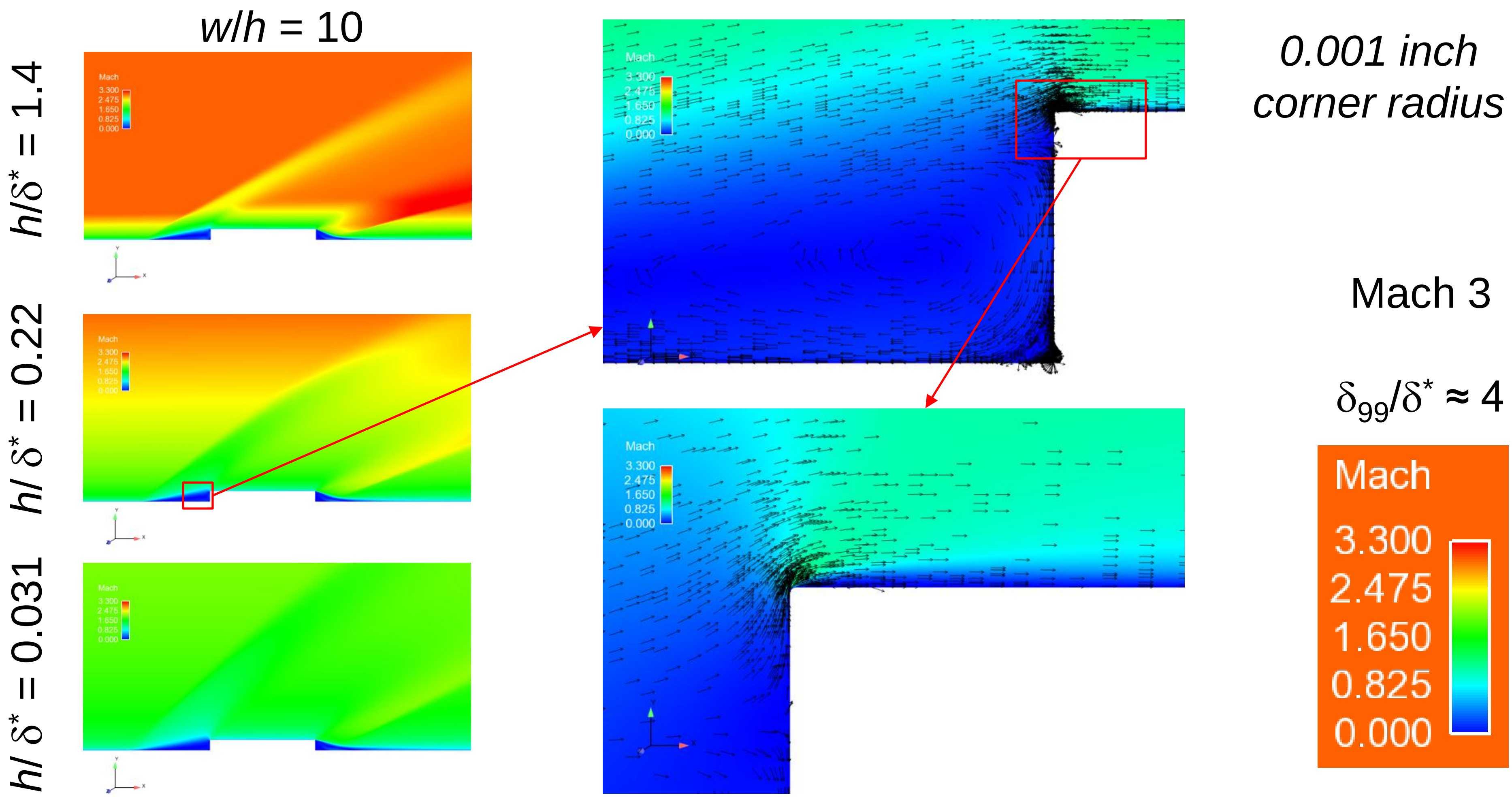
Mach Number Contours – Step Profile



- Flow separation occurs in front of step, creating a recirculation zone and oblique shock
- Flow impacts just below the top corner of the front face, then flows around the corner

Mach Number Contours – Step Profile



- Flow separation occurs in front of step, creating a recirculation zone and oblique shock
- Flow impacts just below the top corner of the front face, then flows around the corner

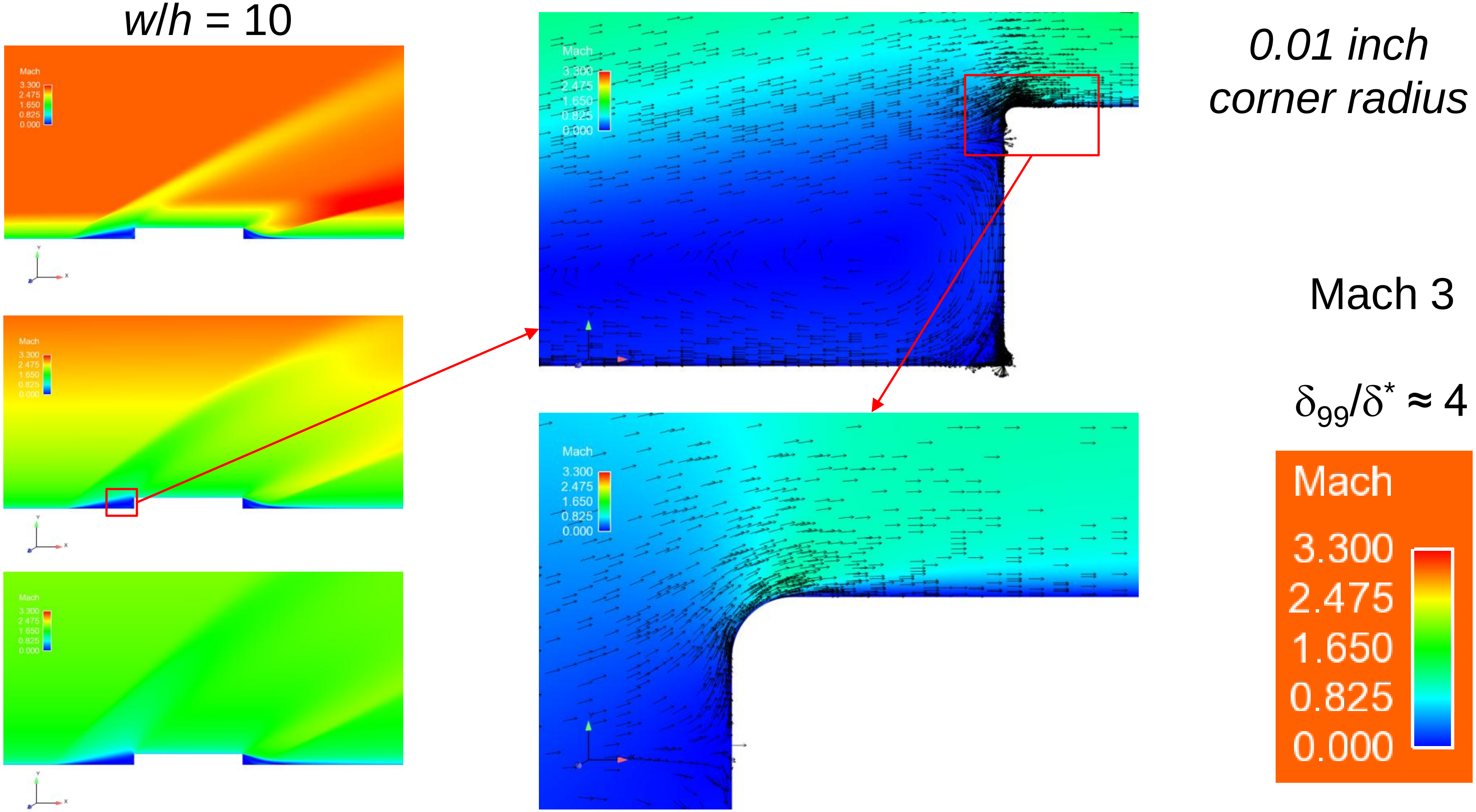
Mach Number Contours – Step Profile

w/*h* = 10

$h/\delta^* = 1.4$

$h/\delta^* = 0.22$

$h/\delta^* = 0.031$



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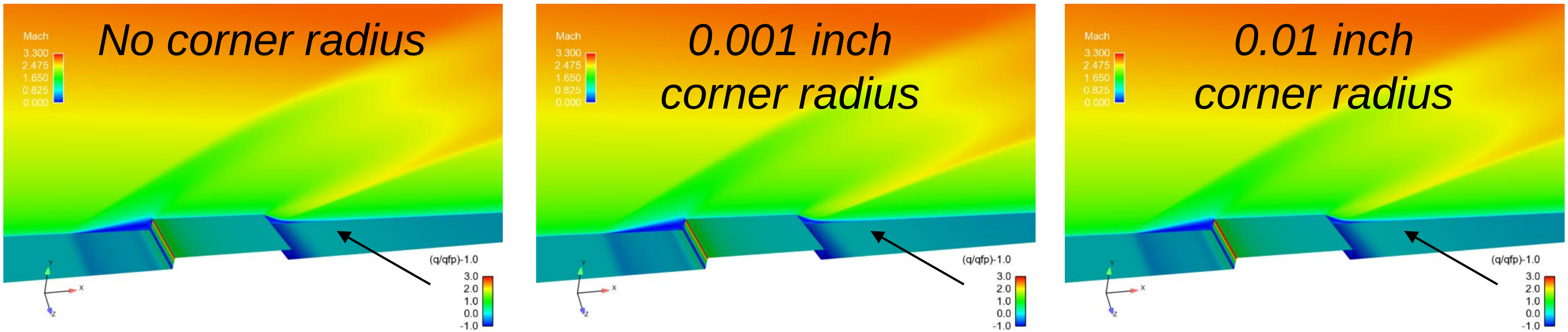
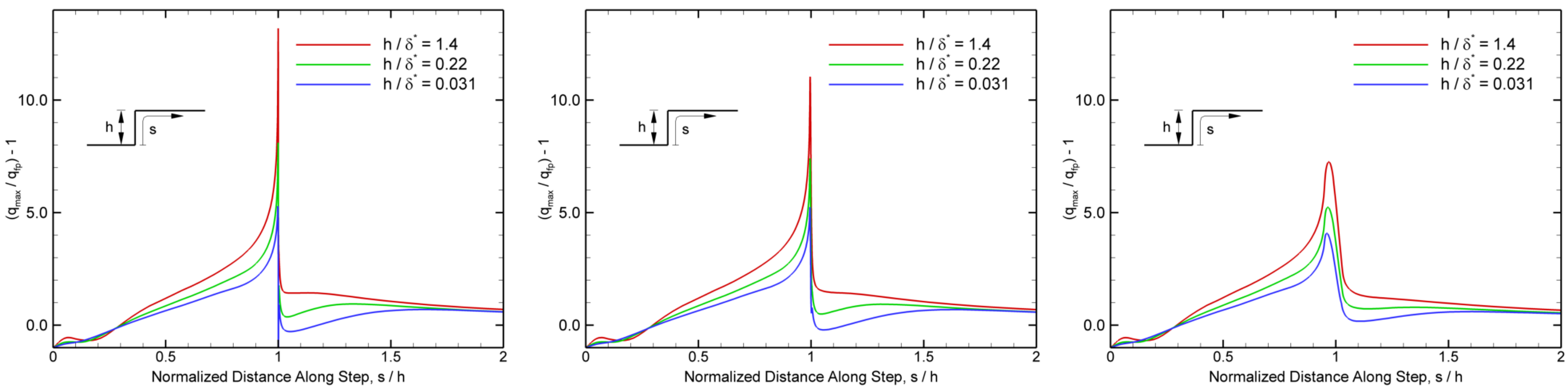
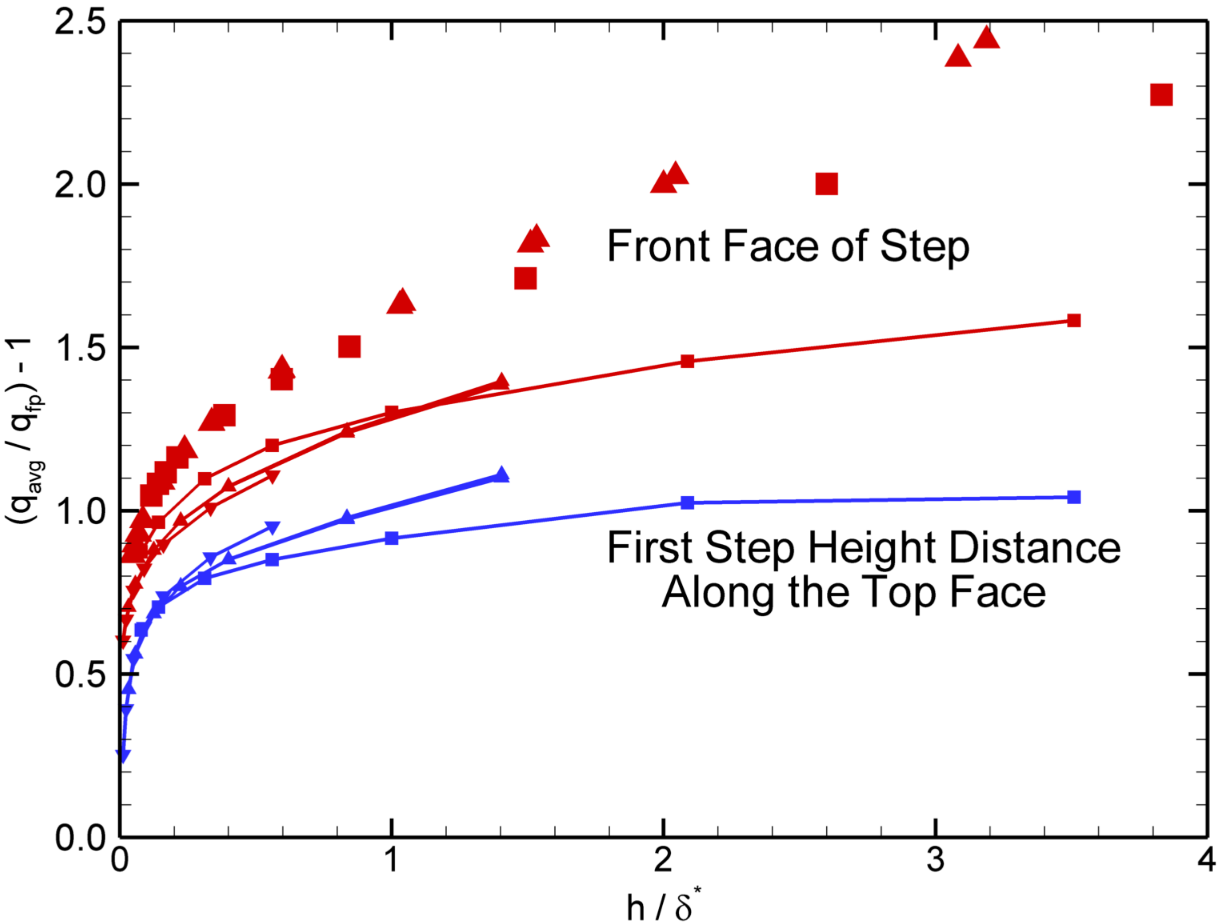
Heating Augmentation – Step Profile





- Note that the images in the upper panel are at conditions of Mach 3, $h/\delta^* = 0.22$
- Overall heating amplification increases with h/δ^*, and decreases near the corner with increasing corner radius

Average Heating Augmentation – Step Profile



Mach 3

$\delta_{99}/\delta^* \approx 4$

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h = 0.5 in = squares (■)
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h = 0.08 in = grad (▼)

- Heating augmentation is function of *h* and h/δ^*
- Step aspect ratio *w*/*h* appears to have little impact on heating near front face
- Note differences between Wilcox and Sarkar CC results (partially related to δ^* and q_{fp})

Conclusions

- Large number of 2-D RANS CFD solutions generated for two types of “smooth” small protuberances (gaussian and circular arc profiles) as well as step protuberances
- For smooth protuberances:
  - strong effect of w/h and h/δ^* on maximum local heating
  - Good agreement between CFD results and the original Jaeck relation in the flow regimes it was intended for
  - Flow separation evident for small h/δ^*, and especially for small w/h
- For step protuberances:
  - Average heat flux in vicinity of front face of step is a function of h and h/δ^*
  - Peak heat flux at front face top corner also scales with h/δ^*, but is reduced by larger corner radii
- Compressibility correction has a significant effect on results
- For all, there is a strong effect from Mach number (not shown)
- Results have been incorporated in a new small protuberance methodology for aerodynamic heating in SLS documentation