Effect of Hybrid Flow Control on a Normal Shock Boundary-Layer Interaction

Stefanie Hirt

Manan Vyas

NASA Glenn Research Center

Supersonics Project and Aerospace Sciences Project

Outline

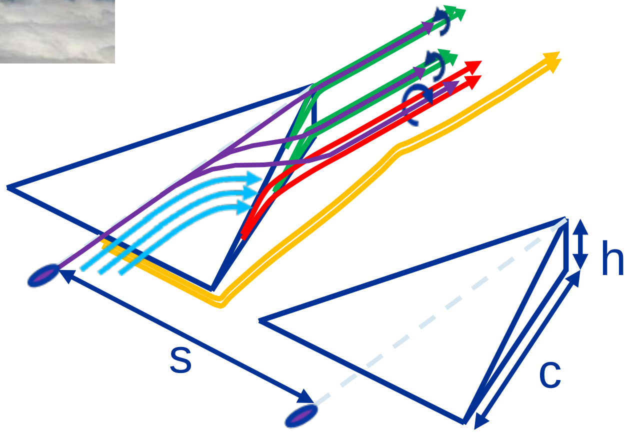
- Background
- Experimental Setup
- Results
  - Baseline
  - Injection Only
  - Design of Experiments
  - Preliminary Results from Recent Testing
- Conclusions

Challenge
Highly integrated inlets

- Fuel-efficient operations
- Reduced emissions
- Noise reduction
- Reduced Drag

- Separation
  - Reduced inlet mass capture
  - Increased Distortion

- Hybrid Flow Control
  - Steady micro-jets with micro-ramp vortex generators
  - Precondition the inlet flow
  - Reduce separation

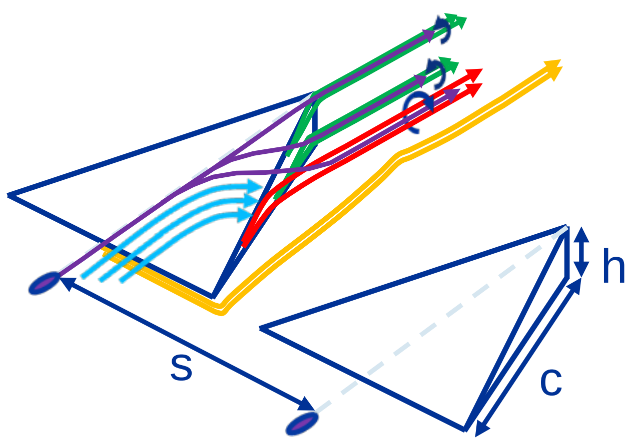


Objective

- Determine which parameters of the hybrid flow control devices were important to understanding their effect on the separation.

- Develop response surface equations to predict the effect of a given ramp configuration.

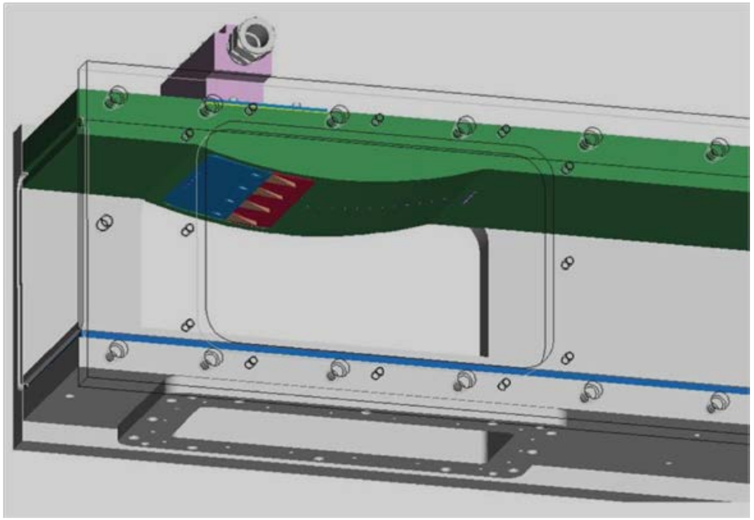
- Hybrid Flow Control
  - Steady micro-jets with micro-ramp vortex generators
  - Precondition the inlet flow
  - Reduce separation

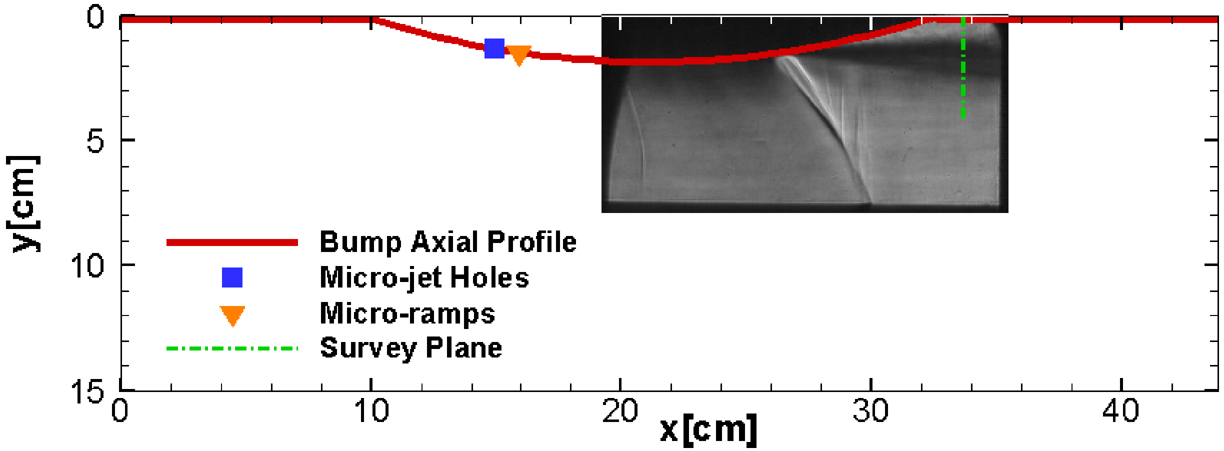


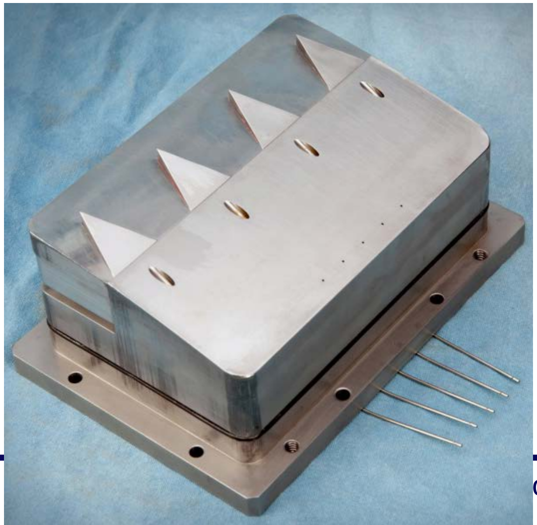
Experimental Setup

15x15cm Supersonic Wind Tunnel

- Mach Number: 0.67
- Reynolds Number: 13.1 E6/m
- Micro-jets: x = 14.9 cm
- Micro-ramps: x = 15.9 cm



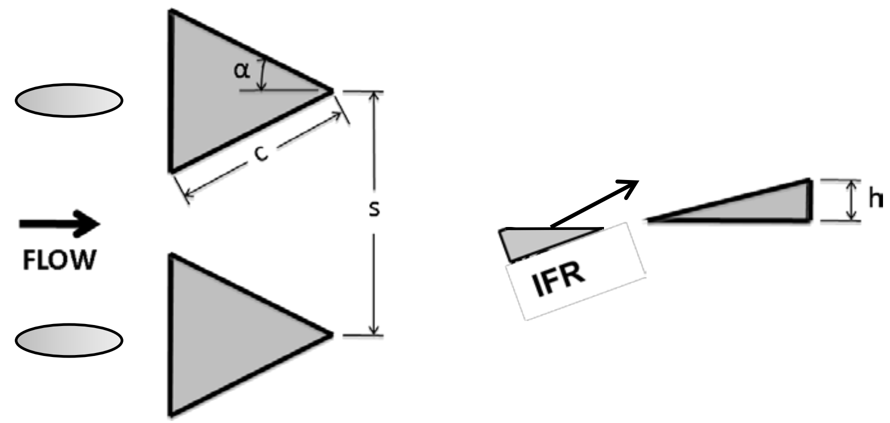


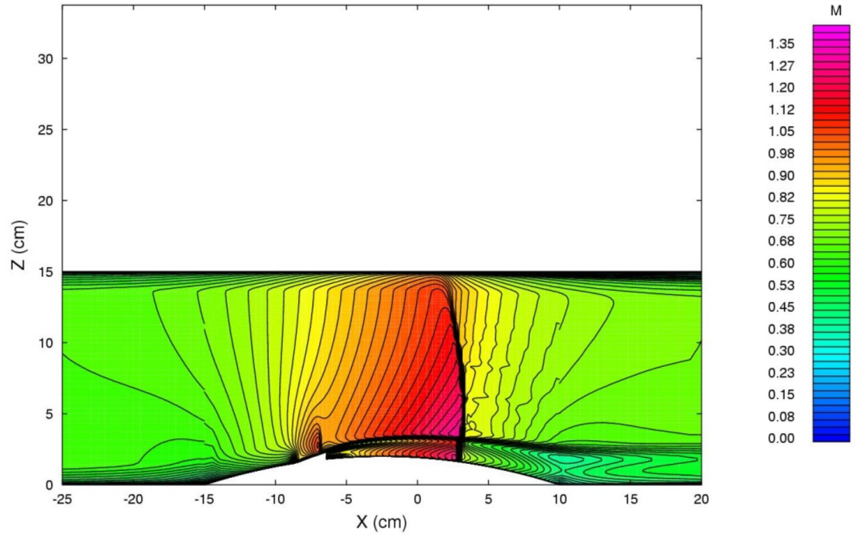


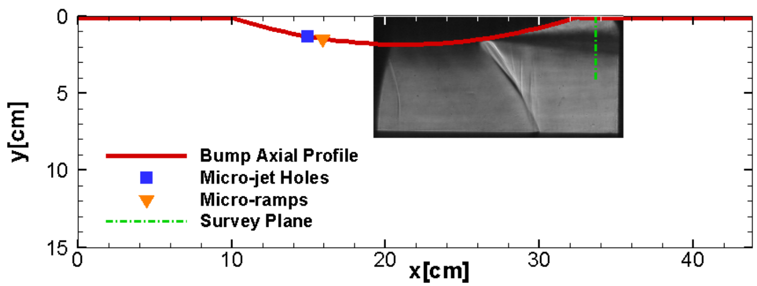
Hybrid Flow Control Design

Based on computational screening study

- Four devices across span
- s = 25, 30, 35 mm
- h = 3, 4, 5 mm
- c = 12, 18, 24 mm
- IFR = 0.0, 0.5, 1.0 %
- α = 24°
- Injection angle = 20°

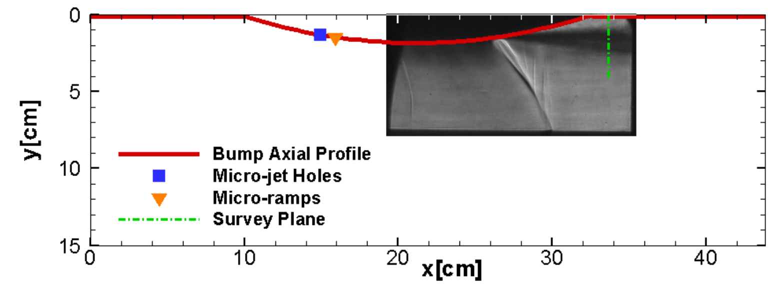


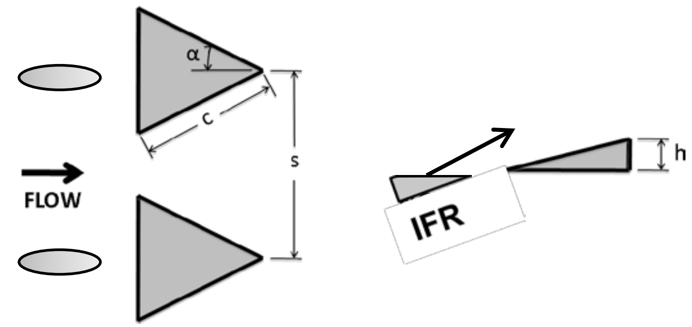


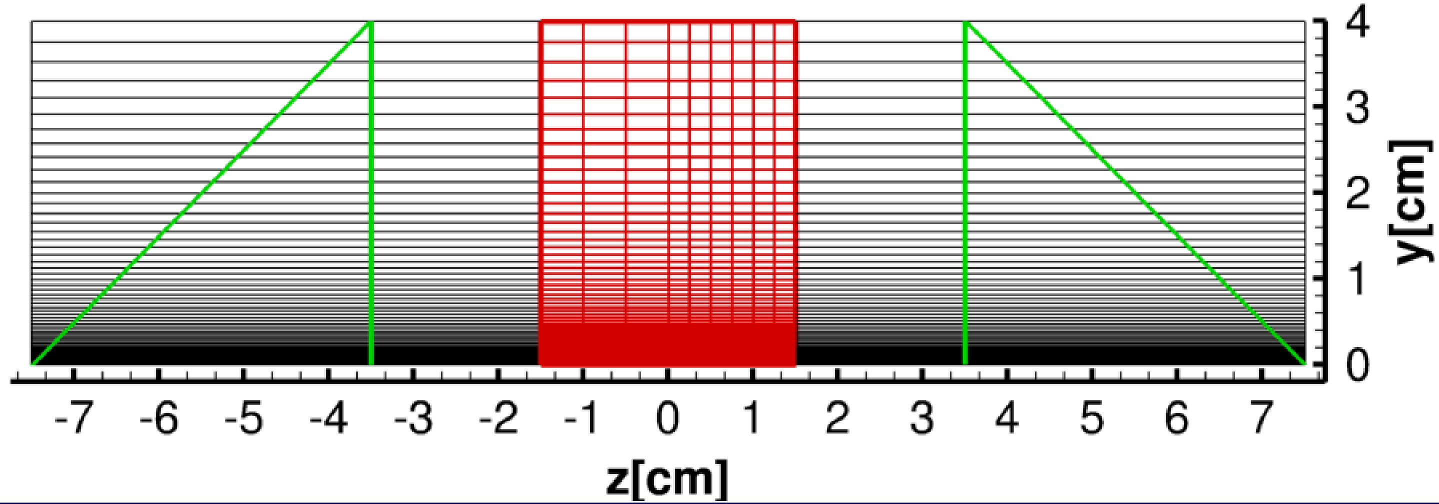


Instrumentation

- Translating pitot probe
  - x = 34 cm
  - Central survey (in red) for all configurations
  - Corner surveys (in green) for select configurations
- Static Pressure Taps axially along bump centerline and spanwise at measurement plane

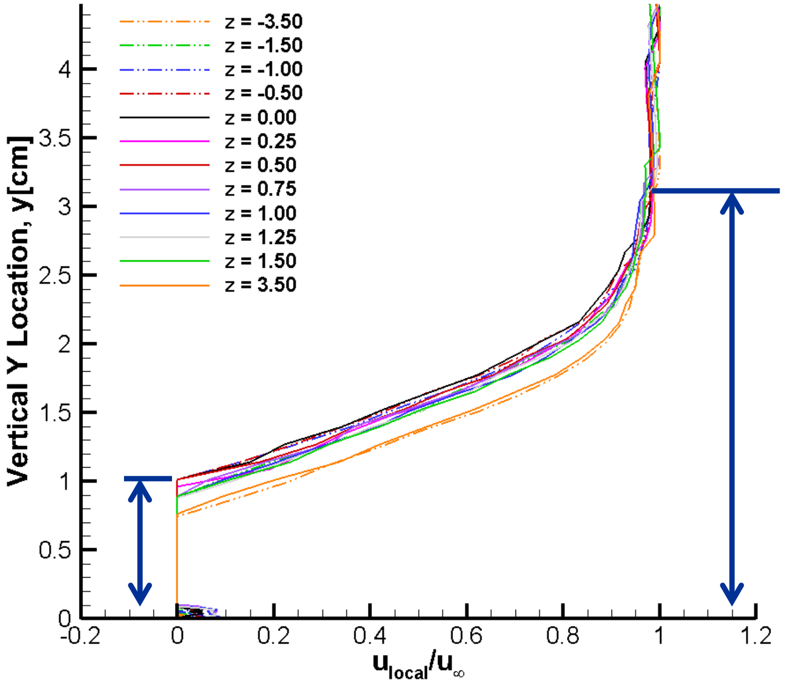


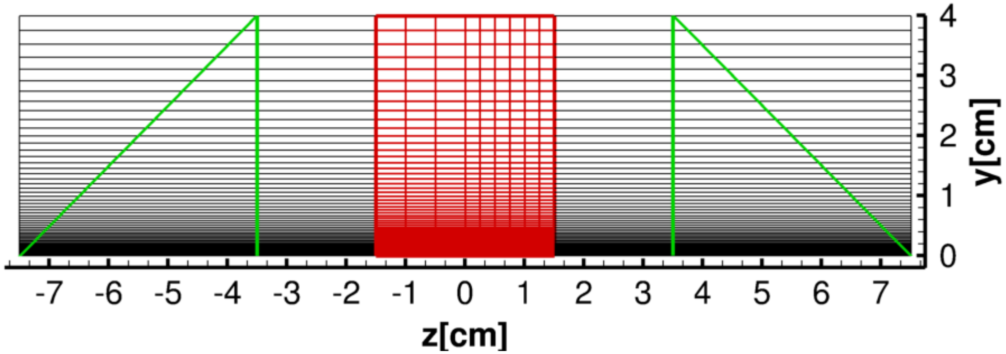




Results

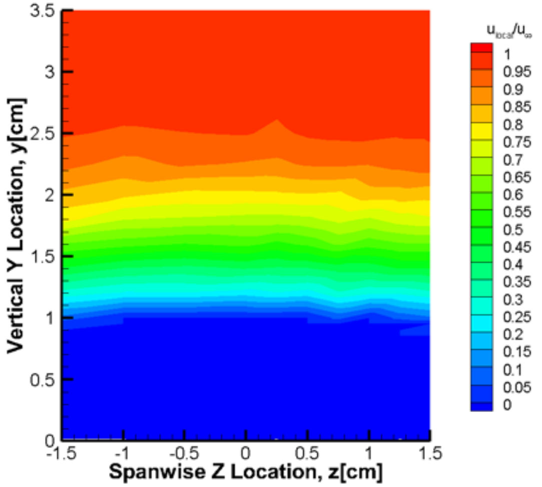
- Boundary Layer Thickness
  - 99% of freestream velocity
- Reversed Flow Thickness
  - Measured zero velocity
- Span-averaged

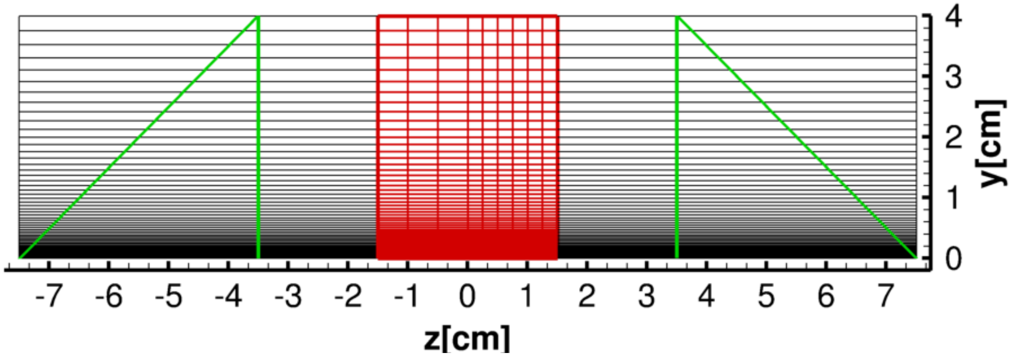


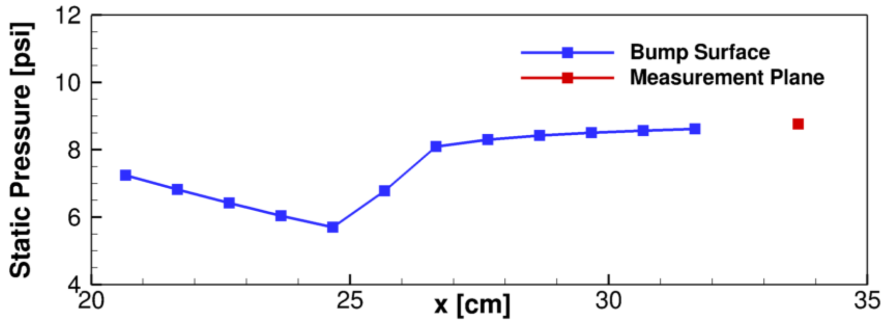


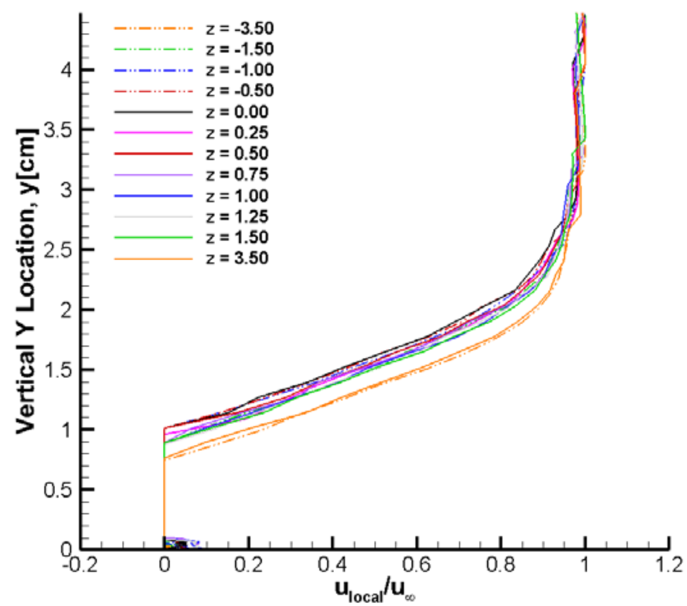
Baseline Case

- Boundary layer thickness: 2.89 cm
- Reversed flow thickness: 0.973 cm
- Velocity contours show uniform flow
- Profiles measured at ±3.5 are fuller
- Static pressure profile shows the shock pressure rise



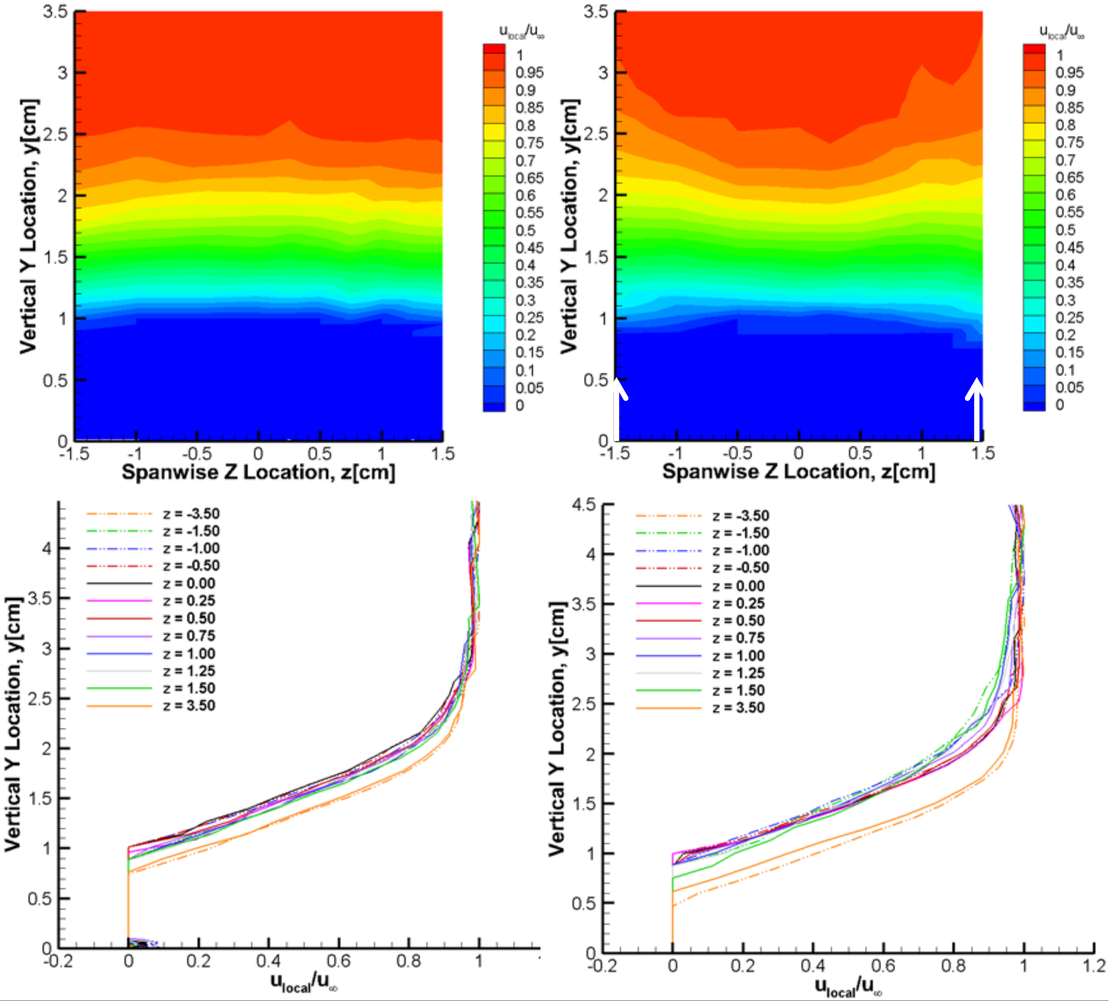






Injection Only

- IFR = 1.0 %, s = 30 mm
- Boundary layer thickness: 2.80 cm
- Reversed flow thickness: 0.903 cm



Design of Experiments

Central Composite Design

- Four factor variables at three levels
- Two response variables
  - Boundary layer thickness
  - Reversed flow thickness
- Response Surface Equation

$$\delta = a_o + a_1 s + a_2 h + a_3 c + a_4 IFR + a_{12} sh + a_{13} sc + a_{14} sIFR + a_{23} hc + a_{24} hIFR + a_{34} cIFR + a_{11} s^2 + a_{22} h^2 + a_{33} c^2 + a_{44} IFR^2$$

- Replicates
  - Center point replicated seven times
  - Six additional replicates

Boundary Layer Thickness

Boundary Layer Thickness

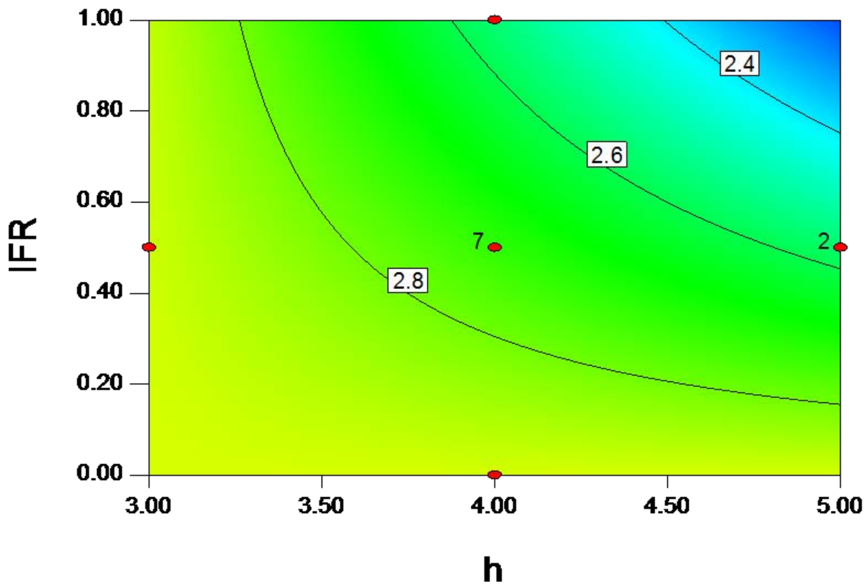
Factorial	**Quadratic 1**	**Quadratic 2**
$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
LOF = 0.5468	LOF = 0.6606	LOF = 0.6820
Variables Included:	Variables Included:	Variables Included:
h, IFR, h-IFR	s, h, IFR, h-IFR, s^2	h, c, IFR, h-IFR, c^2

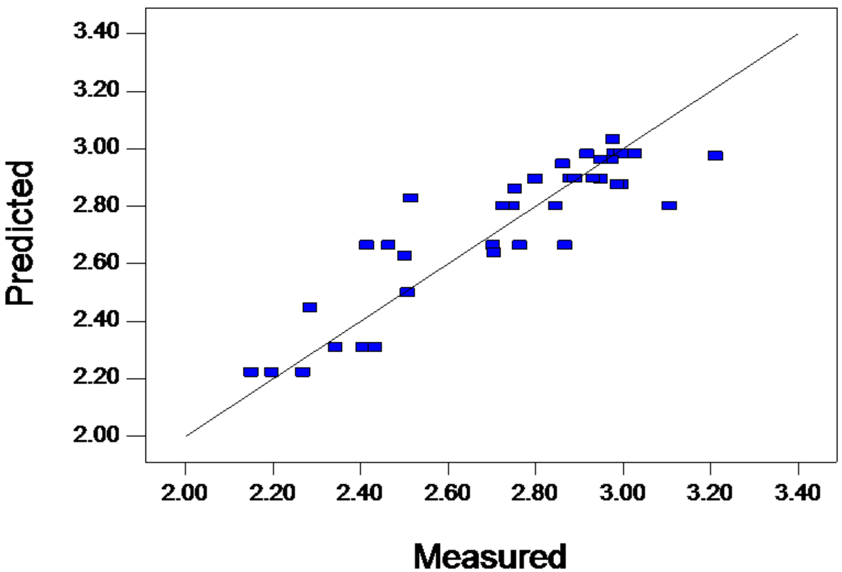
When the spacing increases, the vortices are unable to influence the entire span, and therefore the span-averaged boundary-layer thickness increases. We choose the quadratic 1 model.

Boundary Layer Thickness

- Quadratic 1
  - $R^2=0.797$
  - Pure error mean square = 0.021
    - Standard deviation of replicated points ≈ 0.145 cm

$$\boxed{\begin{gathered}\delta = 6.316 - 0.236s - 0.0011h + 0.952IFR \\ - 0.325hIFR + 0.0041s^2\end{gathered}}$$





Boundary Layer Thickness

Velocity Contours: s = 25 mm, *c* = 24 mm

h = 3 mm, *IFR* = 0.0%

- Slight thickening of the boundary layer in line with the devices, and thinning between the devices

h = 3 mm, *IFR* = 1.0%

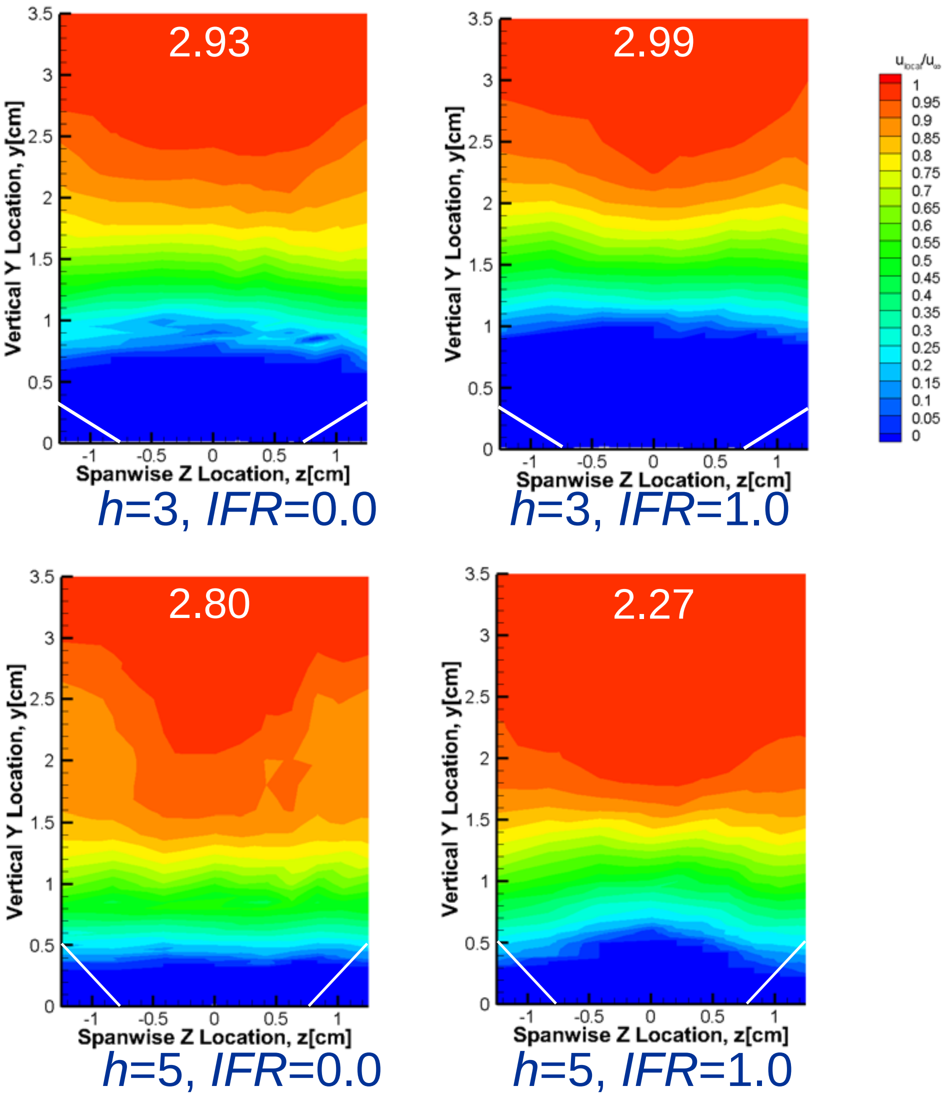
- Slightly increased the boundary-layer thickness compared to no injection

h = 5 mm, *IFR* = 0.0%

- Slightly thinner boundary layer than the baseline case because of the thinning between the devices
- Highly non-uniform across the span.

h = 5 mm, *IFR* = 1.0%

- High momentum flow in the micro-jet reenergized the flow in the velocity deficit region created by the vortex
- Boundary layer was thinned in all measured z-locations from -1.25 to +1.25 cm compared to the baseline



Reversed Flow Thickness

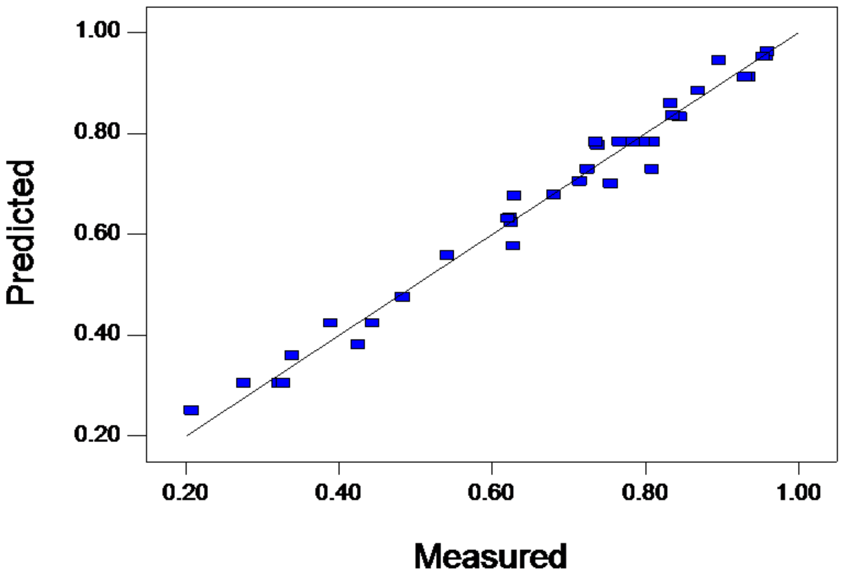
Reversed Flow Thickness

Factorial	Quadratic	Higher Order
$p < 0.0001$	$p < 0.0001$	$p < 0.0001$
LOF = 0.0016	LOF = 0.0079	LOF = 0.1672
Variables Included:	Variables Included:	Variables Included:
s, h, c, IFR, s-h, s-IFR, h-IFR	s, h, c, IFR, s-h, s-IFR, h-IFR, IFR^2	s, h, c, IFR, s-h, s-c, s-IFR, h-IFR, c-IFR, h^2, IFR^2, s-h-IFR, s-c-IFR, s-h^2

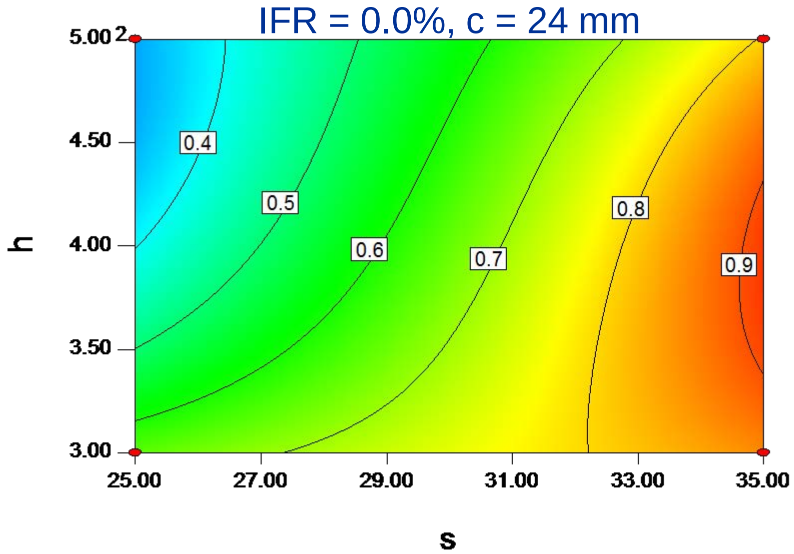
Only the higher order model fits the data. Interactions between sets of three variables are important to understanding the effect of the factor variables on the reversed-flow thickness.

Reversed Flow Thickness

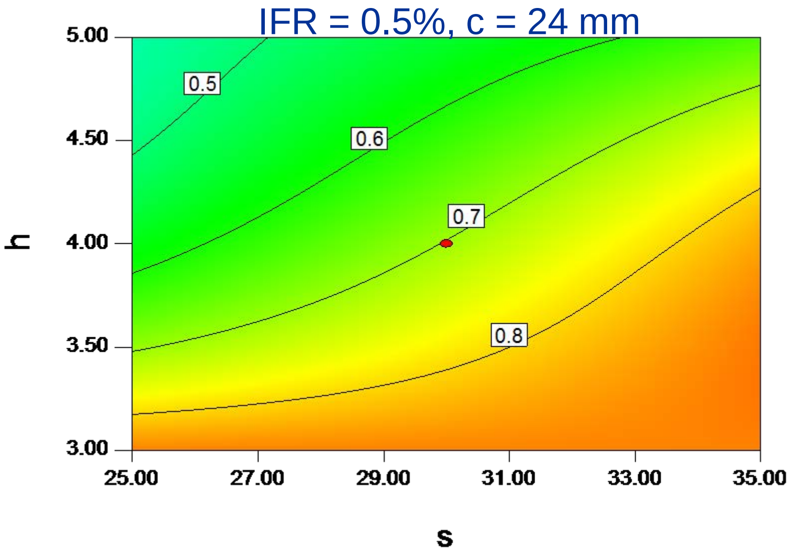
- Higher Order Model
  - R^2=0.98
  - Pure error mean square = 9.38E-4
    - Standard deviation of replicated points ≈ 0.031

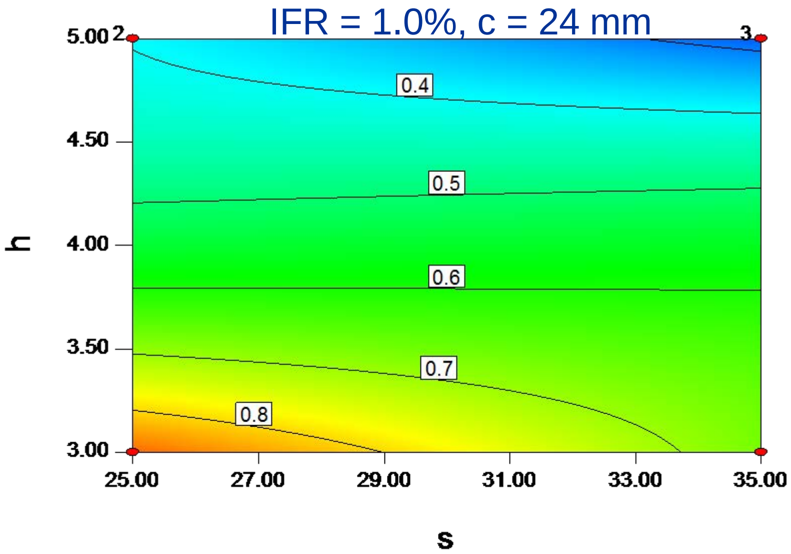


Contours of Reversed Flow Thickness



- s-h-IFR Interaction
  - Without injection, reducing spacing reduces reversed-flow thickness
  - With injection, increasing spacing reduces reversed-flow thickness





Reversed Flow Thickness

Velocity Contours: h = 5 mm, *c* = 24 mm

- Reversed flow is seen as the dark blue region near the wall

s = 25 mm, *IFR* = 0.0%

- Uniformly thinned reversed-flow region

s = 25 mm, *IFR* = 1.0%

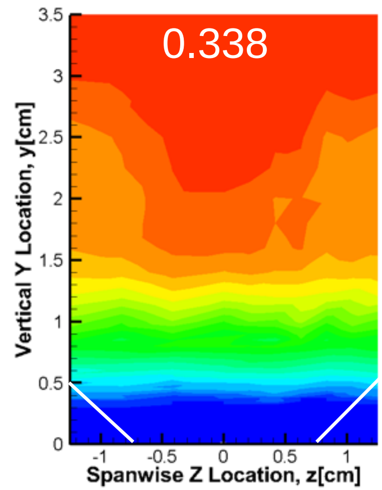
- Reversed-flow thickness decreased across the span
- Greatest reduction in line with the devices

s = 35 mm, *IFR* = 0.0%

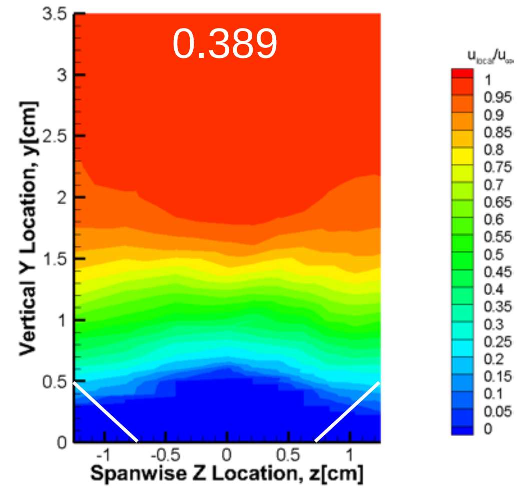
- Reversed-flow thickness slightly reduced in line with the devices, but increased from baseline in between.

s = 35 mm, *IFR* = 1.0%

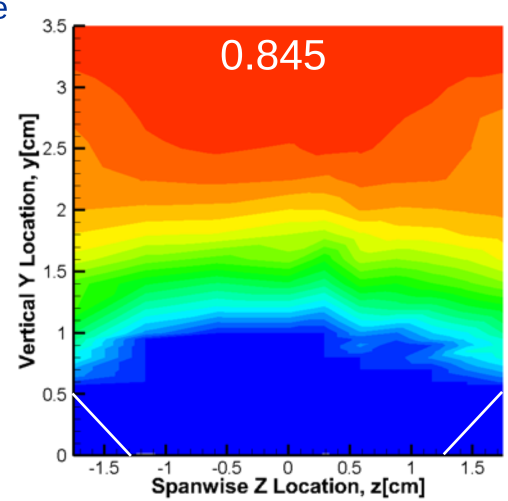
- Reversed-flow thickness decreased across the span
- No reversed flow in line with the devices at z = ±1.75



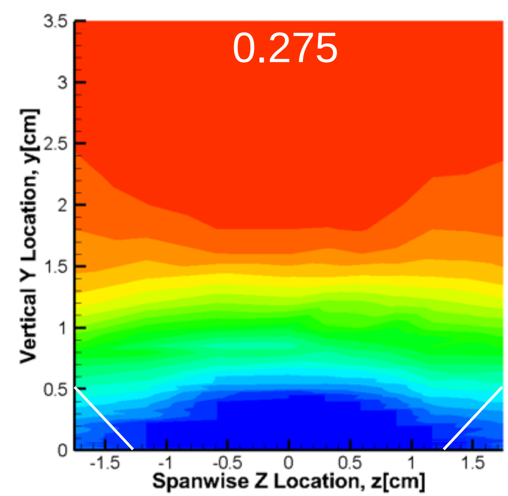
s=25, *IFR*=0.0



s=25, *IFR*=1.0



s=35, *IFR*=0.0



s=35, *IFR*=1.0

Optimization

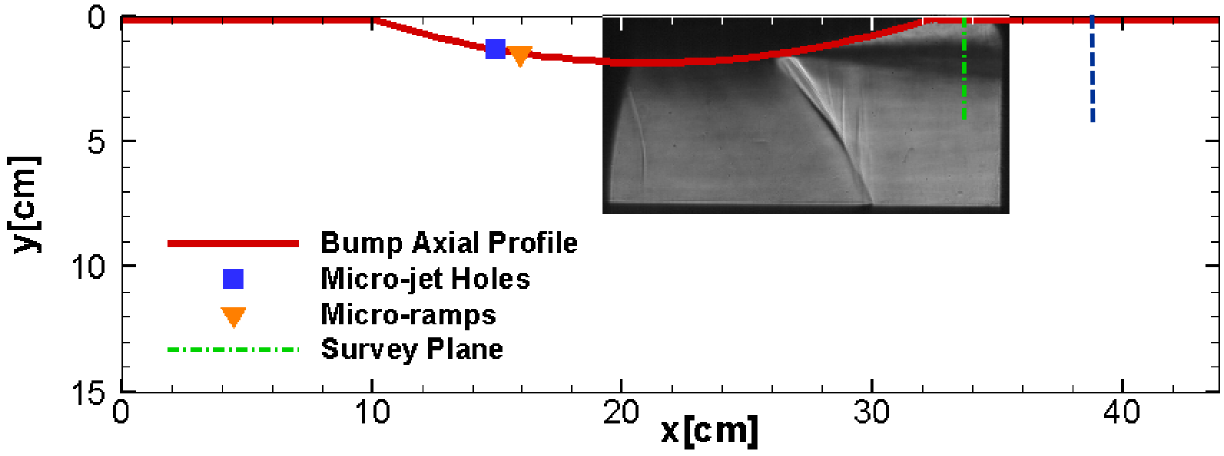
	Factor Variables Baseline	Optimized Variables		
		Boundary-Layer Thickness	Reversed-Flow Thickness	Joint
s [mm]	0.0	28.93	35.00	31.14
h [mm]	0.0	5.0	5.0	5.0
c [mm]	0.0	Not a Factor	24.0	24.0
IFR [mm]	0.0	1.0	1.0	1.0
Predicted Response Values				
δ [cm]	2.89	2.229	-	2.248
RFT [cm]	0.973	-	0.278	0.324

Because increasing the height or chord length of the devices increases drag and the injection flow has to come from elsewhere in the propulsion system, it would be necessary to consider additional response variables to determine if these factors could be increased further.

Preliminary Review of Recent Results

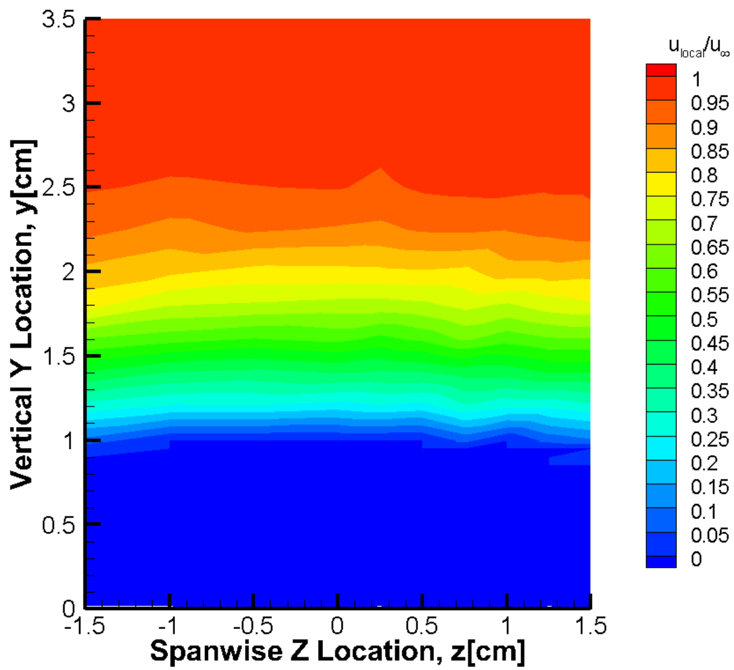
Downstream

- New surveys 10 cm farther downstream
  - Baseline
  - Injection Only
  - Ramps only: 35-5-24-0



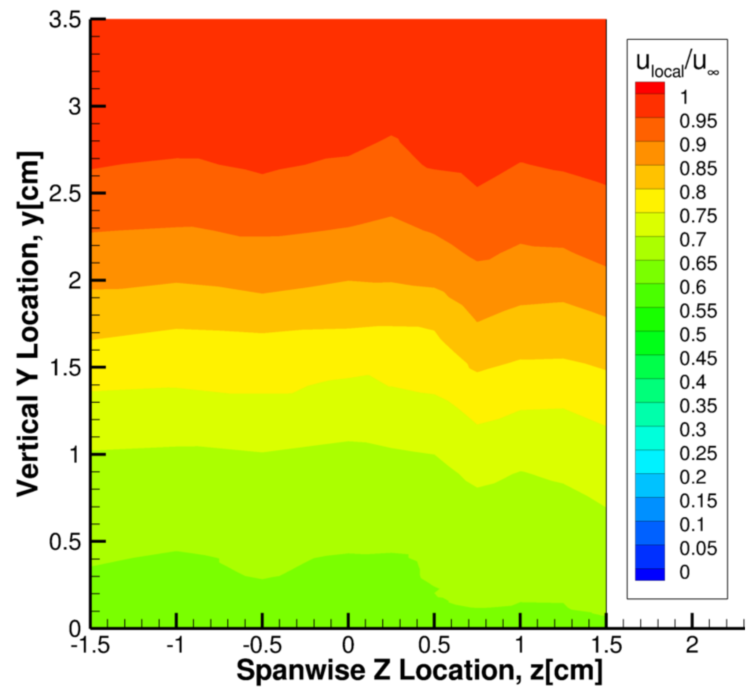
Baseline

- Flow has reattached



x = 34 cm

δ = 2.89 cm



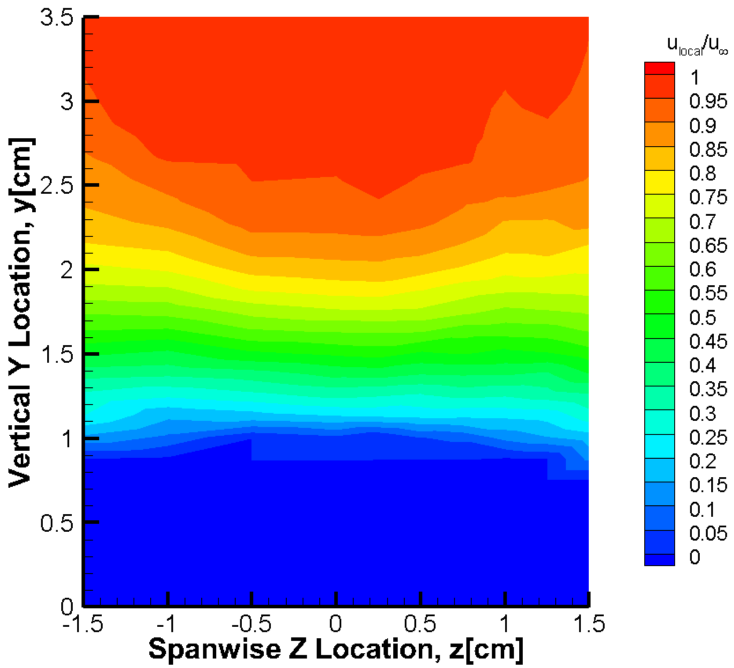
x = 44 cm

δ = 3.33 cm

H_i = 1.36

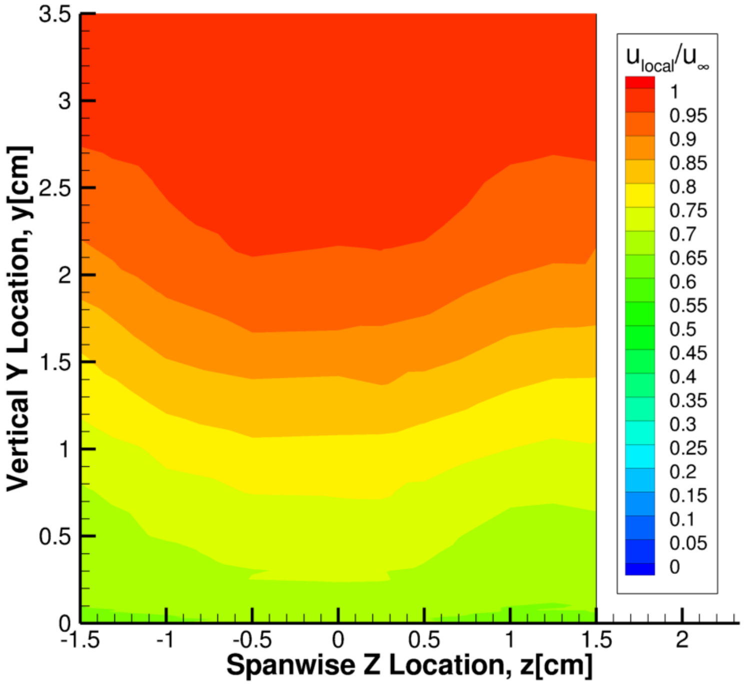
Injection Only

- Region of most improvement is between devices



x = 34 cm

δ = 2.80 cm



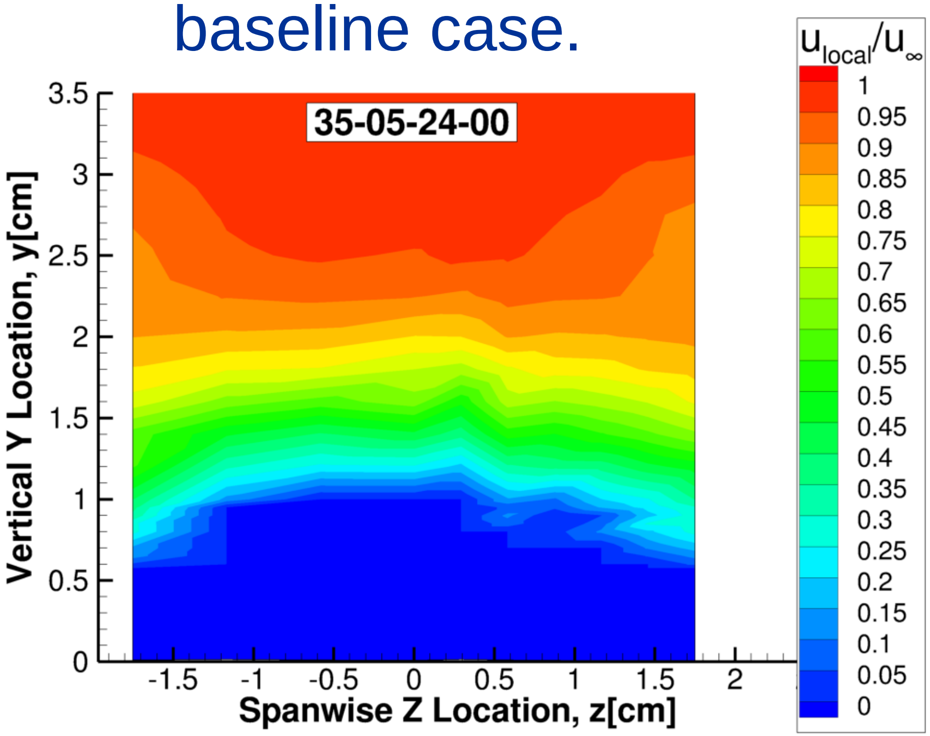
x = 44 cm

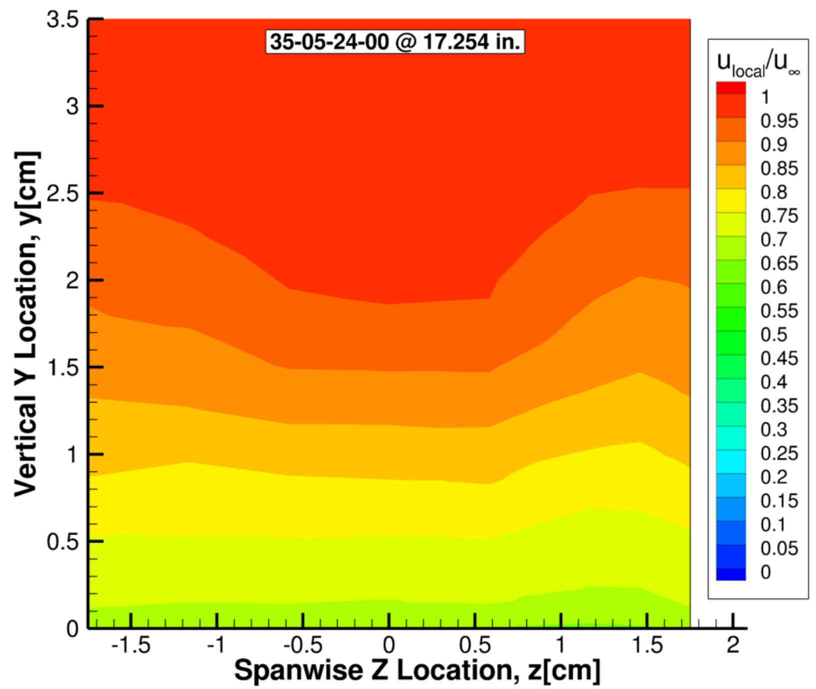
δ = 2.93 cm

H_i = 1.30

Microramps: 35-5-24-0

- Boundary layer is thinner across entire span than baseline case.





x = 34 cm

δ = 2.89 cm

x = 44 cm

δ = 2.68 cm

H_i = 1.25

Conclusions

- Hybrid flow control was able to reduce the boundary-layer thickness and reversed-flow thickness caused by a normal shock boundary layer interaction.
  - Compared to the baseline uncontrolled case which had a boundary-layer thickness of 2.89 cm and a reversed-flow thickness of 0.973 cm, hybrid flow control configurations generated span-averaged boundary-layer thicknesses as low as 2.15 cm and reversed-flow thicknesses as low as 0.207 cm.
  - Improvements were made with micro-ramps only or in the hybrid configuration.
  - Large micro-ramps (h = 5 mm, c = 24 mm) widely spaced with 1.0% injection flow ratio was the only configuration to eliminate the separation in line with the devices and break the separation into pockets.

Conclusions

- Response surface equations were obtained for the response variables in terms of the factor variables tested.
  - The boundary-layer thickness could be modeled with as little as two variables and their interaction, however a more complete model provided slightly better results. Spacing was chosen as a factor in the equation rather than chord length because while both provided statistically valid models, spacing could be explained physically.
  - The reversed-flow thickness required many terms including higher order interactions to get a statistically significant model. A one factor at a time analysis would have missed the interactions that were necessary to understand the effects of the hybrid flow control.

Conclusions

- The hybrid flow control was optimized for this tunnel configuration (e.g. with a parabolic bump to create a normal shock and incoming Mach number of 0.67) on the basis of the response surface equations obtained.
  - A joint optimization of boundary layer thickness and reversed-flow thickness showed the optimum configuration to be *s* = 31.14 mm, *h* = 5 mm, *c* = 24 mm, and *IFR* = 1.0%.
  - For these factor values, the predicted boundary layer thickness was 2.248 cm, and the predicted reversed-flow thickness was 0.324 cm.