Flow characteristics of a strut injector for scramjets: numerical and experimental analysis

Presentation TFAWS2014-I-02

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NASA TFAWS 2014

3-8 August, 2014, Cleveland, OH

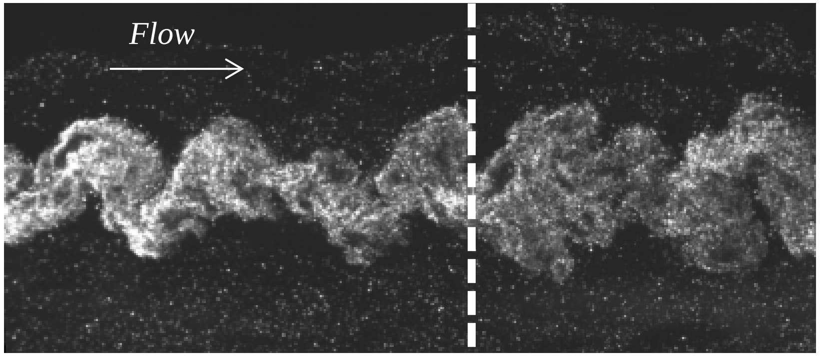
Presented by Valerio Viti

Summary

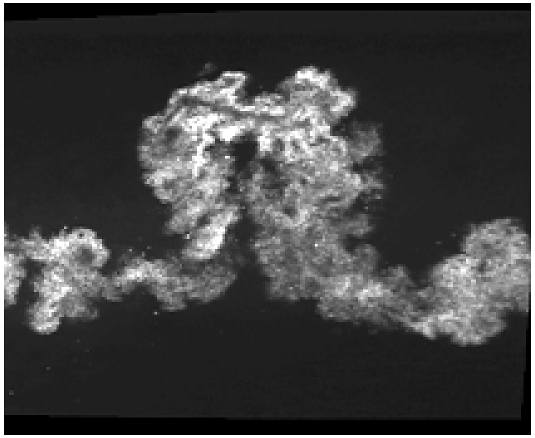
Summary

1. Introduction and Focus of Work (1/4)

- Supersonic flow in the combustor is required to enable flight at hypersonic speeds
  - *Total pressure losses associated with normal shock compression prevent to employ subsonic combustion*
- In the combustion chamber
  - *Residence time of the flow in the combustor is on the order of* 10^{-3}*s*
  - *Fast mixing and efficient combustion required to decrease otherwise excessive engine lengths to minimize drag and weights*
- Mixing strategies based solely on planar shear layers have been considered but compressibility effects hinder the spatial growth of planar shear layers.
- More studies on the effects of streamwise vorticity (distribution, magnitude, etc.) are needed.



Spanwise rollers in a wake in supersonic flow



Plume of an injector modified by a streamwise counter rotating vortex pair (CVP) in a wake in supersonic flow

1. Introduction and Focus of Work (2/4)

- Mixing in the combustor must be enhanced

-Injection systems are required to effectively enhance mixing while reducing losses as much as possible

-Streamwise vorticity can be introduced in order to enhance molecular mixing by the entrainment and stretching of the fuel/air interface

- Intrusive injection systems are necessary

-Low penetration of the fuel plume from wall injectors prevents their use in these geometries

-Pylon injectors promote injection close to the centerline of the combustor

-Parallel injection produces additional momentum in the direction of the thrust

-Pylons and struts can be equipped with multiple vortex generators to enhance mixing: application of the Hypermixer concept

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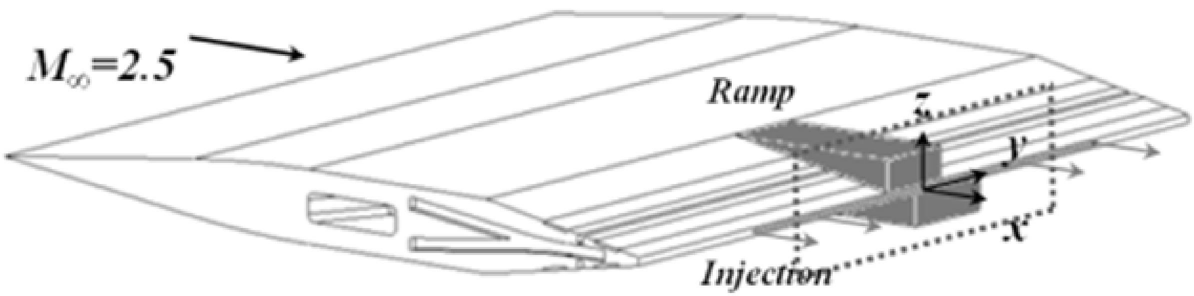
1. Introduction and Focus of Work (3/4)

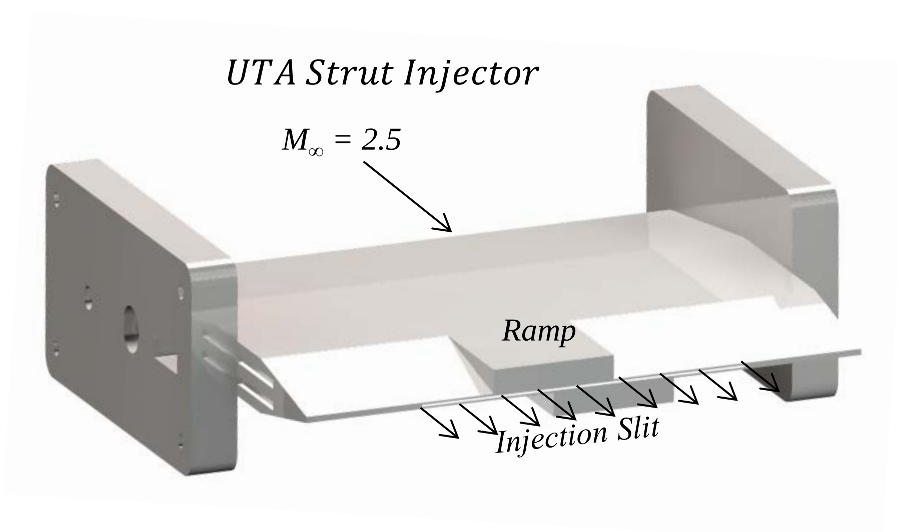
- Questions yet to be answered:
  - *What configuration of streamwise vortices can benefit plume spreading and mixing in an injection system?*
  - *Is it always beneficial to increase the streamwise vorticity content in the flow or are there limitations?*
  - *Is it possible to apply vortex dynamics concepts in high-speed reacting flows?*

↓

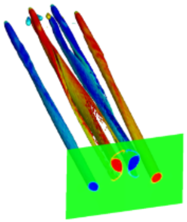
- Provide a systematic study on streamwise vortices in supersonic flow
  - *Despite the fact that streamwise vortices are recognized to improve mixing in supersonic flow, their physics and dynamics are not yet well understood (L. Maddalena, F. Vergine and M. Crisanti, "Vortex dynamics studies in supersonic flow: merging of co-rotating streamwise vortices," Physics of Fluids, AIP, 2014)*
  - *A study on the effect of complex distributions of vortices in a supersonic flow field is still missing. Merging? Non-merging?*
- Investigate the plume of injectant evolving in the presence of pre-imposed streamwise vortices
  - *The analysis of the plume provides useful information on the behavior of the streamwise vortices*

1. Geometry of strut injector





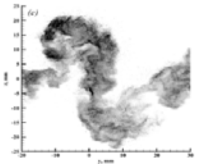
1. Introduction and Focus of Work (4/4)



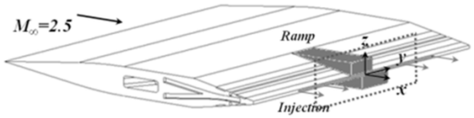
VorTx

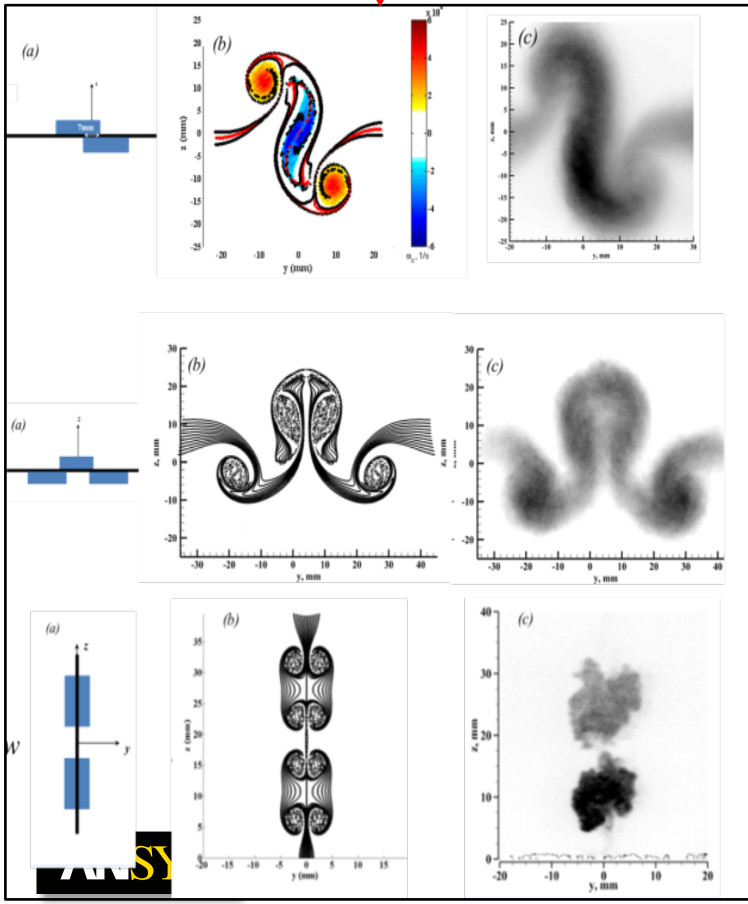
- Reduced order inviscid flow solver for the design of experiments

Experimental measurements

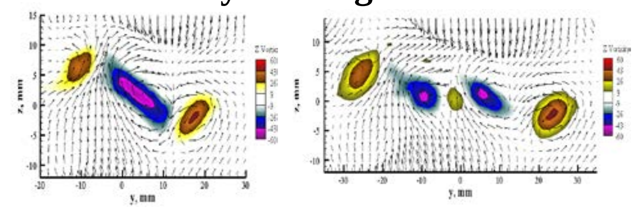


- Instantaneous image of TiO_2 particle seeded flow

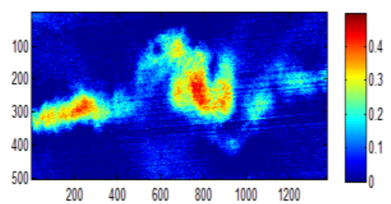




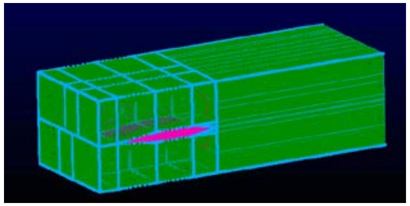
Flow analysis using PIV results



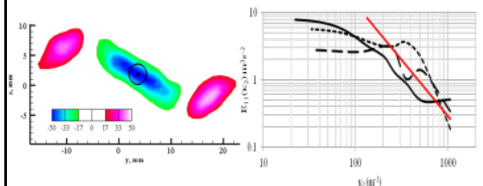
Intrusive and non-intrusive mixing measurements



CFD simulations



Analysis of turbulence and associated scales



Summary

1. Introduction and Focus of Work

2. **Facility Description and Experimental Setup**

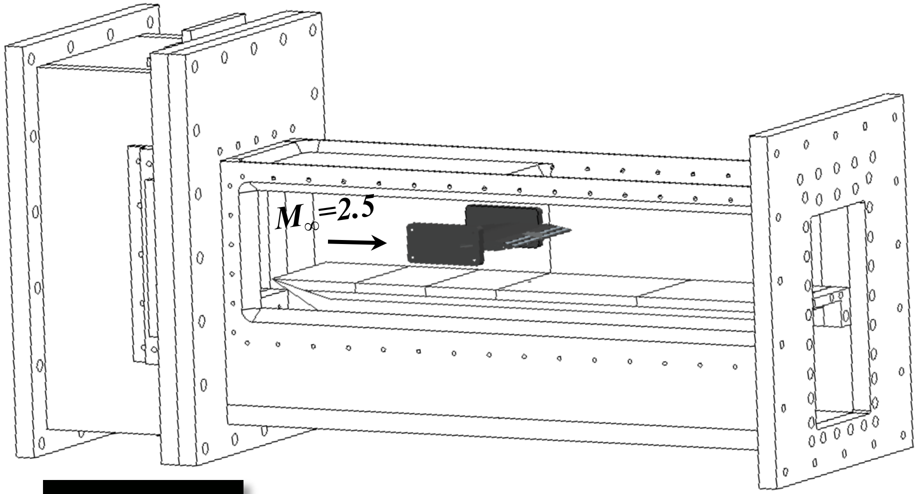
3. Reduced Order Model Predictions and Experimental Results
    - 3.1 Description and Predictions of Reduced Order Model
    - 3.2 Experimental S-PIV Results

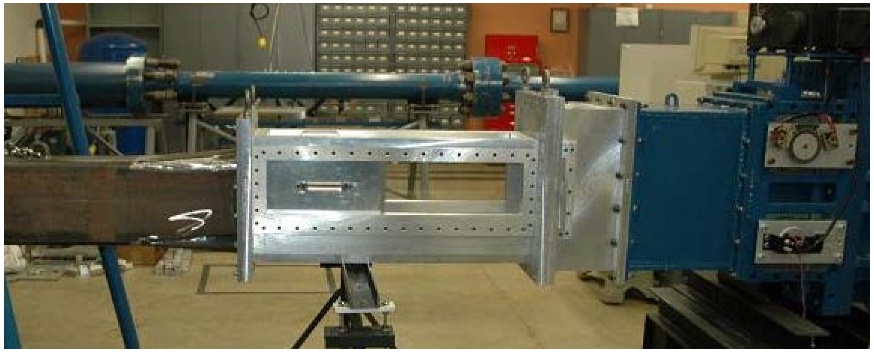
4. CFD Analysis
    - 4.1 Computational Model
    - 4.2 Results

5. Conclusions and Future Work

2. Facility Description and Experimental Setup (1/4)

- Experiments were conducted in the supersonic wind tunnel housed at the University of Texas at Arlington's Aerodynamics Research Center (UTA ARC)
  - *Blow-down type tunnel*
  - *Variable Mach number nozzle (M_∞ = 2.5 for current experiments)*
  - *Nominal stagnation conditions ($p_{0\infty}$ = 610 kPa, T_0 = 294 K)*
  - *Steady state run times of ~10s*
  - *Reynolds number per unit length, Re = 6.45 x 10^7 m^{-1}*





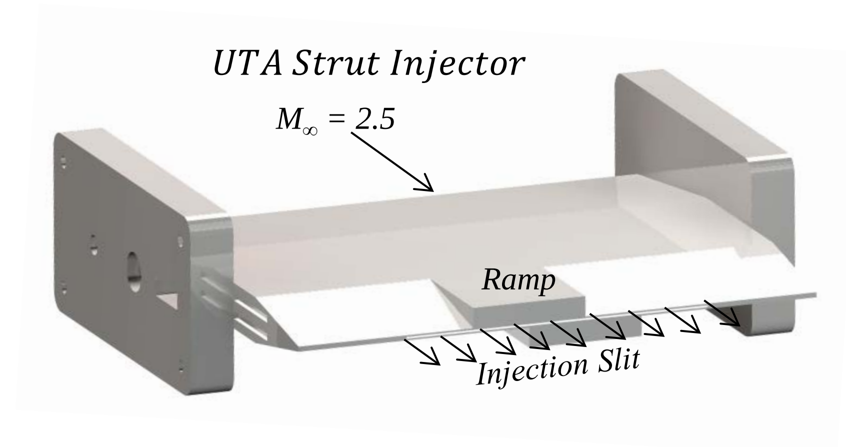
2. Facility Description and Experimental Setup (2/3)

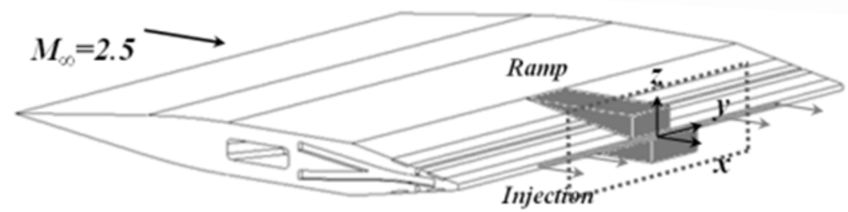
- A strut injector (hypermixer) serves as a platform to study multiple movable ramp configurations. Its body is machined stainless steel and produces a thin plume parallel to the supersonic flow

  - *LE compression angle:* *7°*
  - *TE expansion angle:* *10°*
  - *Injection port:* *102 x 0.5* mm^2

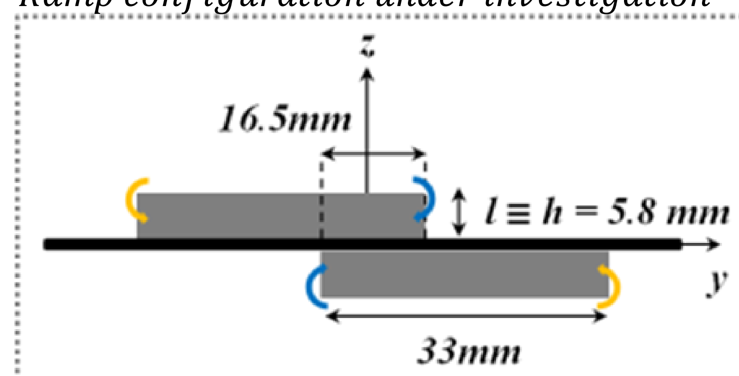
- The flow around the ramps generates streamwise, Counter-rotating Vortex Pairs (CVP's)

  - *The size of the vortices is comparable with the ramp's height and their calculated circulation on the order of 1* m^2/s





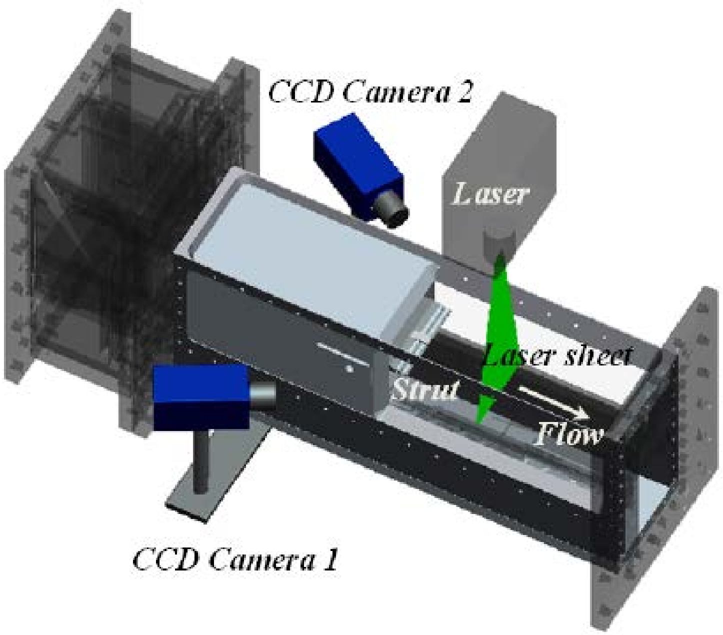
Ramp configuration under investigation

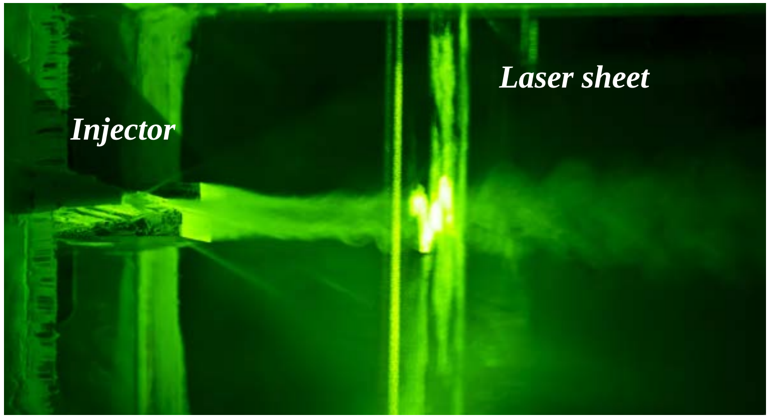


2. Facility Description and Experimental Setup (3/4)

Stereoscopic PIV setup

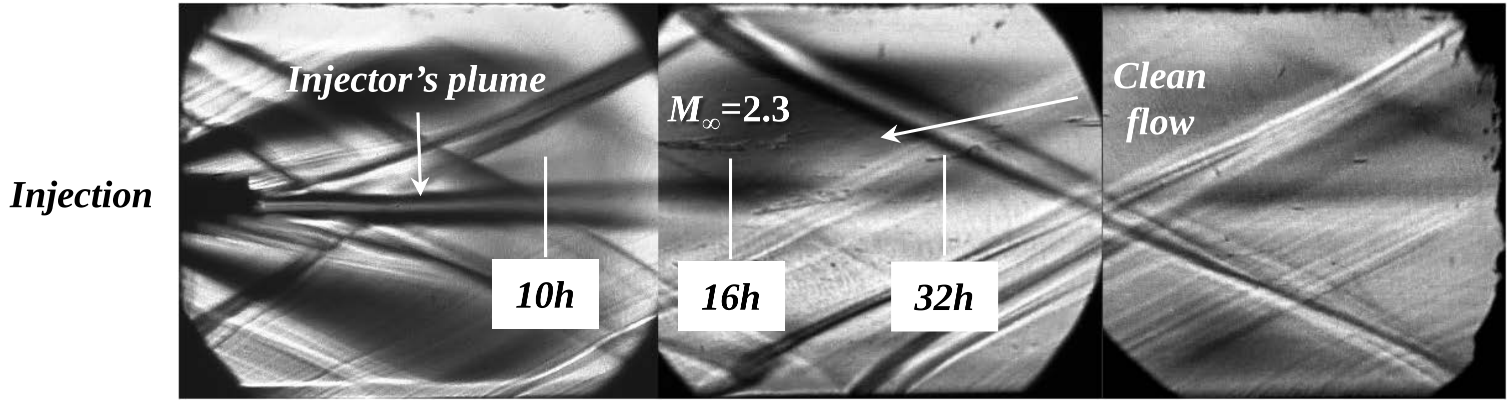
- Laser
  - *New Wave Research Solo PIV 120, Nd:YAG double pulsed laser*
  - *Laser Programmable Timing Unit (PTU): 5Hz*
  - *Laser pulse separation: 1.2μs*
- CCD cameras and resolution
  - *LaVision Imager Intense*
  - *Resolution: ~0.058 mm/px*
- Particles
  - *TiO_2 (proved to most faithfully follow flow)*
  - *Density: 4130kg/m^3*
  - *Specific weight: 3.9g/cm^3 – 4.2g/cm^3*
  - *Primer particle: 20nm*
  - *Cluster particle: 150nm – 250nm*
- Image post-processing
  - *Interrogation area size: 32x32 px^2 (50% overlap)*
  - *Smallest resolved scale: ~3.6 mm*



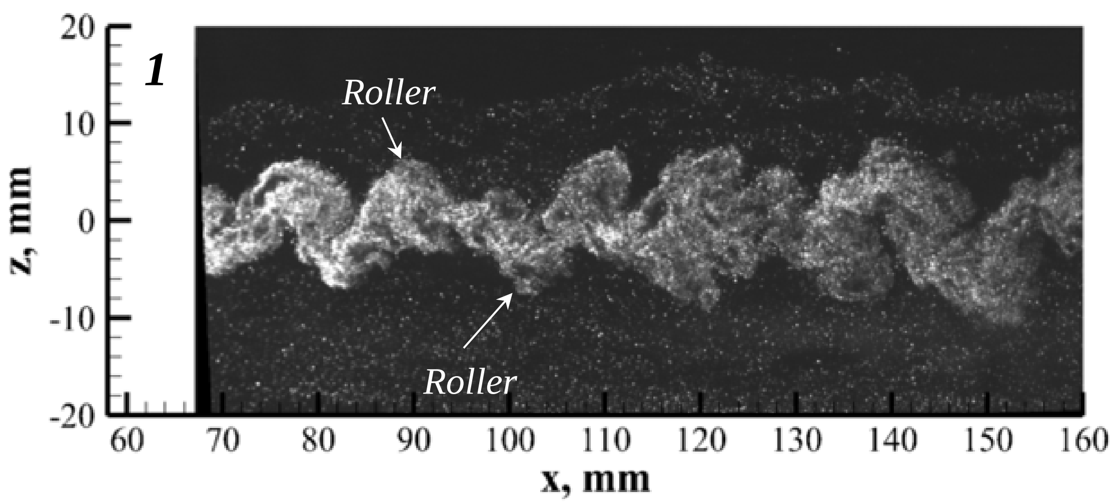


(F. Vergine and L. Maddalena, "Stereoscopic PIV measurements of supersonic, turbulent, interacting streamwise vortices, challenges and application," Progress in Aerospace Sciences, Elsevier, 2014)

2. Facility Description and Experimental Setup (4/4)



- Circulation of the rollers o(Γ) = 10^{-1} m^2/s
- Experimental setup is designed so that the streamwise vortices dominate the flow, their circulation is one order of magnitude higher than the spanwise rollers



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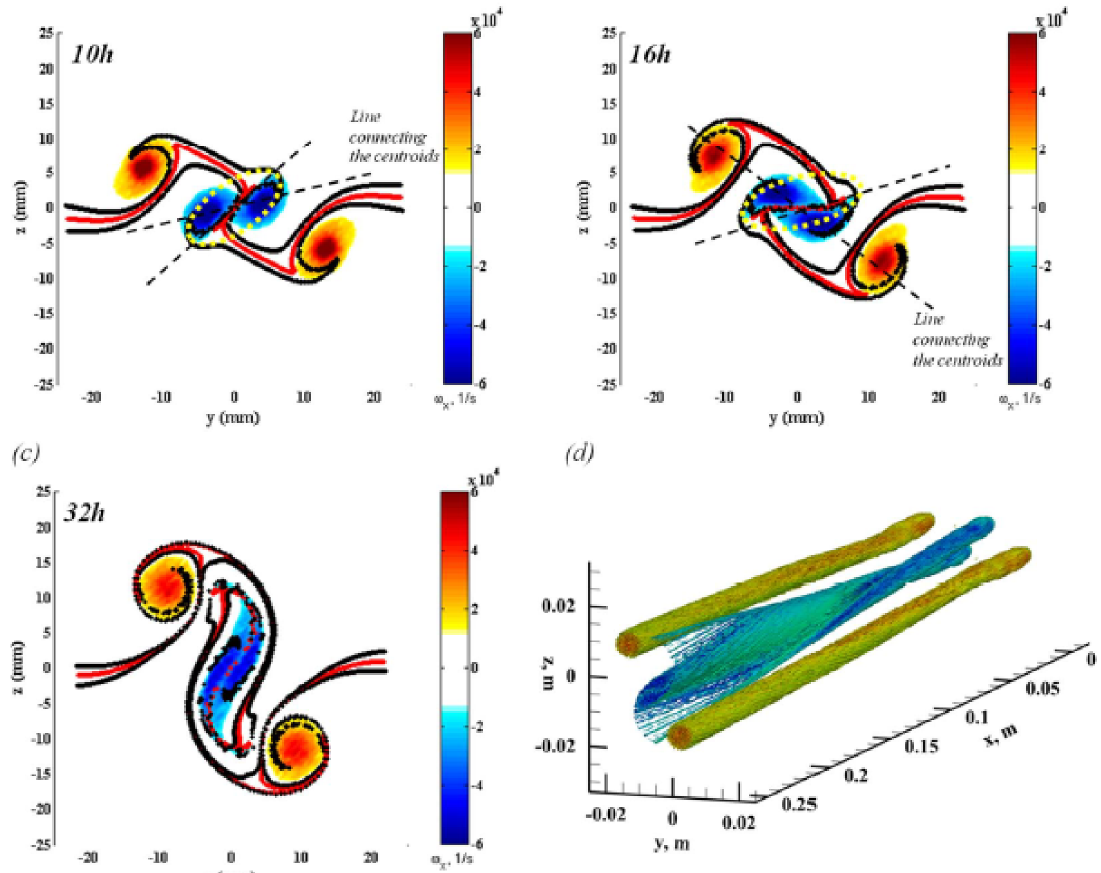
Summary

3.1. Description and Prediction of Reduced Order Model (1/3)

➢ <u>*VorTx*,</u> A reduced-order model developed in-house within the research group is used to predict the flowfield generated by specific ramp configurations, which helps <u>select *a priori* targeted ramp configurations</u> for experimental investigation

➢ *VorTx* model assumptions:

1) Slender body approximation
2) Hypersonic equivalence principle
3) Supersonic lifting line vortex filament model



➢ *VorTx* operation:

- VorTx inputs:
1) Freestream Mach number
2) Convective velocity
3) Initial position of vortices
4) Estimation of circulation of large scale structures

(L. Maddalena, F. Vergine and M. Crisanti, "Vortex dynamics studies in supersonic flow: merging of co-rotating streamwise vortices," Physics of Fluids, AIP, 2014)

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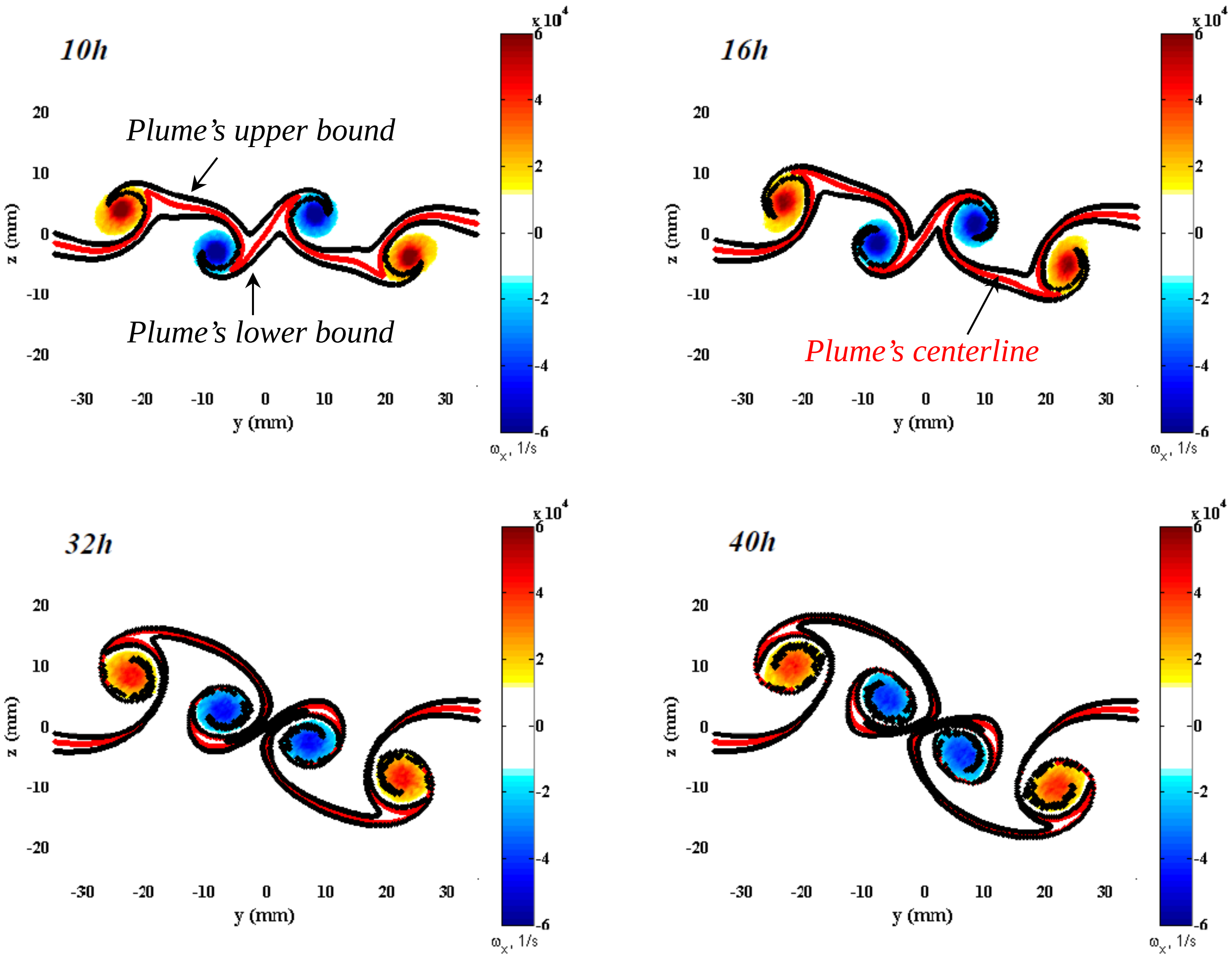
3.1. Description and Prediction of Reduced Order Model (2/3)

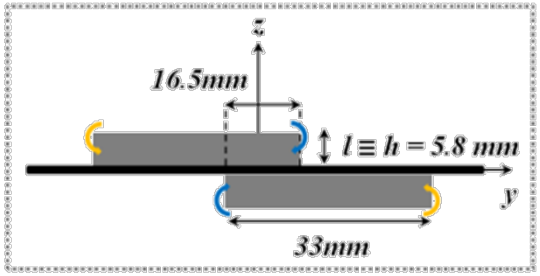
- For the current case, a ramp configuration in which the merging of the central co-rotating structures would not occur was targeted since the merging of the inner vortices had already been targeted and studied in previous investigations by the group



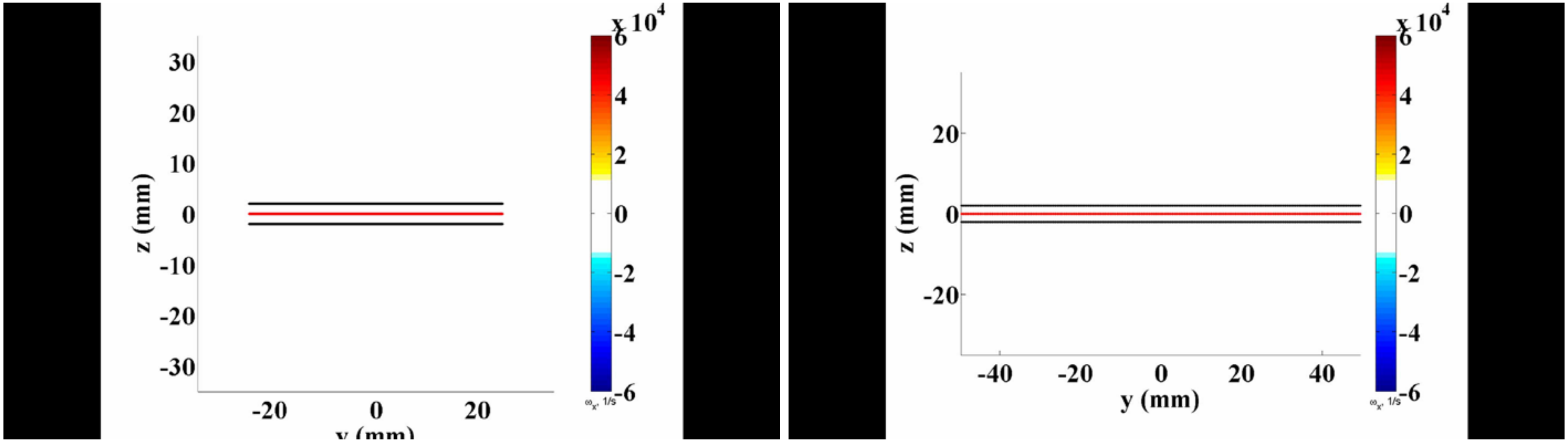
- Comments:

1) The ramps were placed far enough apart to account for the lack of turbulent diffusion in VorTx to ensure that diffusive effects would not result in the merging of the vortices

2) VorTx predicts a scenario in which the two inner co-rotating vortices do not merge, but instead the inner vortices rotate around each other



3.1. Description and Prediction of Reduced Order Model (3/3)



Vorticity unit: ***s^{-1}***

Color code

- ***Orange:***
  Counterclockwise vorticity

- **Blue:**
  Clockwise vorticity

(F. Vergine, M. Crisanti, and L.Maddalena,, "Investigation of the Merging Process and Dynamics of Streamwise Vortices Generated by a Flow-Mixing Device in a Mach 2.5 Flow," AIAA Paper, AIAA 2013-0699, 2013.

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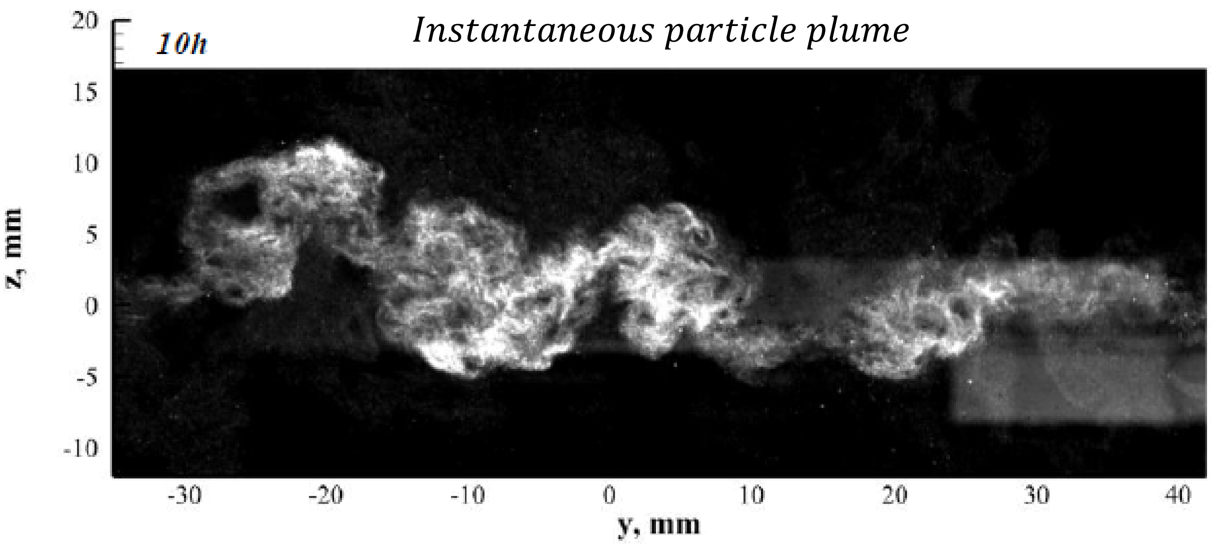
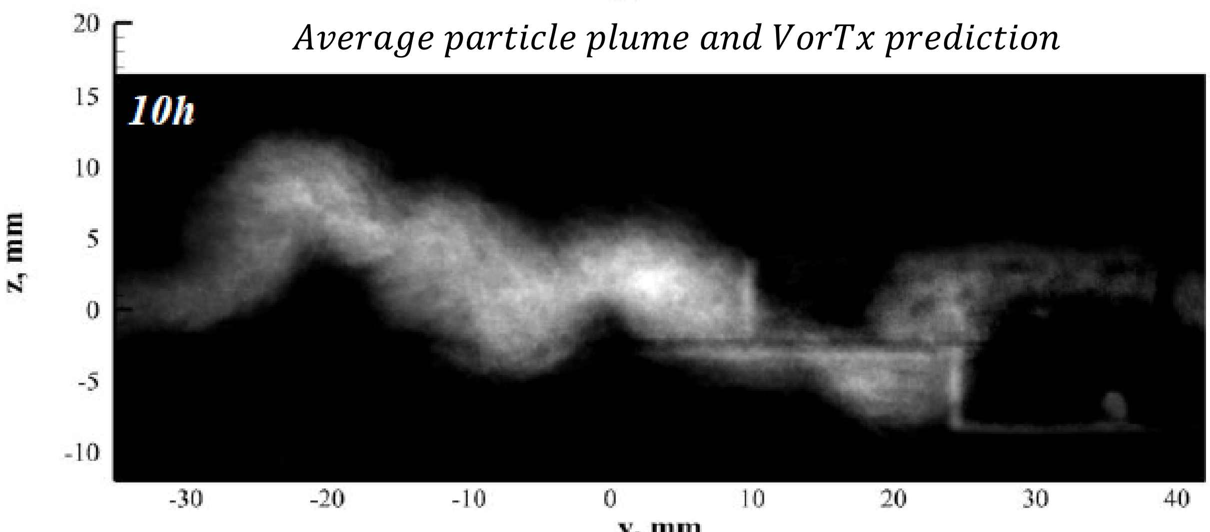
3.2. Experimental S-PIV Results (1/3)

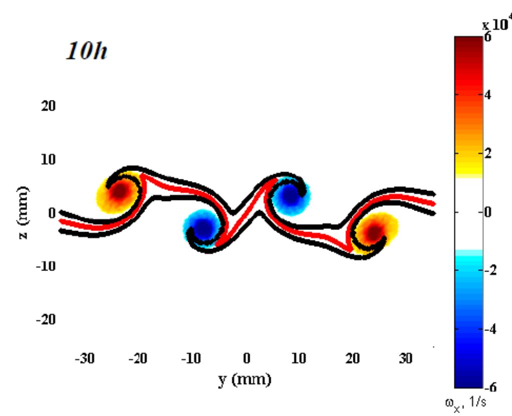




- Comments:

1) The average and instantaneous images of the particle plume allow for observation of the plume shape

2) The plume appears to be asymmetrical, with the left and right lobes of different shape



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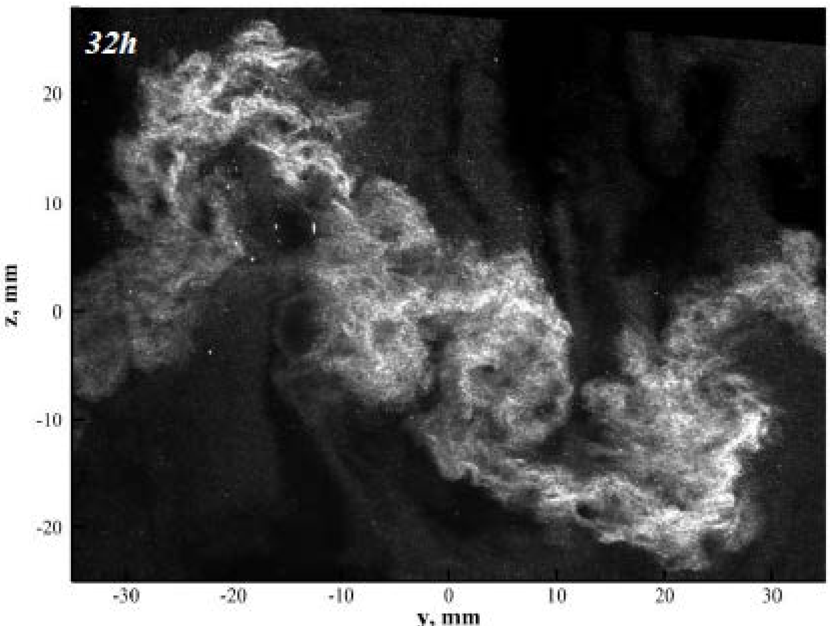
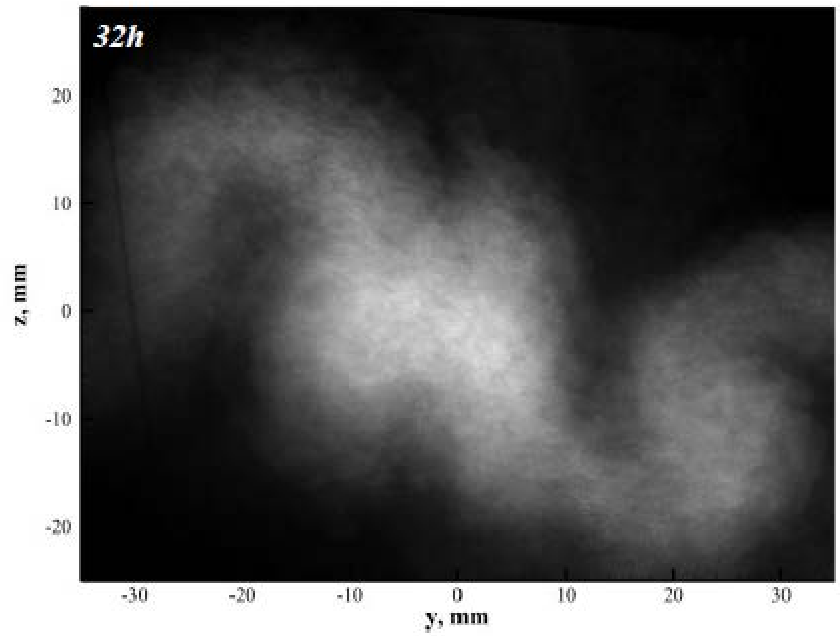
3.2. Experimental S-PIV Results (2/3)

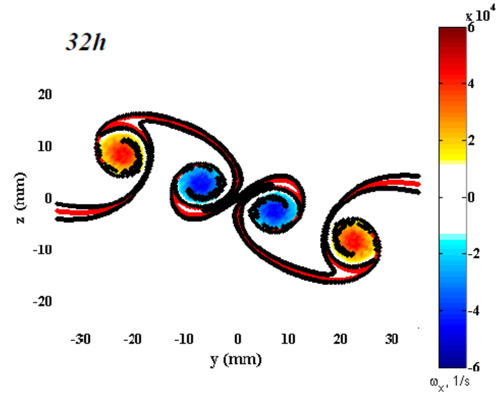




- Comments:

1) At 32h, the plume shape and orientation observed experimentally is quite similar to the plume predicted by VorTx, with two identifiable lobes in the center of the plume

2) The effects of diffusion and entrainment are clearly evident in both the average and instantaneous plume as the center and outer lobes of the plume have grown in area since 10h; however, without modeling either of these phenomena, the reduced order VorTx is still able to predict the plume's shape and evolution



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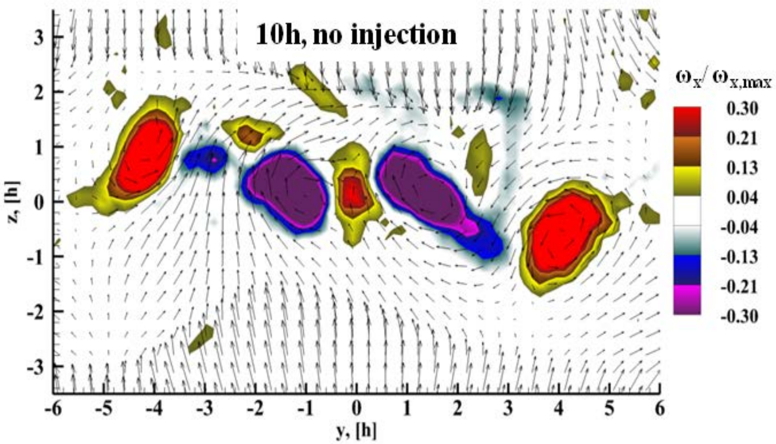
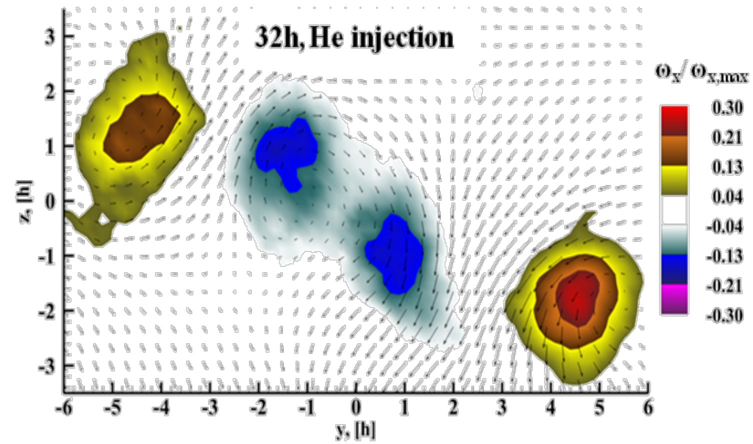
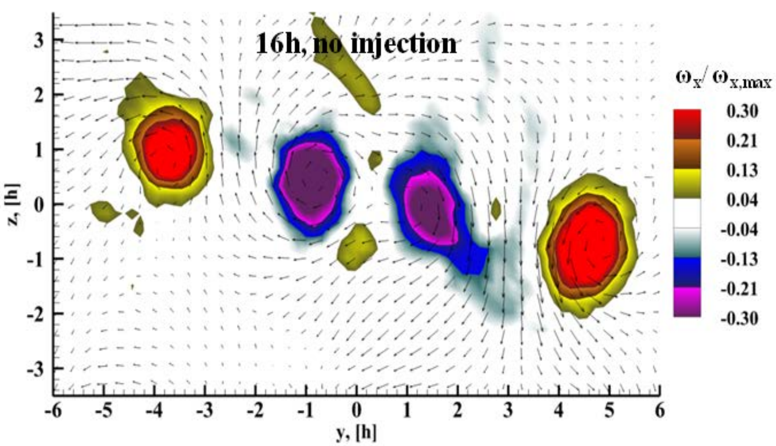
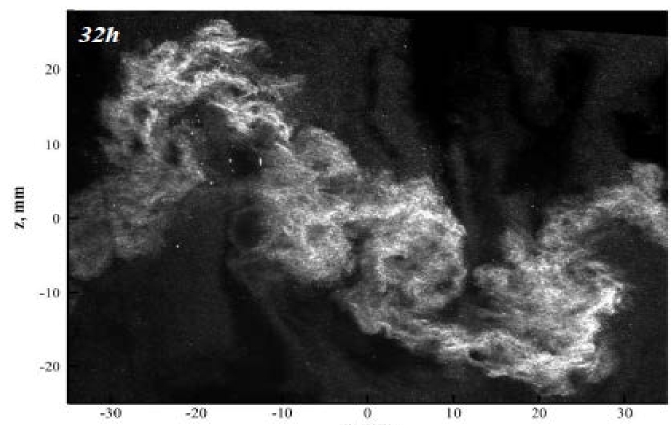
3.2. Experimental S-PIV Results (3/3)

- The resulting normalized plots of streamwise vorticity show that the non-merging scenario that was targeted was indeed achieved; however, in the 10h station an additional fifth structure, a central patch of vorticity is observed between the two inner co-rotating vortices









Central vorticity patch witnessed for different injection and tunnel conditions for this ramp configuration

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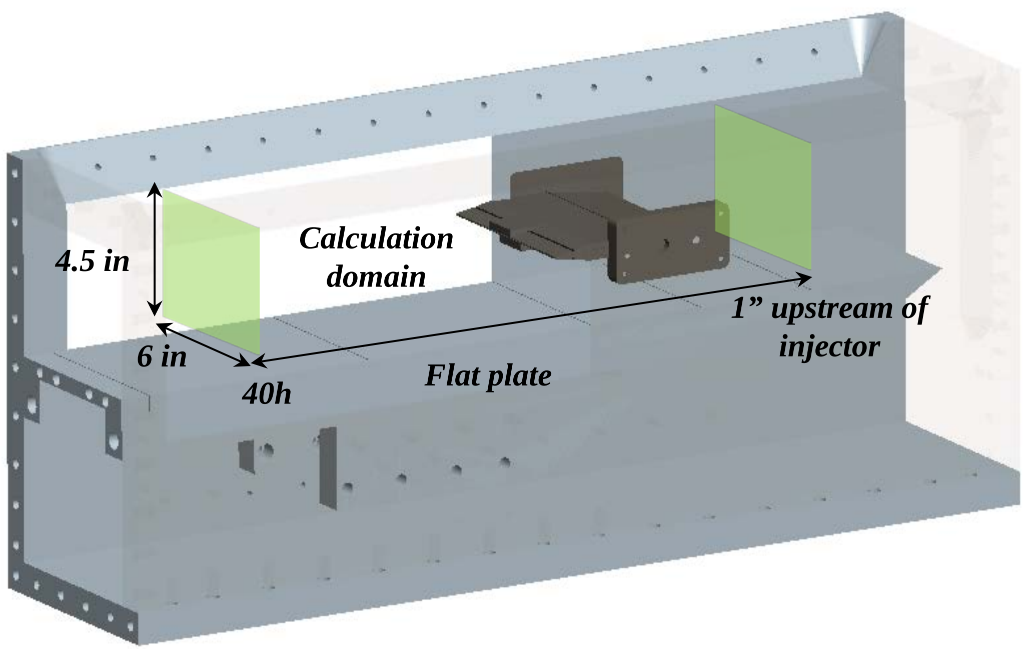
Summary

4.1. Computational Model (1/2)

- In order to complement the experimental analysis, a numerical analysis utilizing a steady RANS CFD calculation using the ANSYS Fluent CFD Package was approached.
  - *Because the near injector flowfield cannot be reliably surveyed experimentally with S-PIV measurements, a direct, one-to-one experiment to CFD comparison is not the objective of the CFD simulations*
  - *The primary goal of the CFD analysis was to give both a qualitative and quantitative picture of the near-injector flowfield, x<8h, in order to investigate the formation, evolution, and role of the central vorticity patch with the hope that an understanding of the fundamental underlying physics of its generation is obtained*
  - *Simulations were performed on the University of Texas at Arlington's High Performance Computing (HPC) facility*



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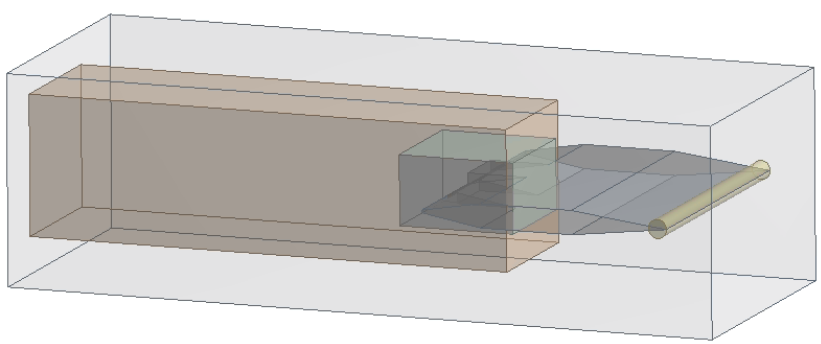
4.1. Computational Model (2/2)

The solver parameters used for the simulation are as follows

- **Formulation:** Implicit, density based, turbulent
- **Flux Type:** AUSM
- **Spatial Discretization**
  - **Gradient:** Least Squares Cell Based
  - **Flow:** Blended 1st/2nd order ($\beta = 0.6$)
- **Turbulence Model:** SST k-ω
- **Boundary Conditions:**
  - Pressure inlet/outlet
  - No-slip adiabatic wall for injector body, slip wall for tunnel walls

BOI construction

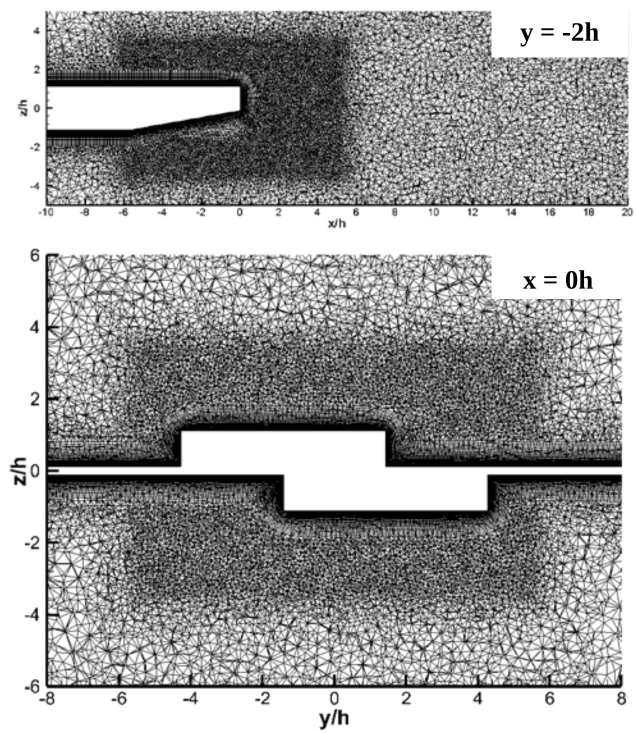


Mesh statistics:

- Primarily 4-node unstructured tetrahedral cells with wedges and pyramids in inflation layer (9.7 M cells <0.2% cells o.q. <0.5)

- 3 bodies of influence for mesh refinement

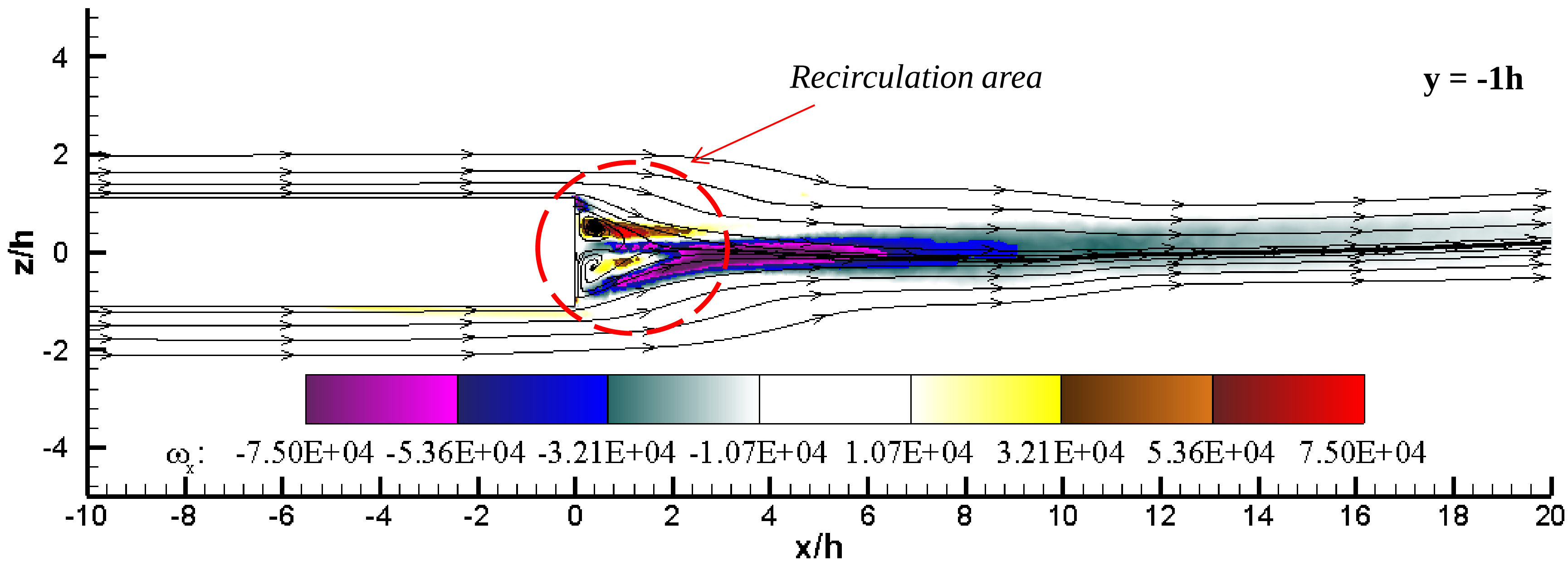
Mesh slices



Summary

4.2. CFD Results (1/6)

- The first comment to be made from the CFD results is on the complex 3D nature of the flowfield
  - *A recirculation area develops immediately behind the backwards face of the expansion ramps*
  - *In the area where the ramps overlap the recirculation area extends to approximately 2h downstream, where the ramps do not overlap the recirculation area extends to the 1h downstream station*
  - *The flow physics are complex in the recirculation region with a production of vorticity contributing to the growth and strengthening of the central vorticity patch (seen in next slide)*



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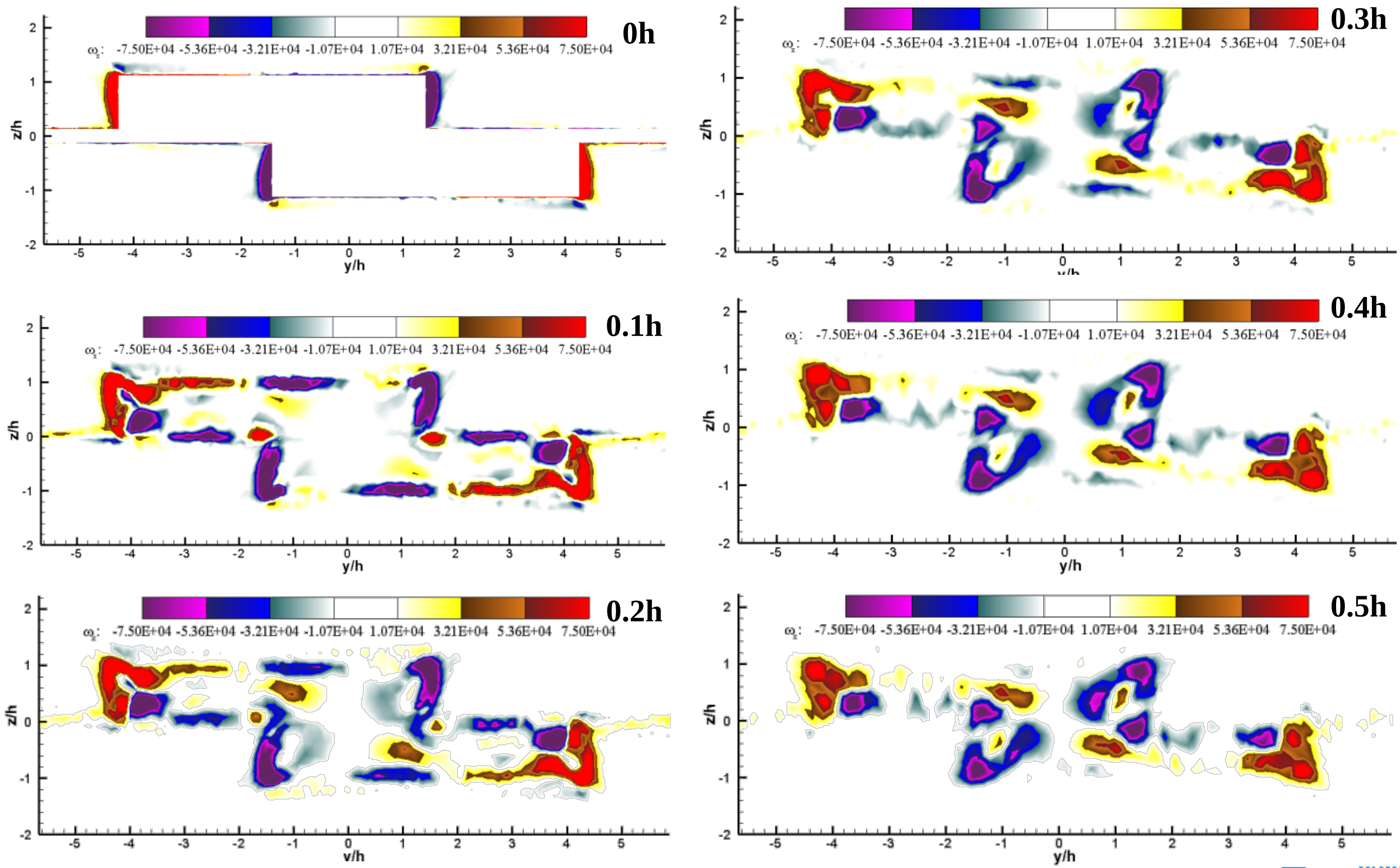
4.2. CFD Results (2/6)

- 0h—0.5h



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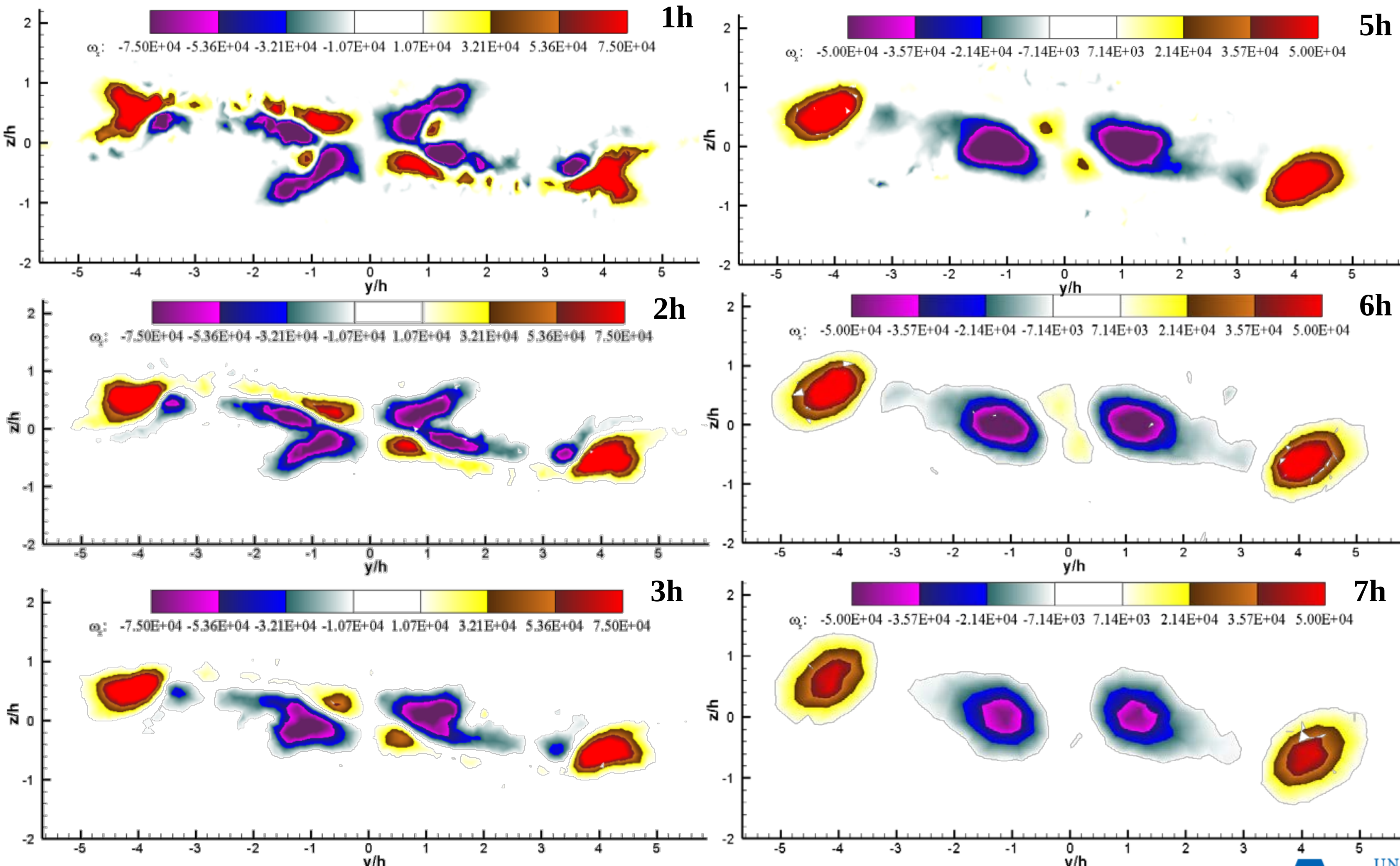
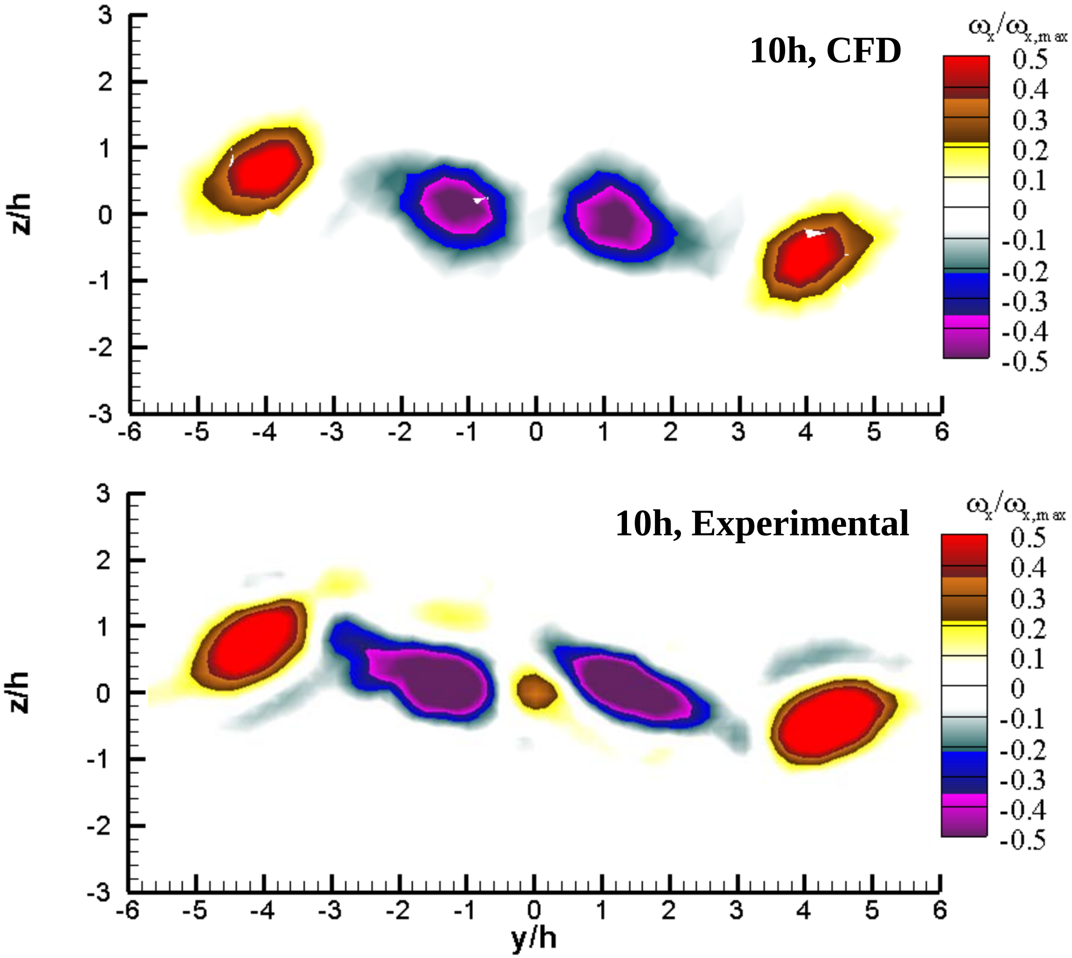
4.2. CFD Results (3/6)

- 1h—7h



- In order to gain a sense of the accuracy of the CFD results compared to the experimental flowfield the 10h downstream stations are compared



- Comments:

1) The central vorticity patch is not evident in the numerical results at the 10h station

2) The experimental results show inner vortices that are more stretched and elliptical than the CFD

3) The CFD is more diffusive (i.e., numerical dissipation) than the experimental results with calculated vorticity under-predicted by approximately 30%

4) The CFD results will, therefore, primarily be used as a qualitative descriptor of the near injector flowfield where the central vorticity patch formation is still evident

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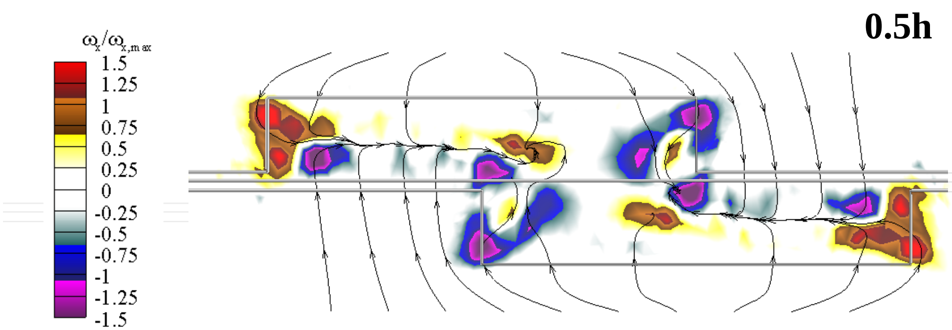
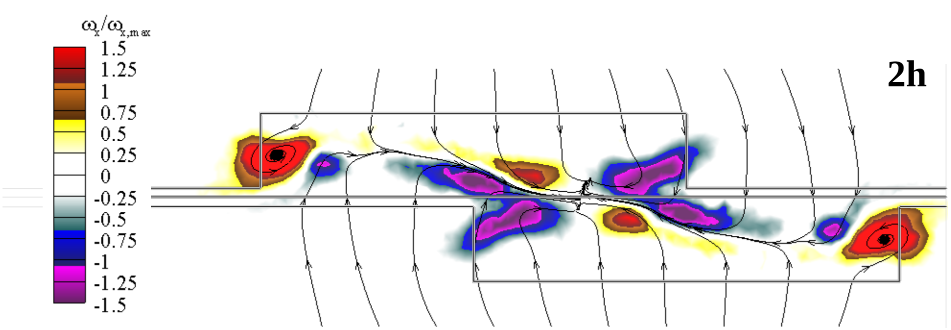
4.2. CFD Results (5/6)

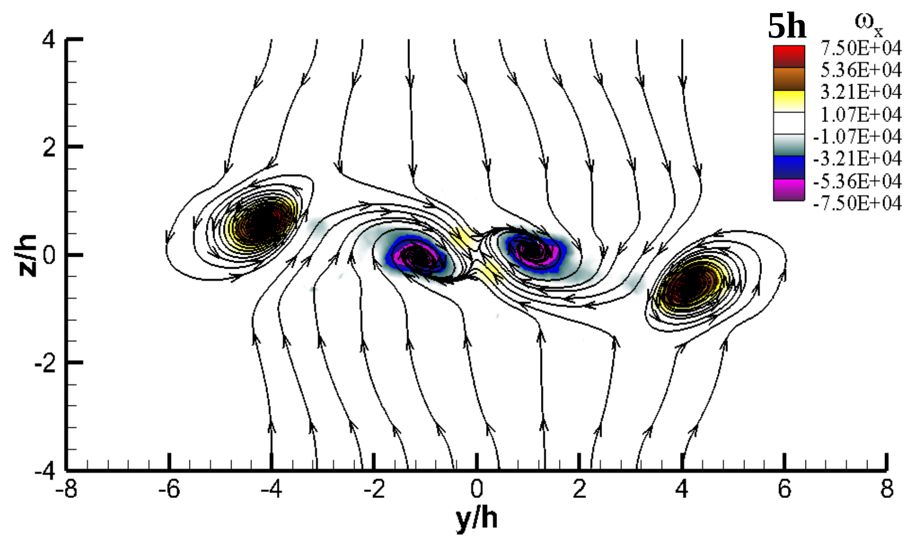
- Comments:

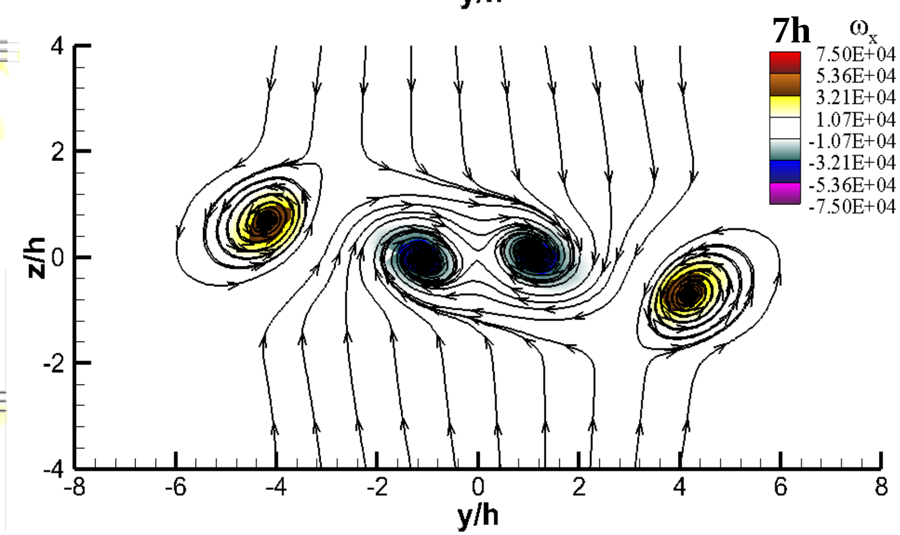
1) The CFD shows the formation of a dividing separatrix streamline in the near injector flowfield

2) Comparing the 5h and 7h stations, the effect of the central vorticity patch is evident as streamlines that are drawn centrally at 5h due to the central vorticity structure, are instead wrapped around both vortices when the patch is not present at 7h



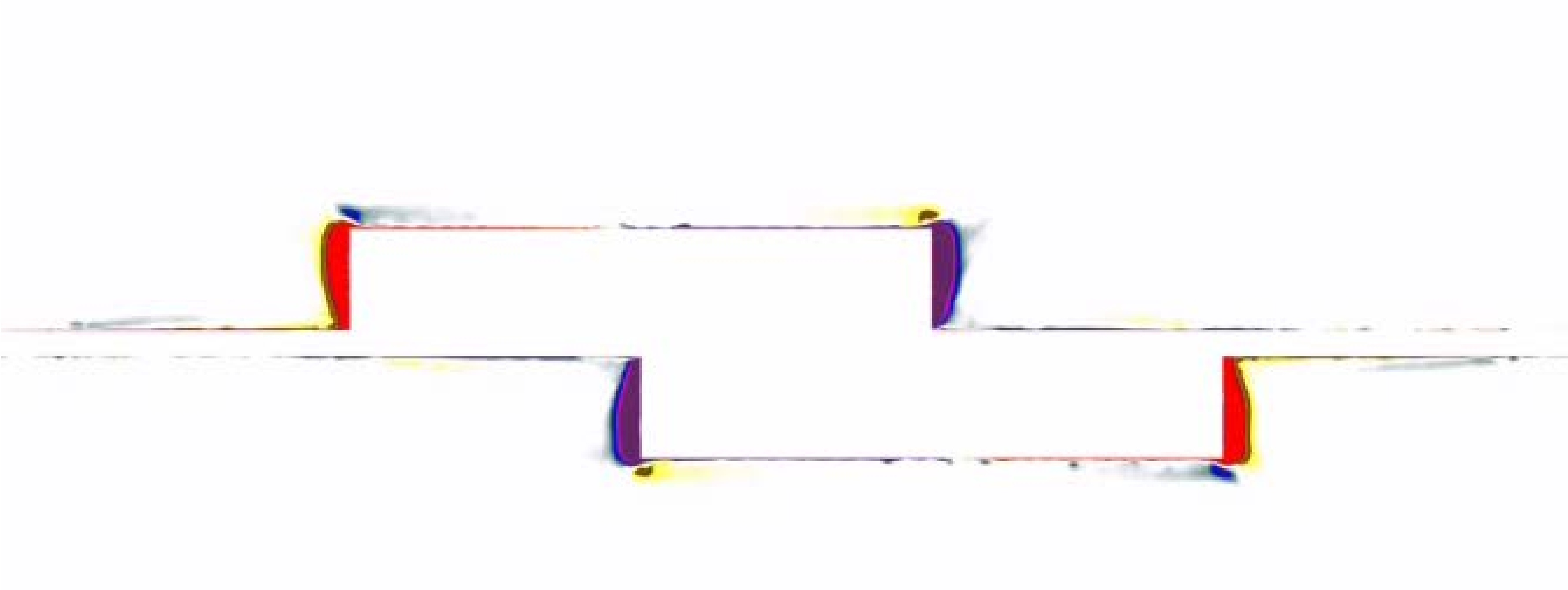






4.2. CFD Results (6/6)

- Animation of vorticity evolution from 0h-8h



Summary

5. Conclusions and Future Work (1/1)

- The analysis combining reduced order model predictions, experimental stereoscopic PIV measurements, and a turbulent RANS CFD calculation has been presented
  - *The reduced order model targeted a non-merging vortex dynamics scenario which was achieved.*
  - *The experiment shows a central vorticity patch, however a comparison with VorTx shows that the global dynamics are not effected, as the VorTx predictions downstream agree very well with the experimental results.*
  - *Though the dynamics are not appreciably altered, the mixing effectiveness could be influenced by the central vorticity patch, this must still be investigated*
  - *The CFD results highlight the formation of the central vorticity patch occurring in the recirculation region, showing a generation of vorticity between 0.1h-1h which come together to form the central vorticity patch and also*

- Future work will include an extension of both the numerical and computational work presented herein.
  - *The future experimental effort will include non-intrusive mixing measurements via Filtered Rayleigh Scattering (FRS), which have already been performed for other ramp configurations, in order to determine the effect of the central vorticity patch on mixing efficiency. Intrusive total temperature and total pressure probing will also allow for total pressure losses associated with the vortical system to be characterized*
  - *The future computational work will seek to increase the complexity and accuracy of the CFD simulations by progressing, incrementally, towards a hybrid RANS Large Eddy Simulation (LES)*

Acknowledgements

This research is sponsored by the NASA Langley Research Center through the NASA Research Announcement Grant Number NNX12AG46A with Dr. Tomasz G. Drozda as the Technical Monitor.

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Thank you