# Development of a Validated CFD Model for the Mixing Behavior of Parallel Triple-Channel Flows

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*Certain commercial equipment, instruments, or materials are identified in this study in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.*

# Introduction

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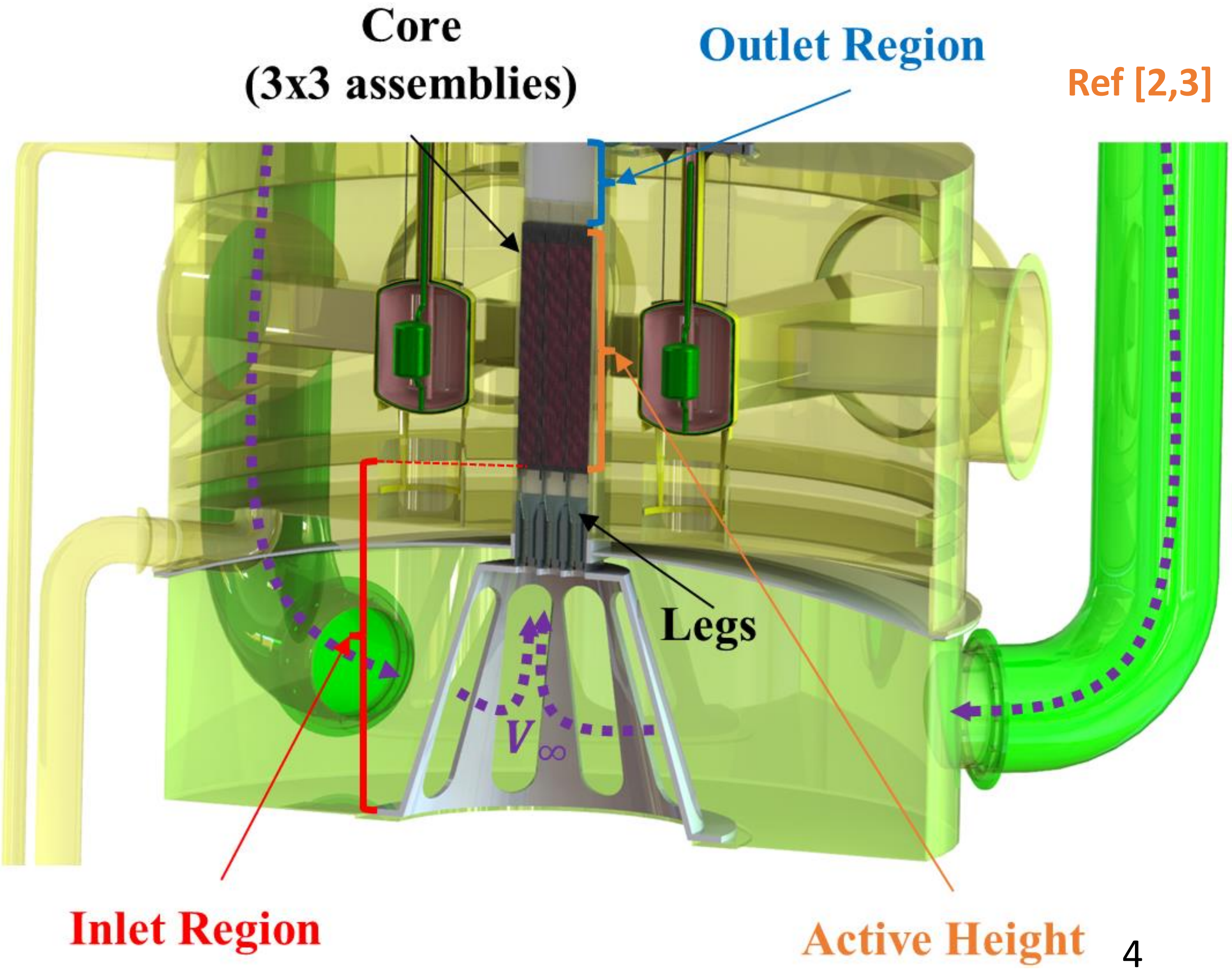
**Amir Dajani**

- Rising Senior at George Mason University
- Bioengineering Major
- Concentration in Imaging
- Minor in Computational Data Sciences

# Nuclear Reactor

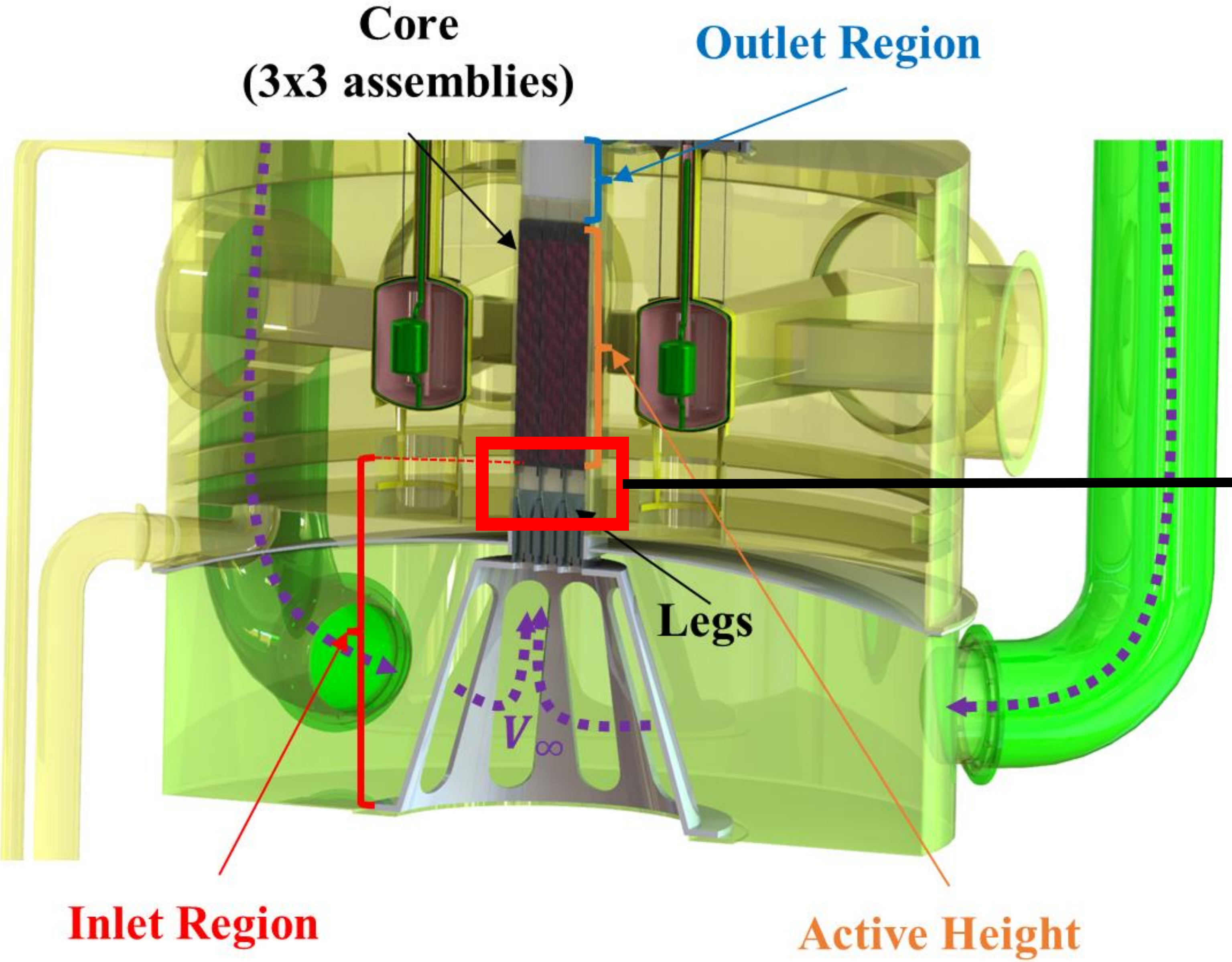
- NIST Neutron Source (NNS)
  - Looking to replace existing reactor (NBSR)
- Three regions of interest to us:
  - **Inlet Region**
    - 3 Legs
    - Separation-**Mix**-Separation
  - Active Height (rectangular channels)
    - Core
    - Fuel Plates
  - Outlet Region
    - Cycles back

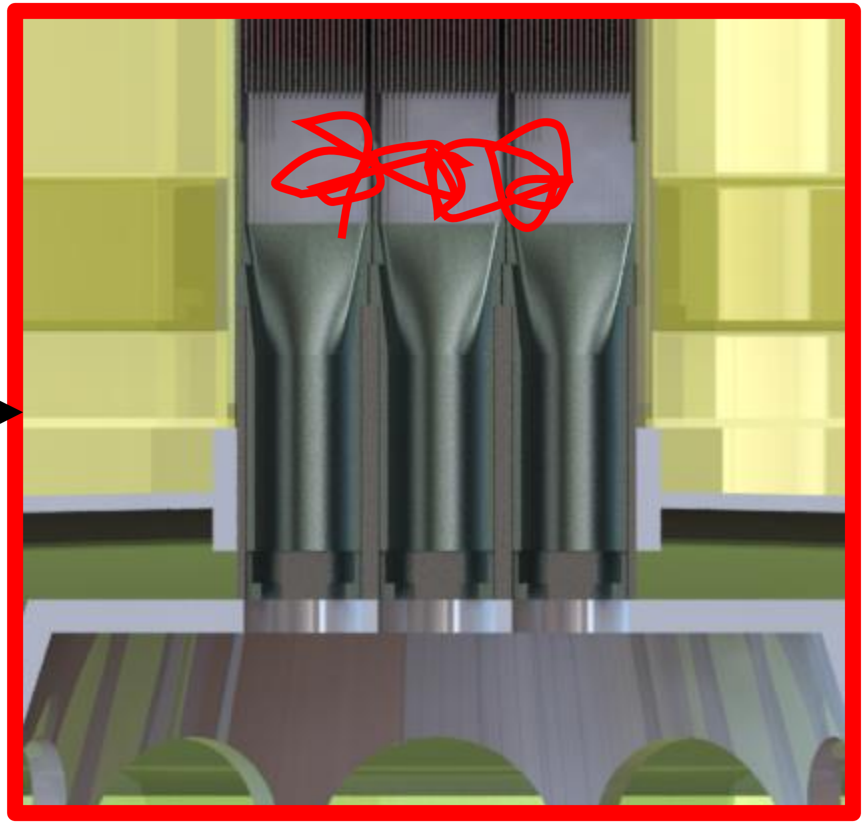
Ref [2,3]



# Problem Area

Ref [2,3]

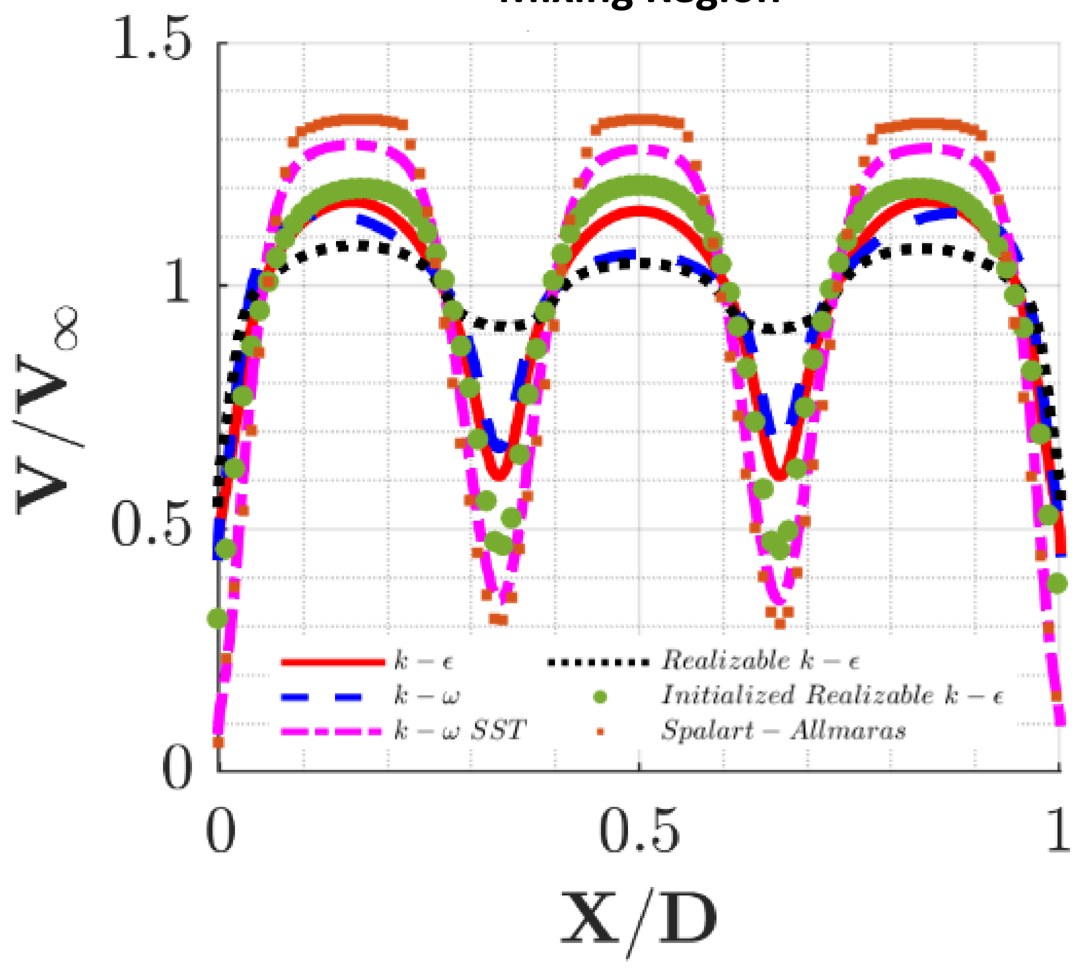


# NNS Inlet Region (from previous study)

- Problem: May have uneven flow distribution into fuel plates
- Insufficient or over-cooling of fuel plates
- Previous work showed **differences of >30% in velocity** prediction based on turbulence model variation only.
- **Needs experimental validation of the mixing phenomenon!**

**My work's motivation!!**



# 3-channel mixing experiment (Literature)

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- Experiment measured velocity distributions in the triple-channel mixing phenomenon.
- Inlet velocity was measured at a shift from the actual inlet (origin).
  - Shift is "~ 1.25 hydraulics diameters" from the inlet
  - This work also investigates 0.7D from the inlet as a shift


ELSEVIER

Experimental Thermal and Fluid Science

Volume 134, 1 June 2022, 110619


## Flow regime and Reynolds number variation effects on the mixing behavior of parallel flows


Abdullah G. Weiss [a], Paul J. Kristo [b], Juan R. Gonzalez [a], Mark L. Kimber [a] [b]


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**Ref [1]**


https://doi.org/10.1016/j.expthermflusci.2022.110619

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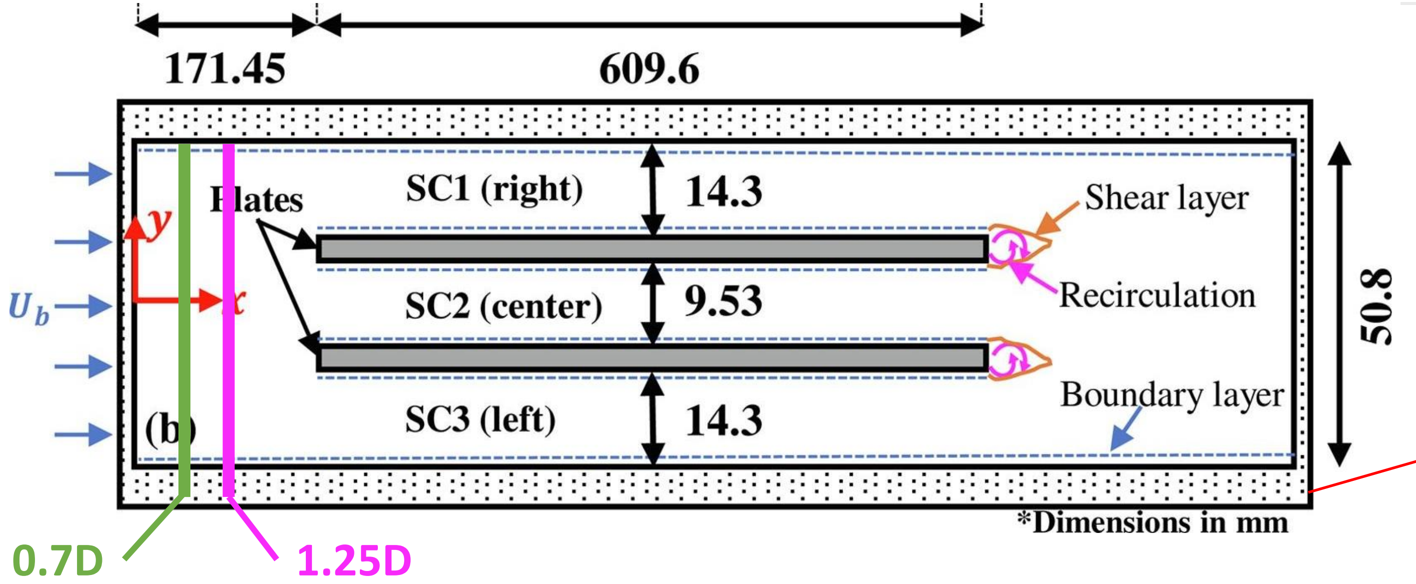
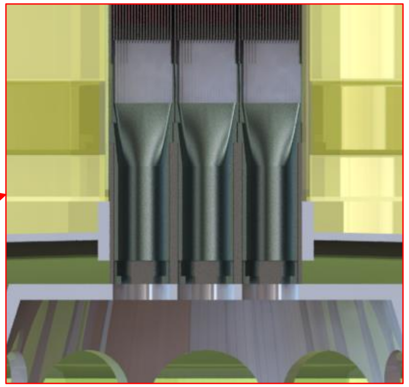



Recall OUR triple-channel mixing (Find the similarities!)



# Project Summary

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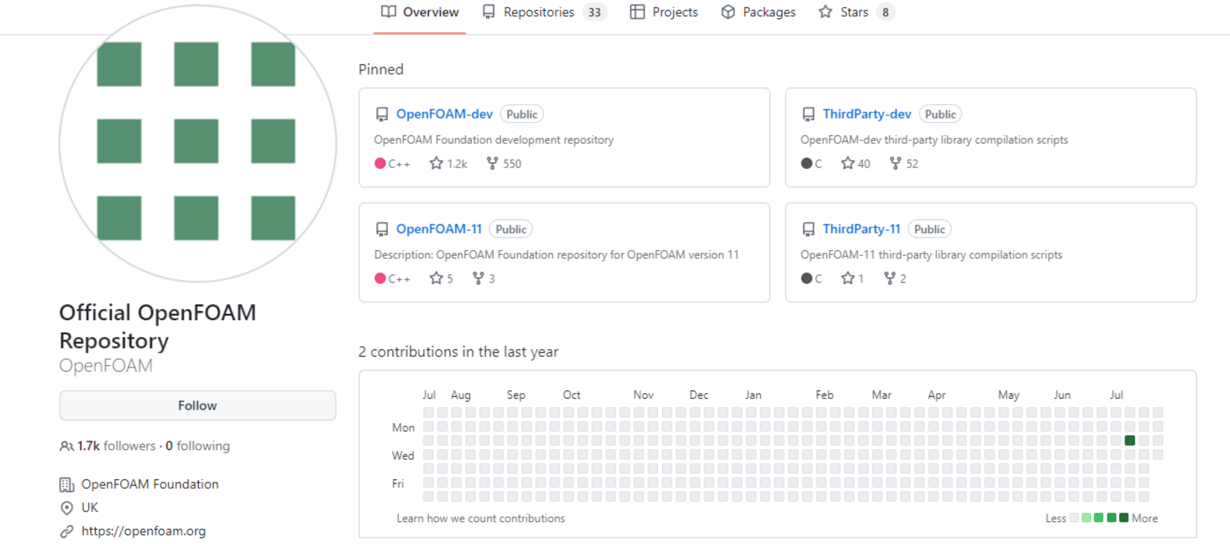
**Goal:**
**Develop Computational Fluid Dynamics (CFD) model of the experiment (literature)**

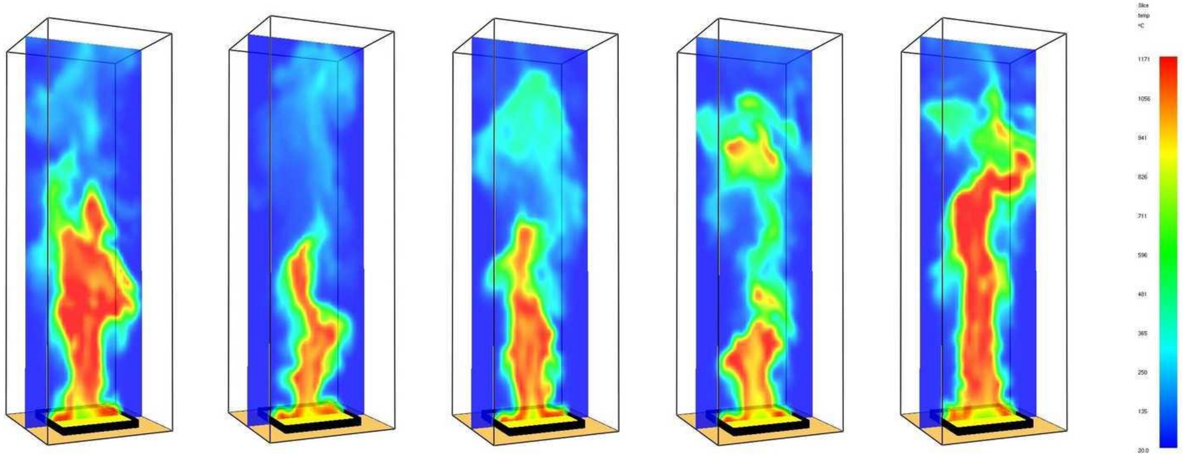
- Using **OpenFOAM** code (v10) for simulations
- Developed mesh in OpenFOAM
    - **BlockMesh utility used**
- Objectives
    - **Compare different turbulence models**
    - Produce contour and line plots of flows behavior
    - Compare CFD results to literature
        - Serves as **validation of CFD model**

OpenFOAM



# Computational Fluid Dynamics (CFD)

- Predict and model physical fluid flow
- Attempts to model the Navier-Stokes equations
  - **Reynolds-Averaged Navier Stokes (RANS) turbulence models are used in this work!**
- Model different types of flow
  - Laminar, Turbulent, incompressible, compressible, etc.
  - Assess presence of turbulence
- Software: OpenFOAM



**Navier-Stokes Equation**

$$\underbrace{\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j}}_{Gas\ Pedal} = - \underbrace{\frac{\partial P}{\partial x_i}}_{Steering\ Wheel} + \underbrace{\nu \frac{\partial^2 U_i}{\partial x_j \partial x_i}}_{Brakes}$$

# Reynolds-Averaged Navier Stokes (RANS)

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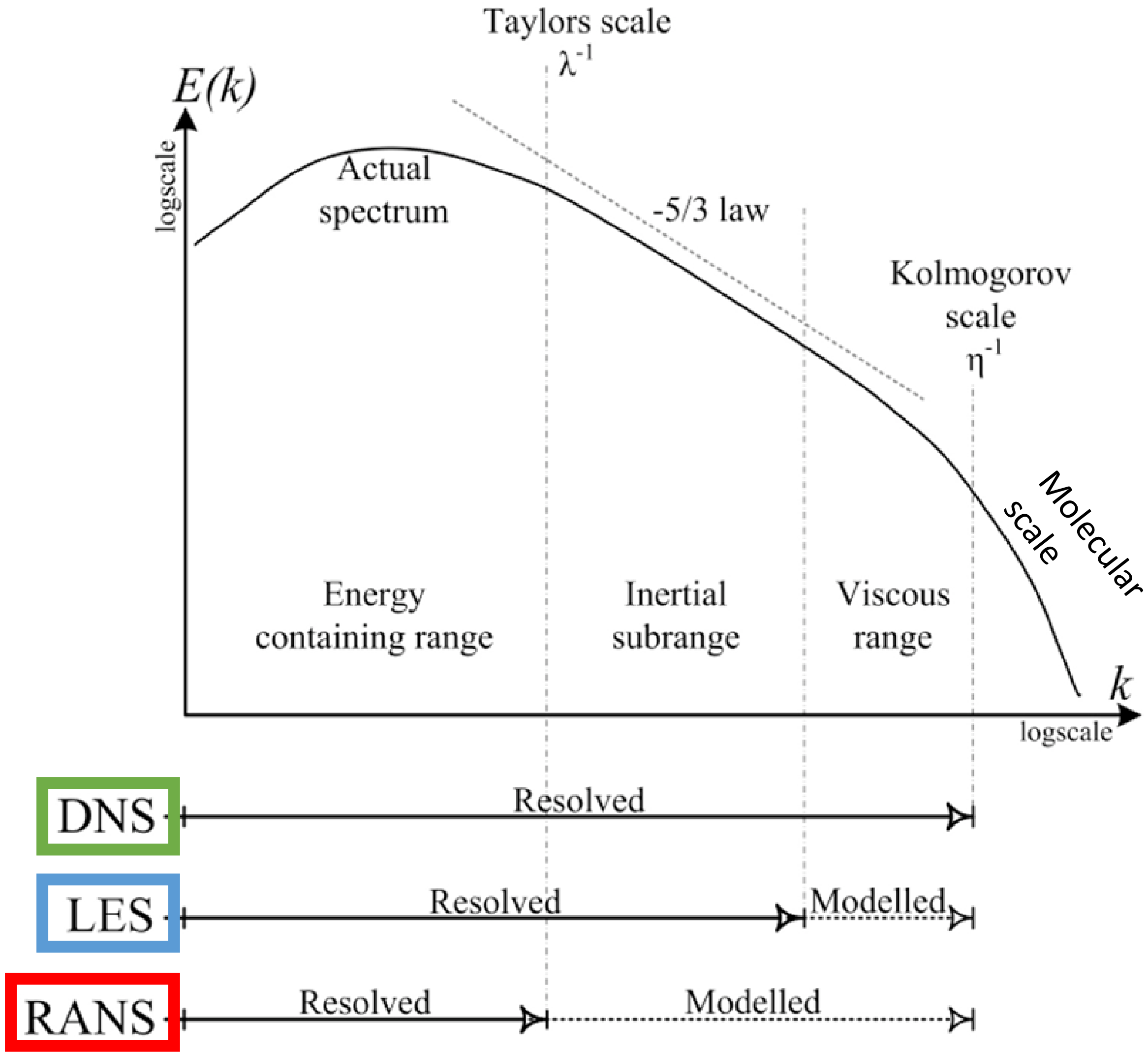
- **RANS** resolves larger Eddies only
    - Not exact solutions
    - Captures up to Energy containing range
    - Good for practical applications
    - Most computationally efficient
- **LES** resolves both larger and smaller Eddy's to a certain extent
    - Captures up to Inertial subrange
- **DNS** captures everything in simulation up to Viscous range
- There are multiple RANS models, and this study will investigate 4 of them.



# Models

- RANS models used in this project
  1. $k$-$\epsilon$ (2-eqn model)
  2. $k$-$\omega$ (2-eqn model)
  3. Spalart-Allmaras (1-eqn model, models $\nu_t$ transport)
  4. $k$-$\omega$ SST (shear stress transport) (2.5-eqn model)

$k$ = *turbulent kinetic energy*
$\epsilon$ = *k dissipation rate*
$\omega$ = *k specific dissipation rate*
$\nu_t$ = *turbulent viscosity*

As an example

$k$-$\epsilon$ Transport eqns.

Turbulent kinetic energy ($k$) transport equation

$$\frac{\partial k}{\partial t} + \langle U_j \rangle \frac{\partial k}{\partial x_j} = -\langle u_i u_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j} - \epsilon + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\boldsymbol{\sigma_k}}\right)\frac{\partial k}{\partial x_j}\right]$$

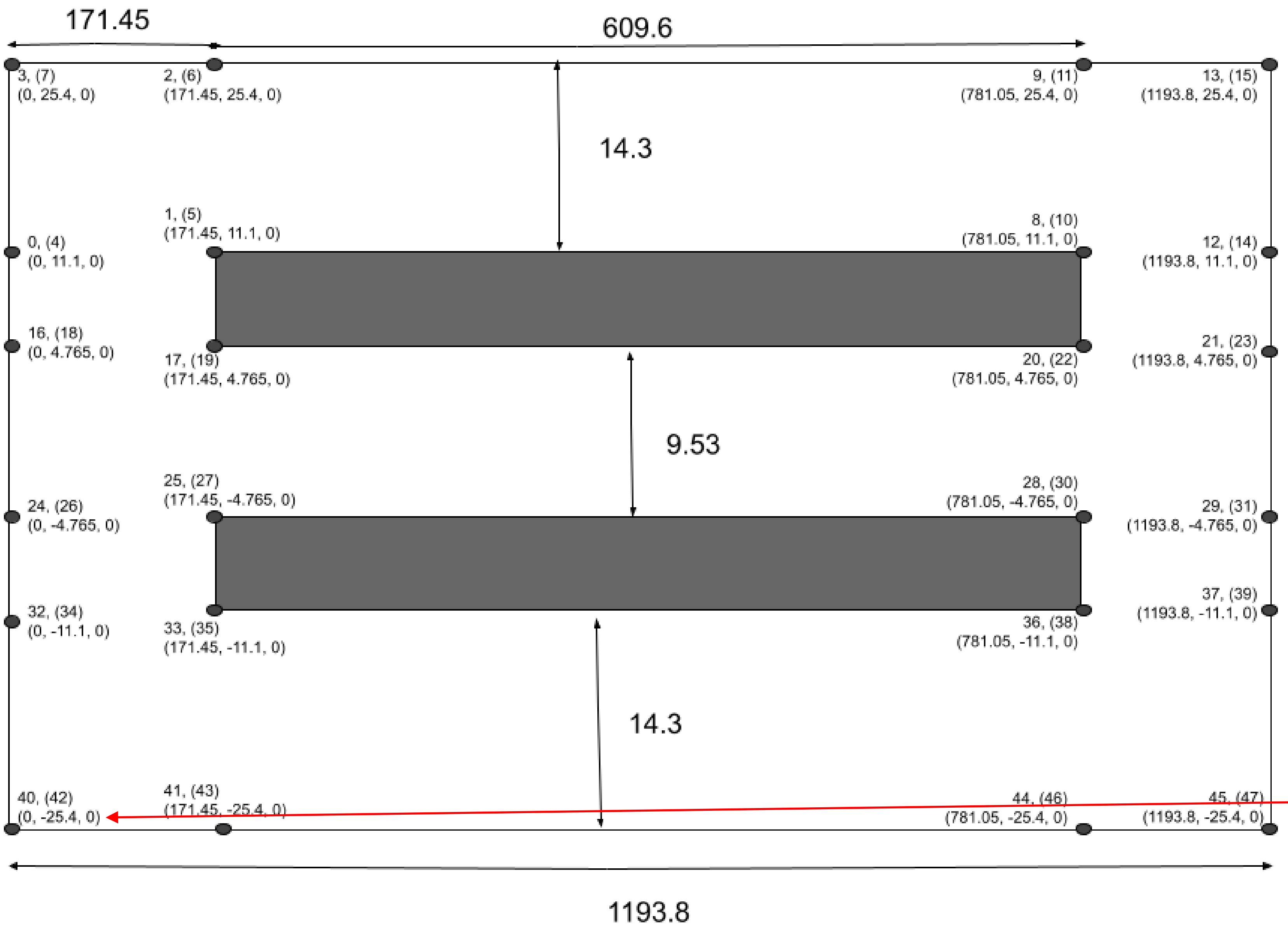
Dissipation rate ($\epsilon$) transport equation

$$\frac{\partial \epsilon}{\partial t} + \langle U_j \rangle \frac{\partial \epsilon}{\partial x_j} = -\boldsymbol{C_{\epsilon 1}} \frac{\epsilon}{k} \langle u_i u_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j} - \boldsymbol{C_{\epsilon 2}} \frac{\epsilon^2}{k} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\boldsymbol{\sigma_\epsilon}}\right)\frac{\partial \epsilon}{\partial x_j}\right]$$

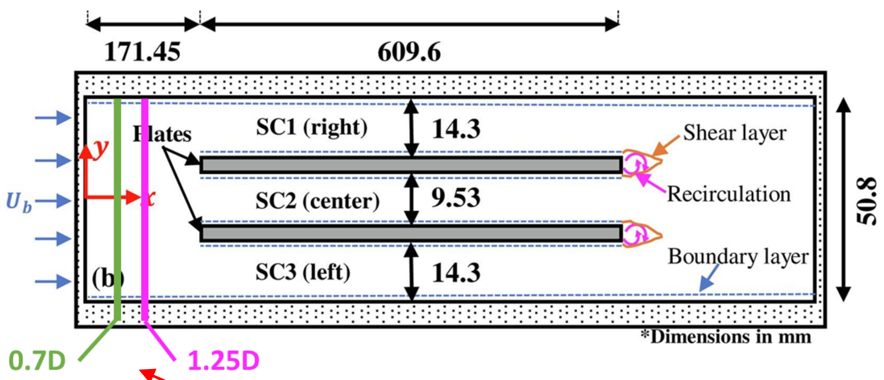
$$\nu_t = \boldsymbol{C_\mu} \frac{k^2}{\epsilon}$$

| $\boldsymbol{C_\mu}$ | $\boldsymbol{C_{\epsilon 1}}$ | $\boldsymbol{C_{\epsilon 2}}$ | $\boldsymbol{\sigma_k}$ | $\boldsymbol{\sigma_\epsilon}$ |
|---|---|---|---|---|
| $\mathbf{0.09}$ | $\mathbf{1.44}$ | $\mathbf{1.92}$ | $\mathbf{1.0}$ | $\mathbf{1.3}$ |

# Geometry




**Hydraulic diameter = D = 72.57 mm**

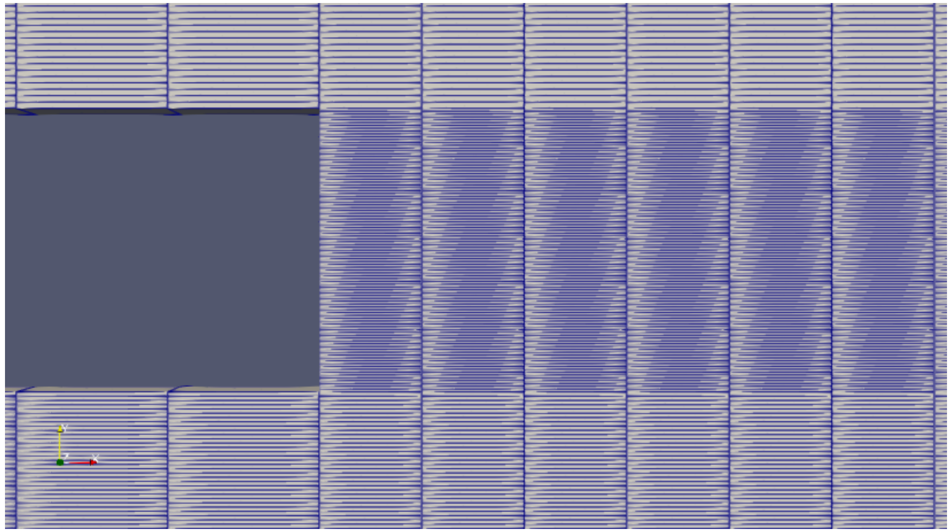


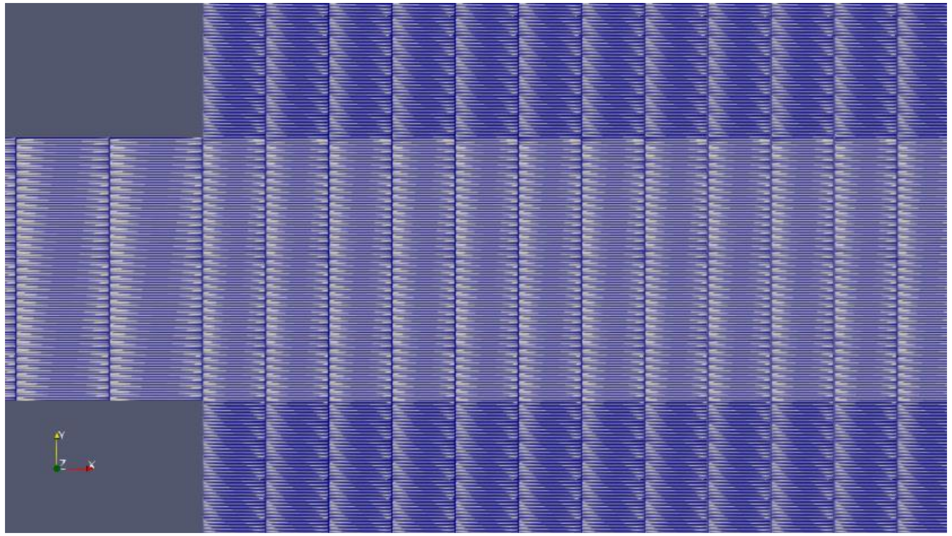

Recall the shifts!!!

Note our coordinates (origin behind the shifts)!

# Geometry and Mesh

- OpenFOAM software
  - Geometry and mesh constructed in OpenFOAM with blockMesh utility
    - Use VSCode IDE for code editing
  - Specify vertices, dimensions, size, locations, etc. of blocks of the mesh
- View the geometry and mesh in ParaView





# Boundary Conditions

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- Given in Literature:
  - **Hydraulic Diameter (D): 0.07257 m**
  - **Inlet Velocity (Ub): ~8.3 m/s**
  - Average Temperature: 24.35 °C
  - Turbulence Intensity (Ti): ~0.05
  - $C_\mu$: 0.09

This is important!!!
(for normalization)

- Derived Values:
  - Viscosity: $\boldsymbol{\nu} = \mathbf{-10.9184} * \boldsymbol{ln}(\mathbf{24.35}) + \mathbf{48.48063} = 1.36 * 10^{-5} \frac{kg}{m*s}$
  - Turbulent Viscosity: $\boldsymbol{\nu_t} = \mathbf{15}\boldsymbol{\nu} = 2.04 * 10^{-4} \frac{kg}{m*s}$
  - Turbulent Kinetic Energy (k): $\boldsymbol{u_{rms}} = \boldsymbol{Ti} * \boldsymbol{Ub} = 0.415, \boldsymbol{k} = \frac{\mathbf{3}}{\mathbf{2}}(\boldsymbol{u_{rms}})^{\mathbf{2}} = 0.2583$
  - Dissipation Rate: $\boldsymbol{\epsilon} = \boldsymbol{C_\mu} * \frac{\boldsymbol{k^2}}{\boldsymbol{\nu_t}} = 29.38$
  - Specific Dissipation Rate: $\boldsymbol{\omega} = \frac{\boldsymbol{\epsilon}}{\boldsymbol{C_\mu} * \boldsymbol{k}} = 1.26 * 10^3$

# Refining Mesh

Inlet Velocity = Ub = 8.3 m/s

| | Velocity Convergence (U/Ub) | | |
|---|---|---|---|
| | **Top channel** | **Middle channel** | **Bottom channel** |
| ***k*-$\epsilon$** | 0.0012 | 0.0034 | 0.0011 |
| ***k*-$\omega$** | 0.0014 | 0.0075 | 0.0022 |
| **Spalart-Allmaras** | 0 | 0.0021 | 0.0001 |
| ***k*-$\omega$ SST** | 0.0008 | 0.0017 | 0.001 |

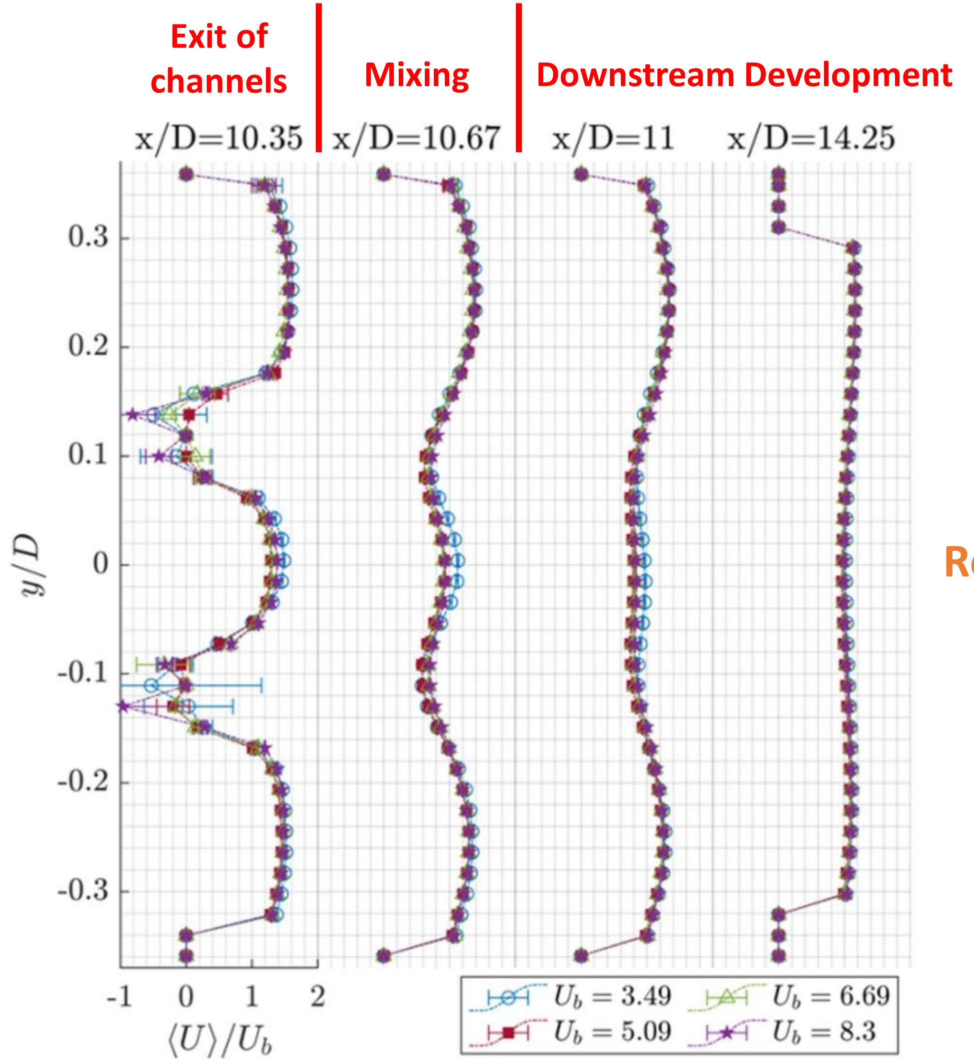
**All meshes were convergent to within less than 1 cm/s**

# Convergent Mesh Metrics

| | | $k$-$\epsilon$ | $k$-$\omega$ | Spalart-Allmaras | $k$-$\omega$ SST |
|---|---|---|---|---|---|
| $y^+$ | **Min** | 0.881 | 0.125 | ~7 | 0.122 |
| | **Max** | 88.5 | 42.728 | ~31 | 31.744 |
| | **Avg** | 10.312 | 6.342 | ~19 | 3.782 |
| **Max Skewness** | 5.810e-13 | | | | |
| **Volume** | **Min** | 6.034e-11 | | | |
| | **Max** | 4.843e-10 | | | |
| | **Avg** | 5.292e-05 | | | |
| **Face Area** | **Min** | 6.034e-08 | | | |
| | **Max** | 3.387e-06 | | | |
| **Max Aspect Ratio** | 36.197 | | | | |

# Spanwise Velocity Distribution

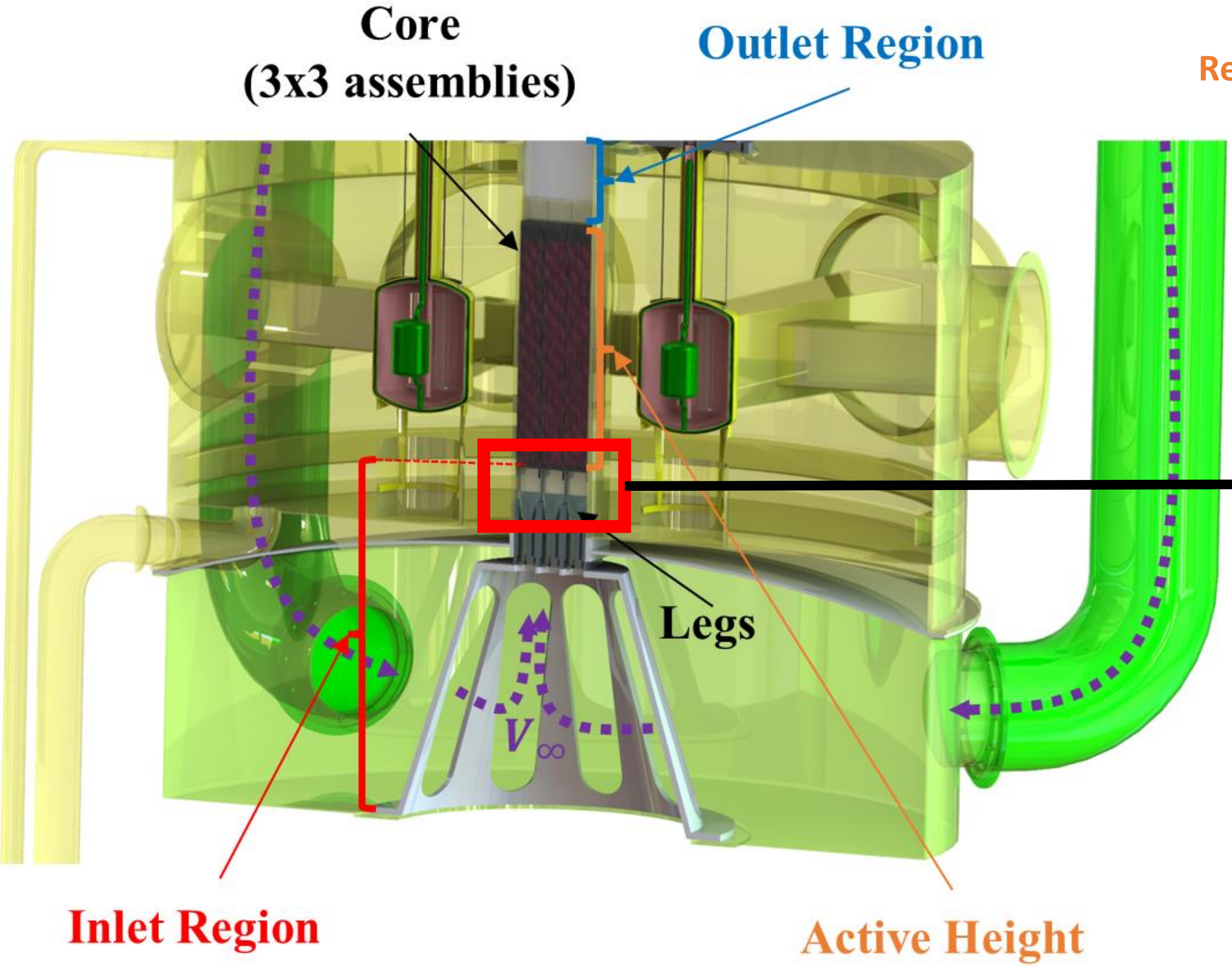
- Create Spanwise Velocity Distribution at each x/D location
  - x/D location: 10.35, 10.67, 11, 14.25
- Plot results
  - U/Ub vs y/D
  - Compare with results of literature
- Do this process for each RANS model
- Plot all on the same plot
- Account for the horizontal shift
  - Inlet profiles captured at 1.25 away from the origin (approximate value) in literature
  - Shift of 1.25 and 0.7 conducted for this project

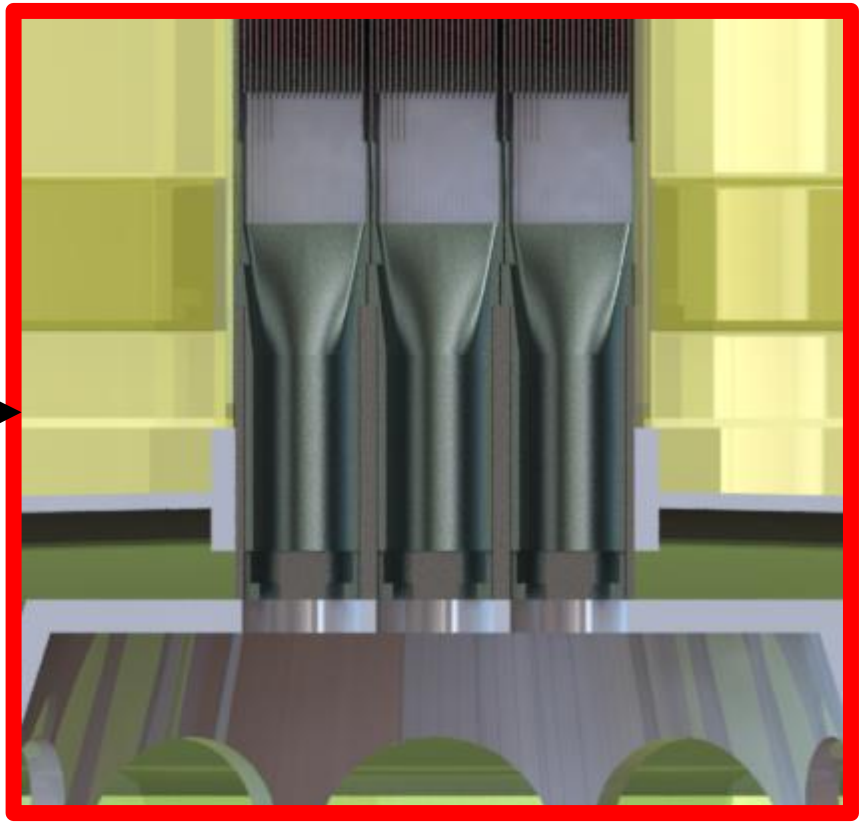



Ref [1]

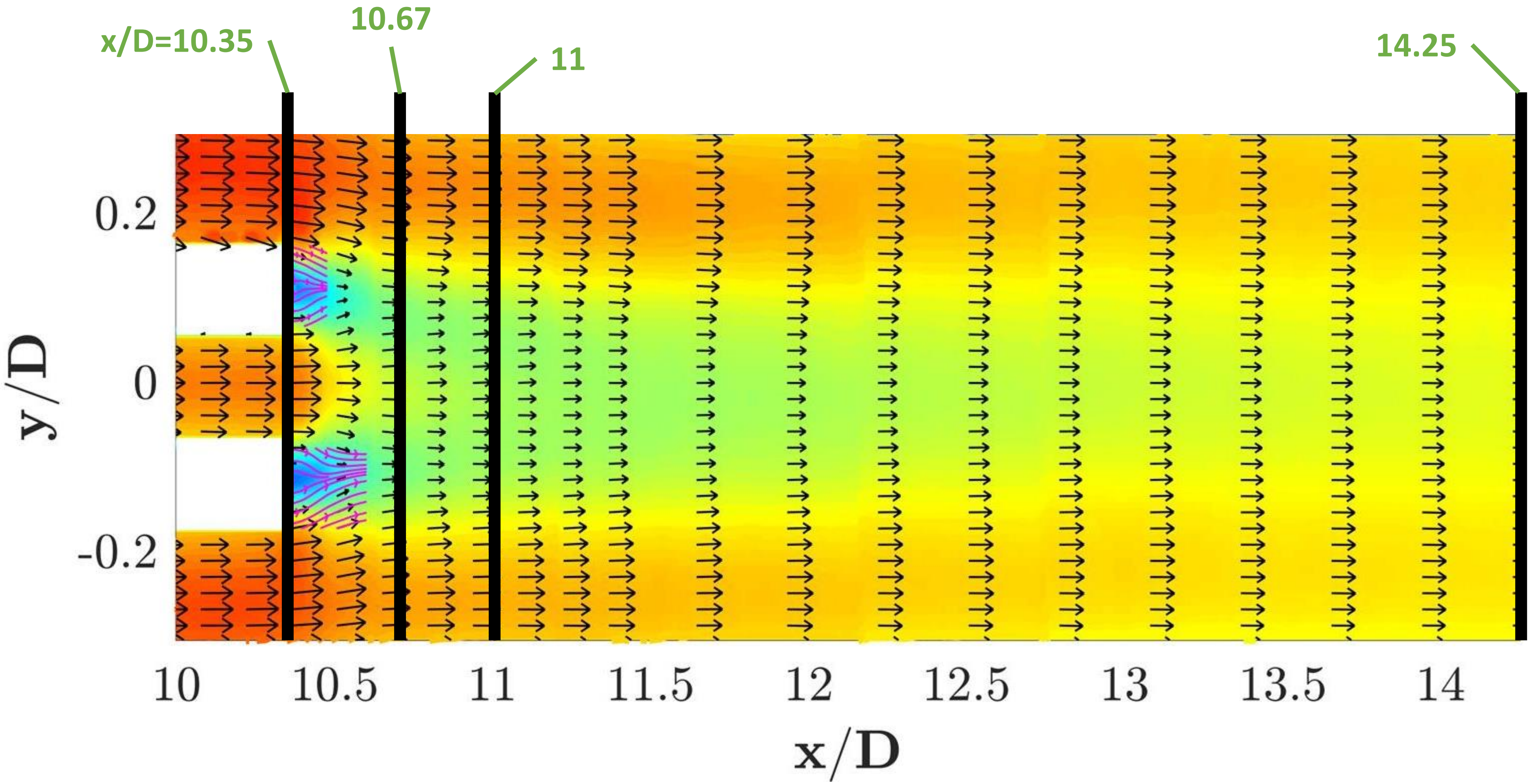
# Reminder

Ref [2,3]



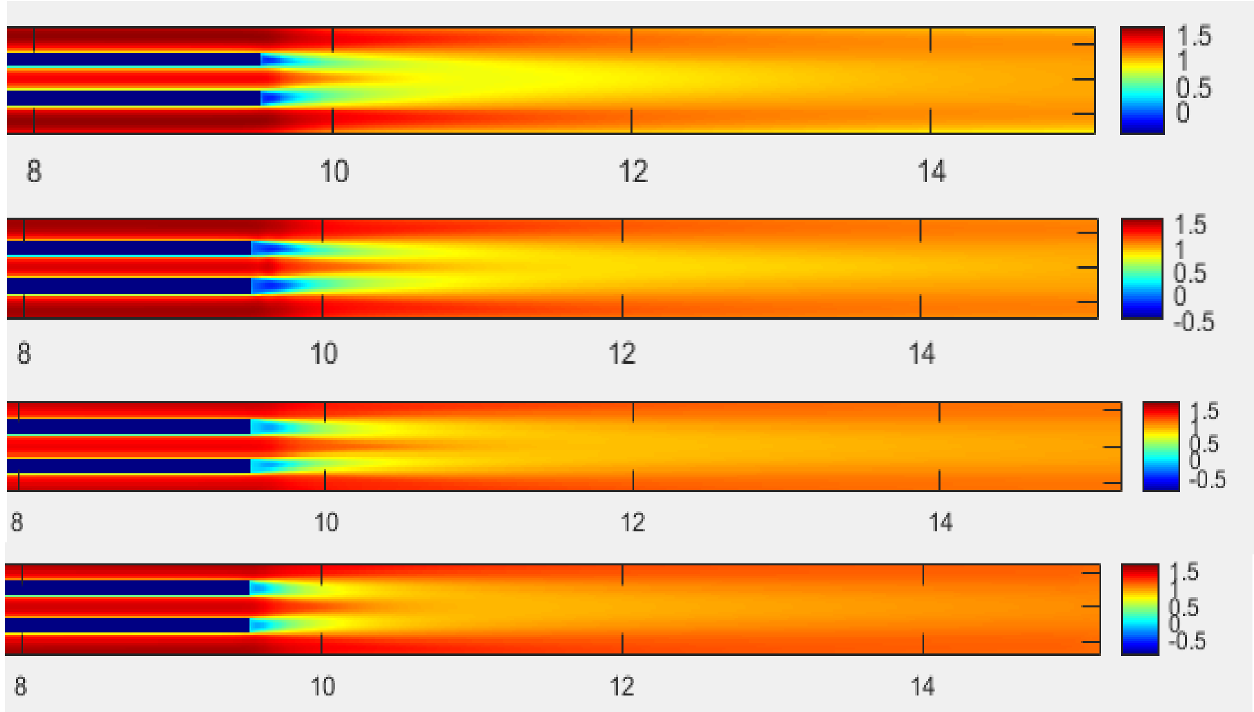



# Contour Plot




Ref [1]

# Contour Plots

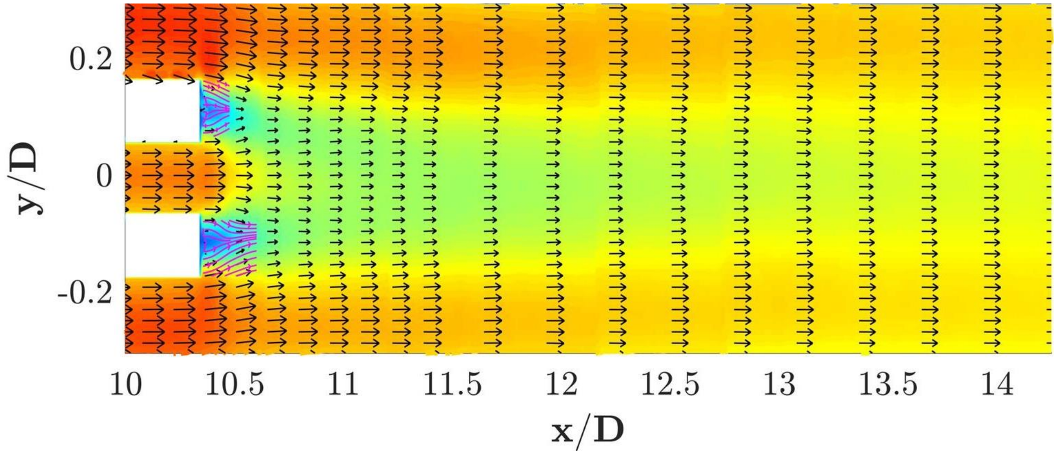



*k-ϵ*

*k-ω*

*k-ω SST*

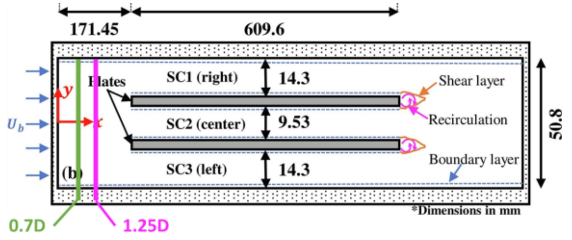
Spalart-Allmaras

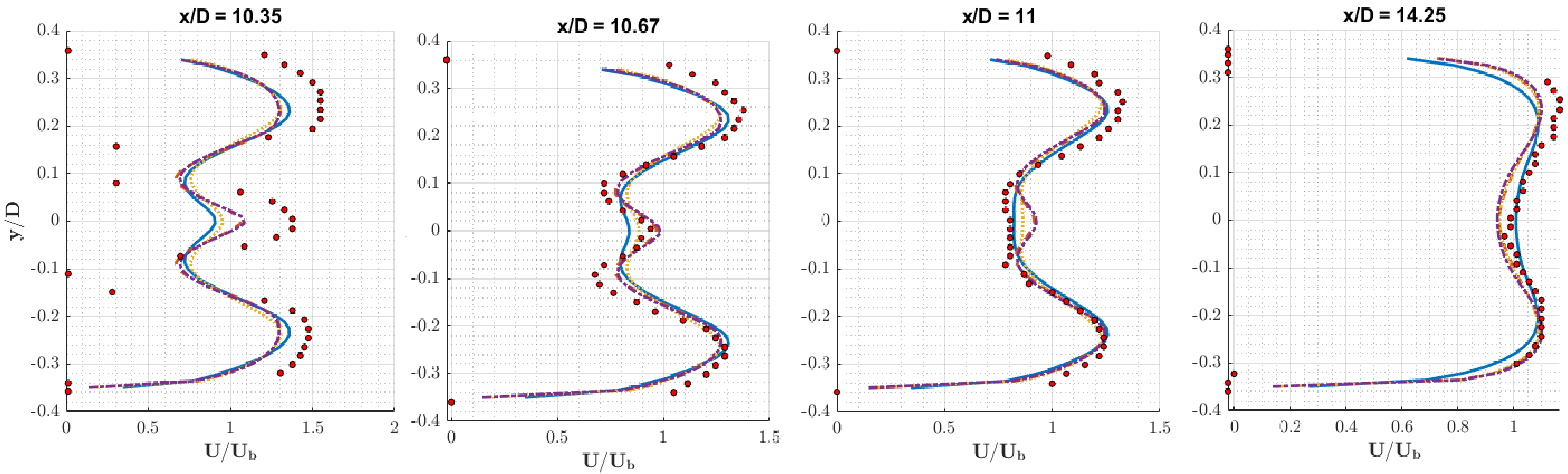


# Spanwise Velocity Distribution with shift of 1.25

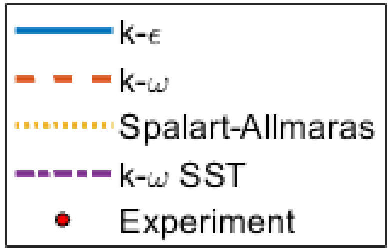
Estimated shift

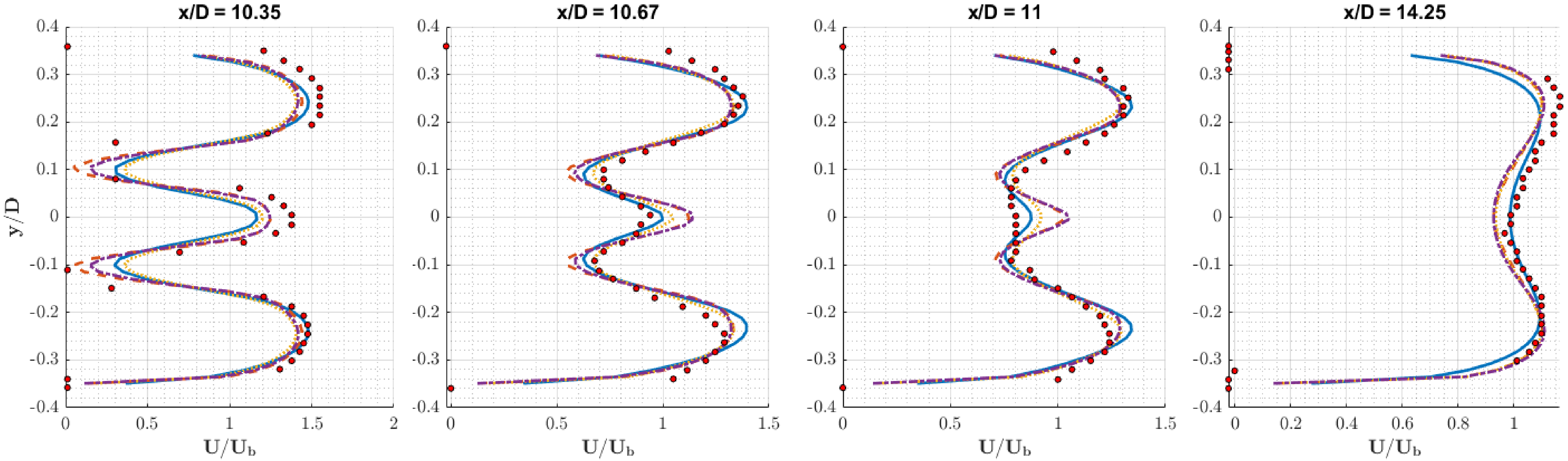
1.25 Hydraulic Diameters from physical inlet of test section



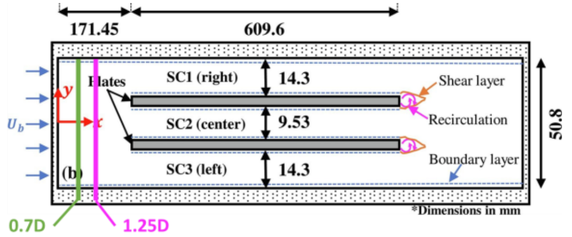
# Spanwise Velocity Distribution with shift of 0.7




Estimated shift

0.7 Hydraulic Diameters from physical inlet of test section



# Conclusion

- RANS seems appropriate for modeling the mixing behavior of Parallel Triple-Channel Flows
    - Future use: Researchers, scientists, engineers
- 0.7 shift from origin displayed closer fit to data
- Best models: k-Epsilon and Spalart-Allmaras

# Acknowledgements

**Mentors:** Abdullah Weiss, Anil Gurgen
**NCNR SURF Directors:** Susana Marujo Teixeira, Julie Borchers, Leland Harriger

# References

**[1] Weiss, Abdullah G., et al. "Flow regime and Reynolds number variation effects on the mixing behavior of parallel flows." Experimental Thermal and Fluid Science 134 (2022): 110619.**

**[2] Weiss, Abdullah G., Joy S. Shen, and Anil Gurgen. "A Turbulence Model Sensitivity Analysis on the Hydraulic Behavior in the Inlet Plenum of the Proposed NIST Neutron Source Design." Proceedings of the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20).**

**[3] Shen, Joy, et al. "A Turbulence Model Sensitivity Analysis of Thermal-Hydraulic Properties on The Pre-Conceptual NIST Neutron Source Design." Proceedings of the International Conference on Nuclear Engineering. 2023.**

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# Questions??

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