Advances in Fiber Alignment for TuFF Preforms:

Investigating Fiber Orientation Dynamics and Process Optimization

Presenter: Navid Niknafs

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Project Overview

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"Advances in Fiber Alignment for TuFF Preforms"

(January 2022 - Present)

Objectives

- Investigate dynamics of fiber alignment within a water film.
  - Propose a physics-based model fiber reorientation.
  - Optimize the throughput of TuFF.
- Improve quality of TuFF preforms for thin ply (8 gsm blocks)
  - Reduce window gap size distribution
  - Retain areal weight uniformity
- Approach
  - Benchmark current alignment process
  - Propose a physics-based model for fibers reorientation
  - Identify origin of window gap formation
  - Design, fabricate new scalable spillway
  - Conduct experiments and characterize microstructure

Navid Niknafs
Postdoctoral Researcher

Suresh Advani
Professor

John W. Gillespie, Jr.
Professor

Dirk Heider
Associate Professor

Shridhar Yarlagadda
Associate Professor

Pavel Simacek
Research Associate

Joseph Deitzel
Sr. Scientist

John Tierney
Sr. Scientist

Uday Balaga
Ph.D. Student

Alex Vanarelli
Composites Design Manager

John Morris
Research Technician II

Christopher Blackwell
Mechanical Engineer
(**C.A. LLC**)

Project Overview - TuFF Thin Ply (8gsm building block using baseline alignment process)

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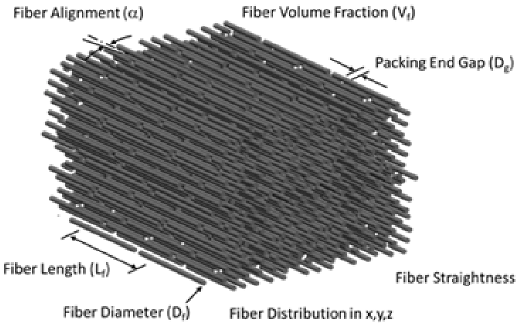
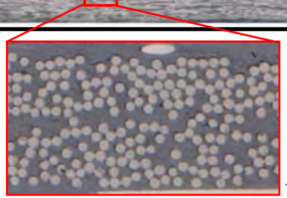
- Highly aligned short fiber (IM7 3mm) in form of sheets:
  - IM7 3mm LM-PAEK
  - Fiber aspect ratio: 600:1
  - 95% fibers aligned ± 5°
  - 300psi consolidation pressure,
    380C process temperature 50% nominal FVF.
  - Cross-ply laminates (areal weight of 90° layer included 60 gsm , 120 gsm and 240 gsm)

Fiber Volume Fraction			
	60 gsm	120 gsm	240 gsm
Mean (%)	35.9	42.1	47.4
SD	5.5	2.8	1.2
CV (%)	15.5	6.6	2.6

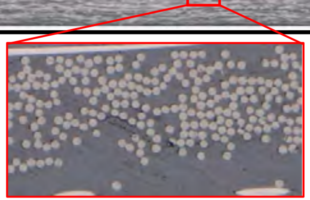


- Variability increases in thin ply 90-degree layers as areal weight decreases
  - Resin content
  - Fiber dispersion
  - Local FVF
  - Ply thickness

➢ 60 gsm



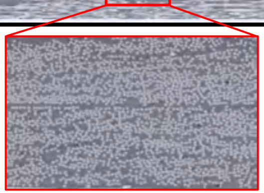
$FVF \approx 35\%$



$FVF \approx 28\%$

➢ 120 gsm

$FVF \approx 49\%$



$FVF \approx 47\%$

Project Overview – Variation in TuFF Thin Ply

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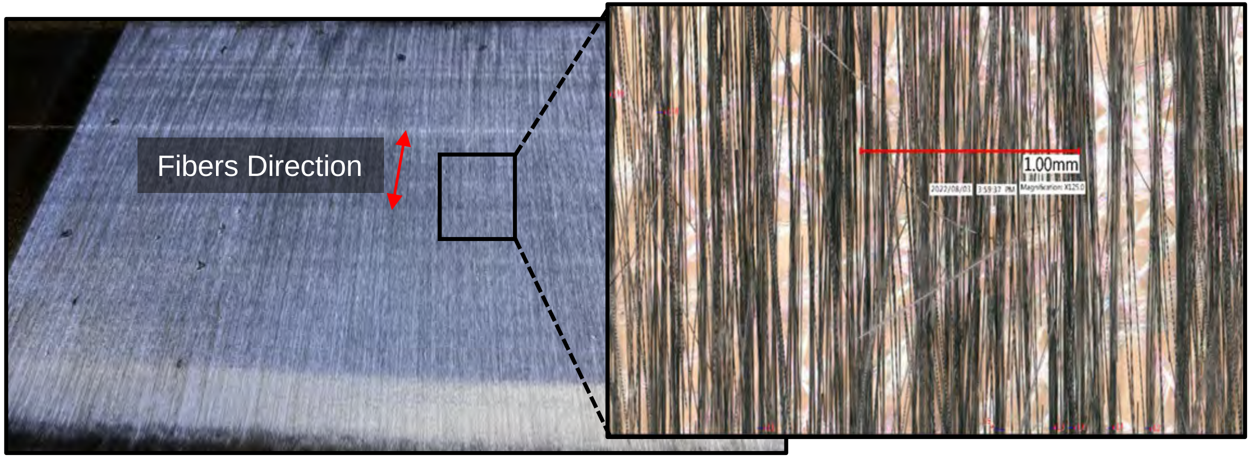
- Hypothesis: <u>Reducing window gap size</u> in preform will lead to
  1) increase in Fiber Alignment
  2) reduction in the variability.

- To achieve higher FVF (57%):
  - ✓ 8 gsm preforms are stacked
  - ✓ Nesting occurs to fill window gaps
  - ✓ 120 gsm stack is current limit



- Approach
  I. Characterize the <u>fiber alignment process</u>.
  II. Develop a <u>physics-based model</u> for fiber orientation dynamics on the spillway.
  III. Identify <u>source of window gaps</u> during fiber alignment.
  IV. Develop technique to <u>measure distribution of window</u> gap in preform.
  V. <u>Develop new spillway</u> for window gap reduction.
  VI. Conduct key experiments to <u>demonstrate feasibility.</u>

Process Characterization

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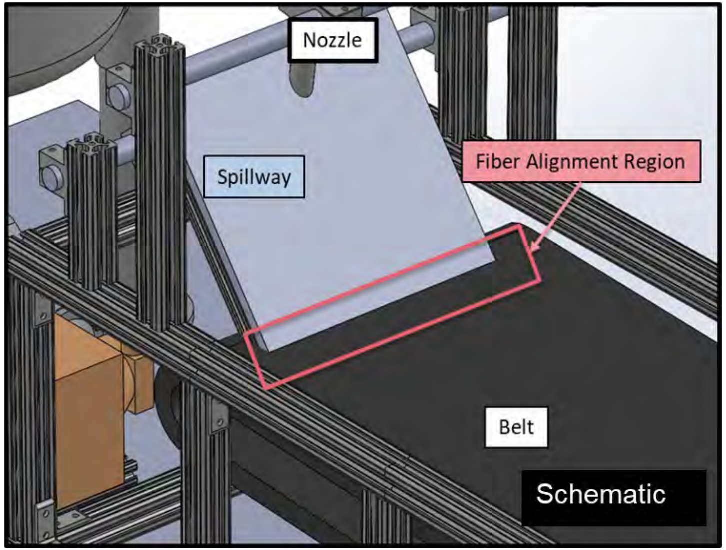
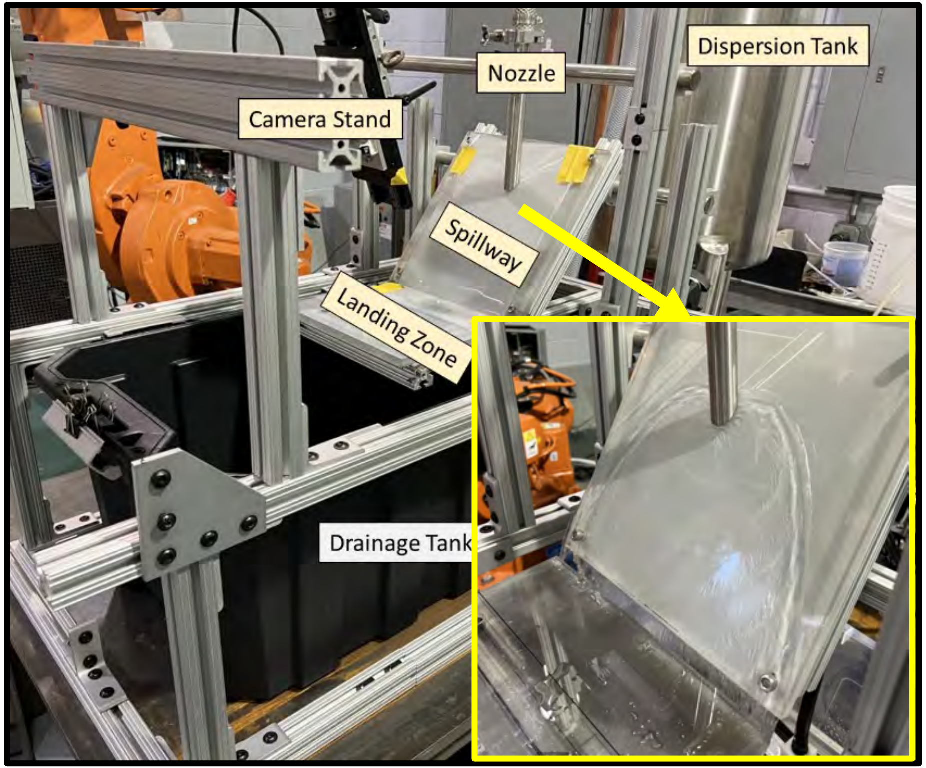
- Experimental Setup for Process Characterization

  I. Water Film Thickness (confocal Displacement sensor)
  II. Fiber Alignment Dynamics (Highspeed Camera)





Process Characterization- Water Film Thickness

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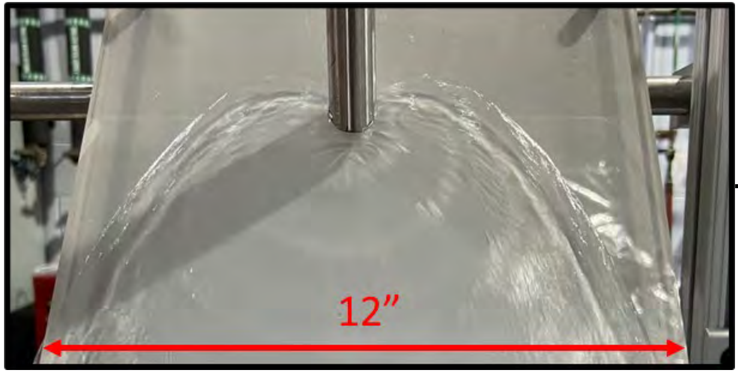
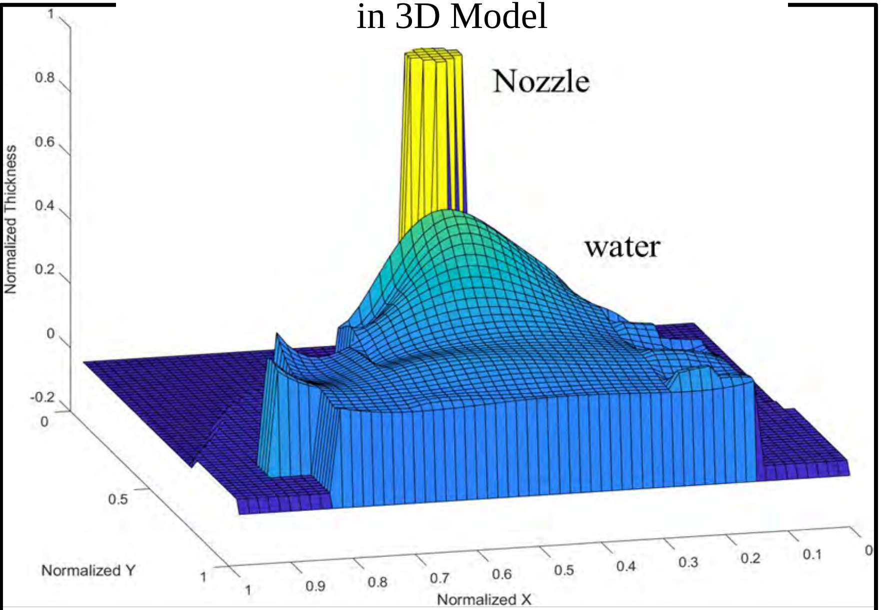
- Water Film Thickness Measurement



Water/Fiber jet on the spillway

Experimental Measurements Constructed in 3D Model

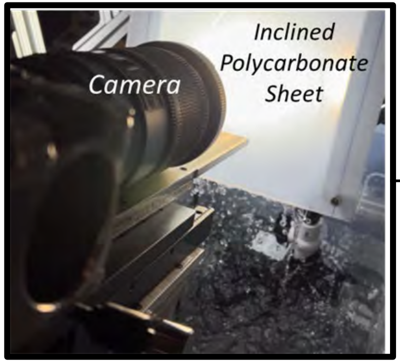


Water Film Thickness (ConfocalDT)

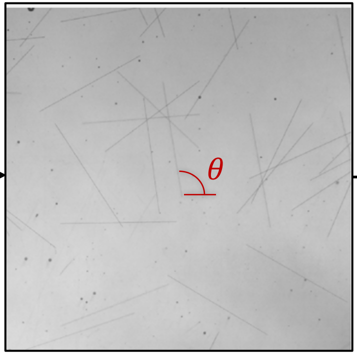
*Normalized Experimental Data

Process Characterization: Experimental Investigation of Fiber Alignment

- Highspeed imaging

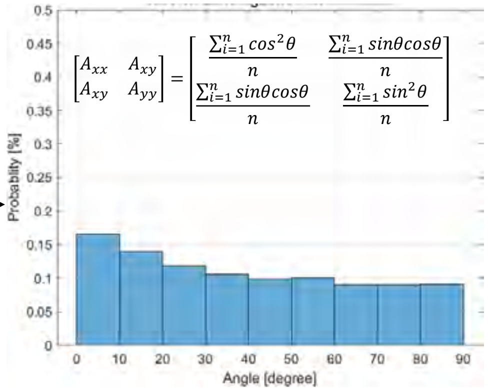


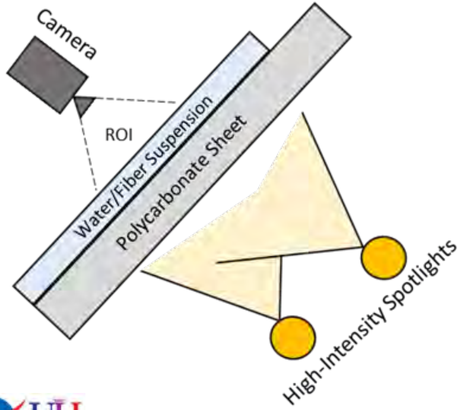
Highspeed imaging (8k fps) of fibers within flow



Orientation Distribution

$$\begin{bmatrix} A_{xx} & A_{xy} \\ A_{xy} & A_{yy} \end{bmatrix} = \begin{bmatrix} \frac{\sum_{i=1}^{n} cos^2\theta}{n} & \frac{\sum_{i=1}^{n} sin\theta cos\theta}{n} \\ \frac{\sum_{i=1}^{n} sin\theta cos\theta}{n} & \frac{\sum_{i=1}^{n} sin^2\theta}{n} \end{bmatrix}$$





❖ Image Analysis for Fiber Orientation Dynamics

Raw Image | Filter | Fiber Detection

Physics Based Model: Problem Formulation

- Fiber position and orientation is described by its centroid position x_c and its orientation p.
- Fibers are subjected to a velocity field along their length.
- The transferred momentum to fibers from water rotates fibers with respect to the fiber relative velocity.

➢ Conservation of Linear momentum

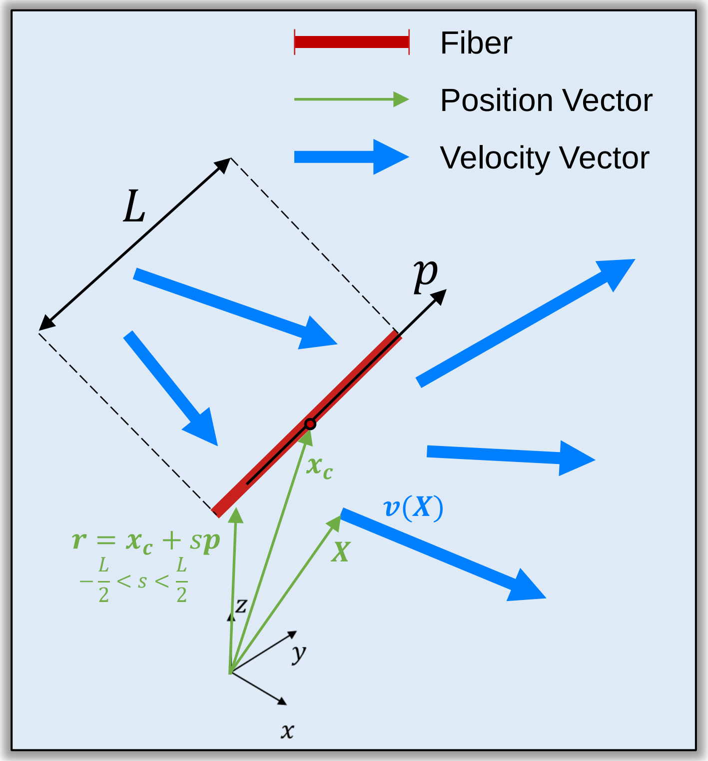
$$\int_{\frac{-L}{2}}^{\frac{L}{2}} \boldsymbol{v}\,(x_c + s\boldsymbol{p}) - \dot{\boldsymbol{x}}_c - s\dot{p}\; ds = 0$$

➢ Conservation of Angular momentum

$$\int_{\frac{-L}{2}}^{\frac{L}{2}} (\boldsymbol{v}(x_c + s\boldsymbol{p}) - \dot{\boldsymbol{x}}_c - s\dot{\boldsymbol{p}}) \times (x_c + s\boldsymbol{p}) ds = 0$$

$$\dot{\boldsymbol{x}}_c = \boldsymbol{V}_x$$

$$\dot{\boldsymbol{p}} = \frac{\boldsymbol{V}_p \cdot \boldsymbol{V}_p}{\boldsymbol{V}_p \cdot \boldsymbol{V}_p - (\boldsymbol{p} \cdot \boldsymbol{V}_p)^2} (\boldsymbol{p} \times \boldsymbol{V}_p)$$



Process Characterization – Physics Based Model

- Fiber orientation dynamics within a thin water film
  - o Benchmark: obstacle on the spillway

Experimental Measurements
- Water film Thickness
- Fibers Velocity

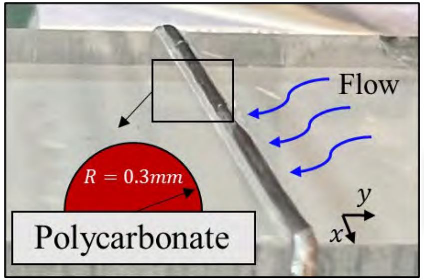
→ COMSOL →

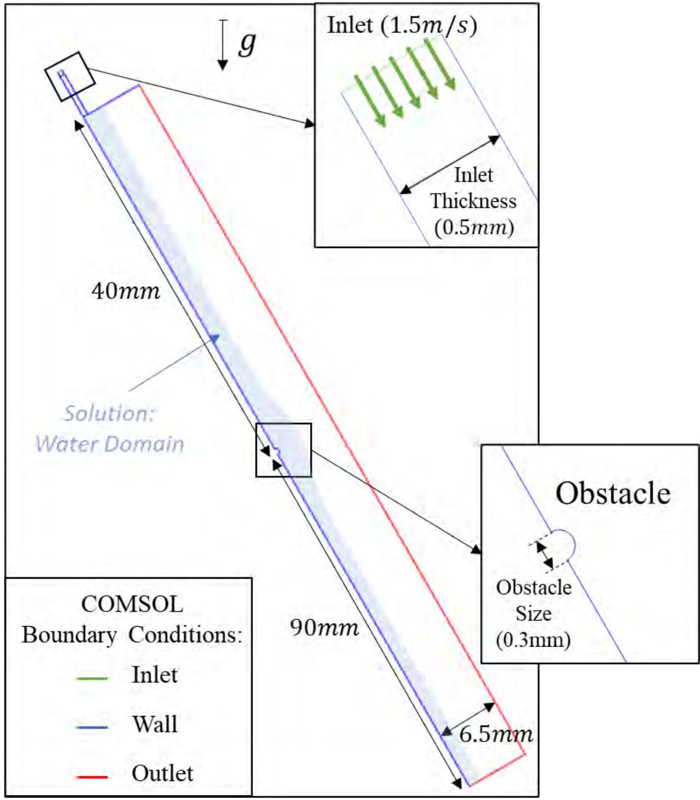
Digital Twin Model
- Velocity Field

↓

Fiber Orientation
- Physics-based model

→ Model Validation

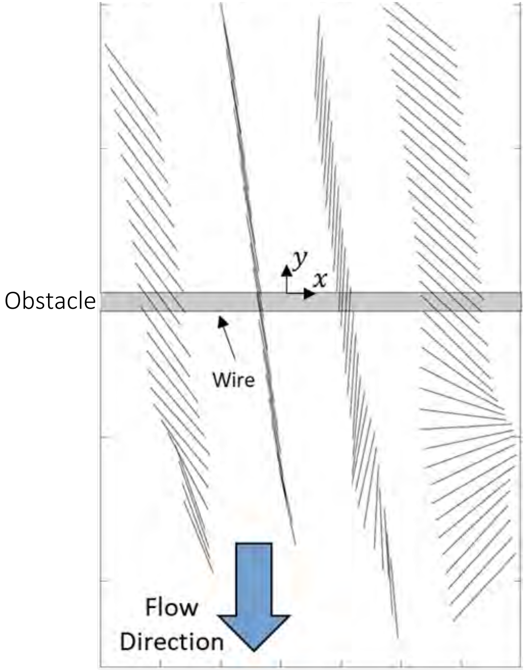


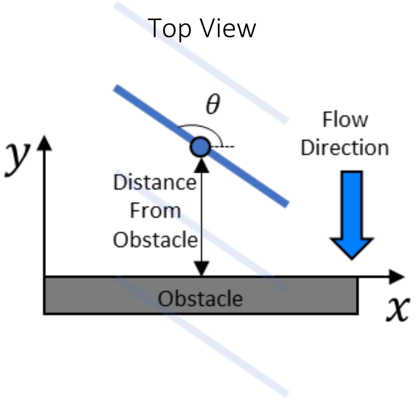


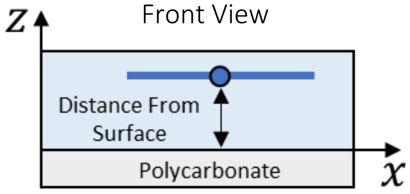
Physics Based Model Validation

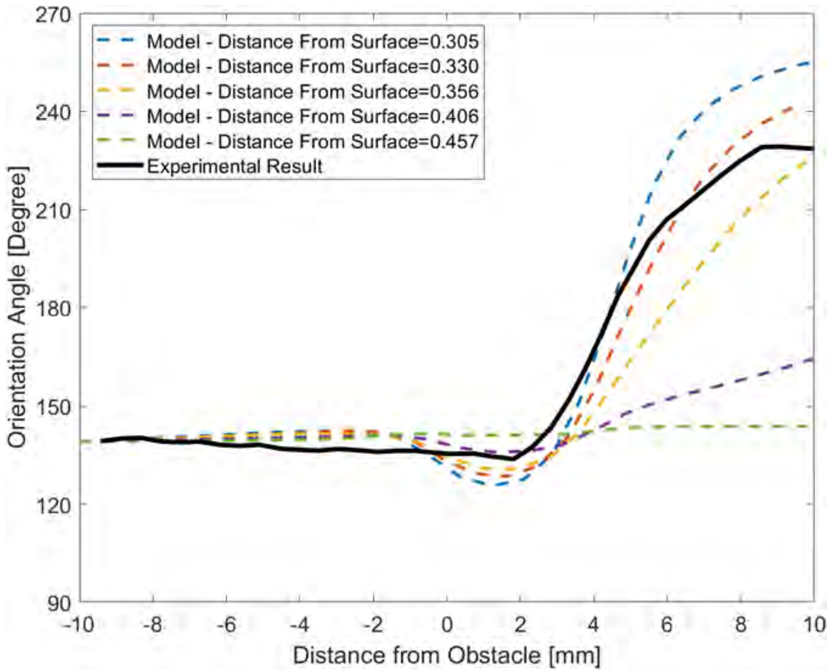
- Fiber Orientation Dynamics
- Experimental data limitation: Distance of Fibers from Spillway Surface

Digitized Experimental data





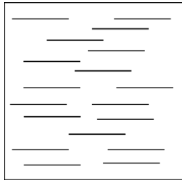




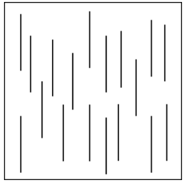
- Effect of obstacle on fiber orientation distribution.

- Fiber Orientation Distribution Tensor:

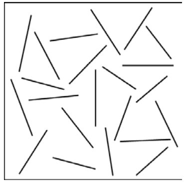
$$A_2 = \begin{bmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{xy} & A_{yy} & A_{yz} \\ A_{xz} & A_{yz} & A_{zz} \end{bmatrix}$$



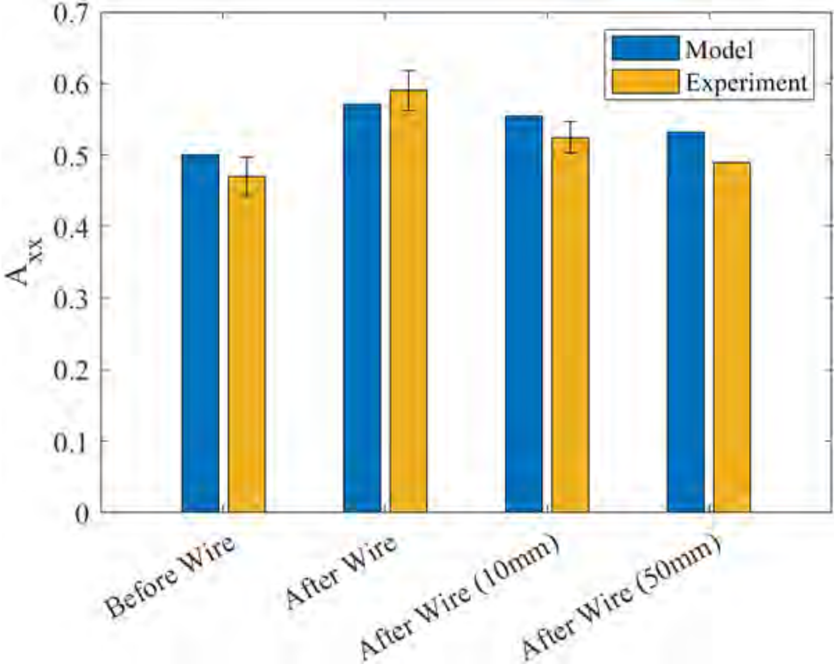
$$A_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$



$$A_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

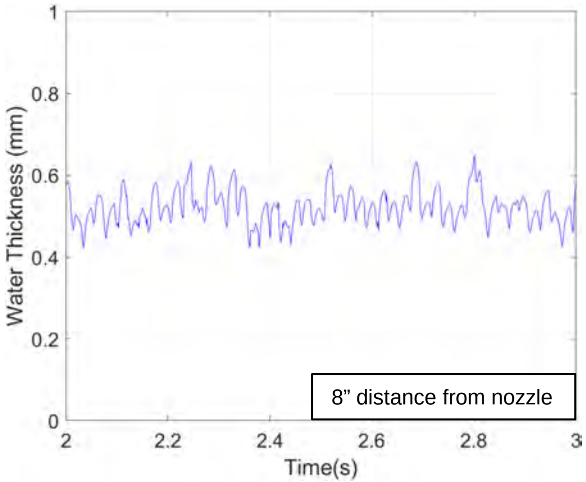


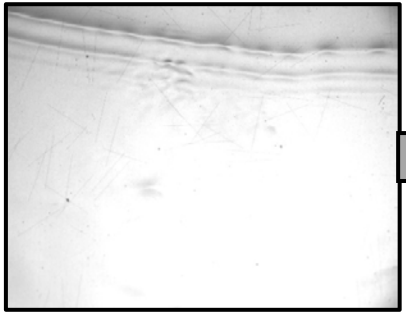
$$A_2 = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

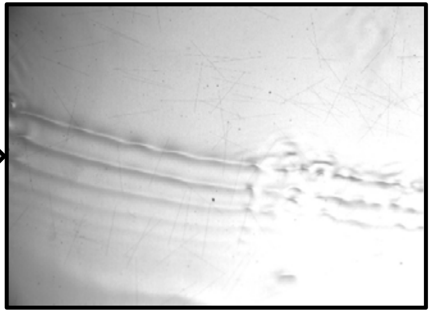


Process Characterization – Water Film Thickness

- Frequent waves in measured data.
- Consistent waves within the flow.
- Waves visualization
- Analysis of wave's frequency





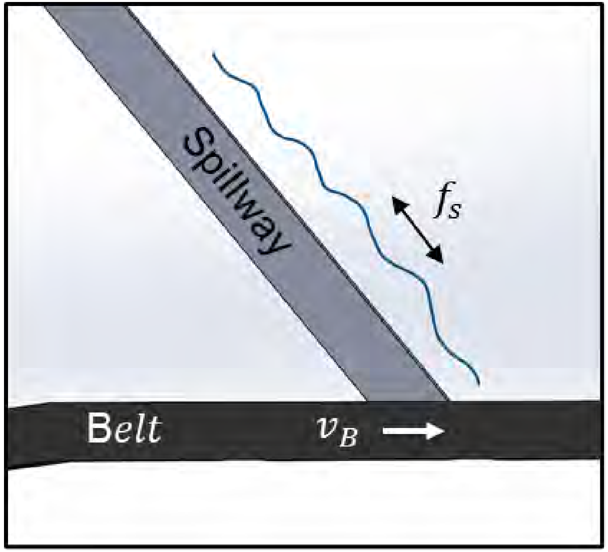


Waves Frequency 45Hz

Pump-induced waves within the flow.

Hypothesized Source of Windows - Waves on the Spillway

- Hypothetical Characteristic Length of Windows (λ^*)



f_s : Frequency of waves

v_B : Belt Speed

λ^*: Characteristic Length of Windows

$$\lambda^* = \frac{v_B}{f_s}$$

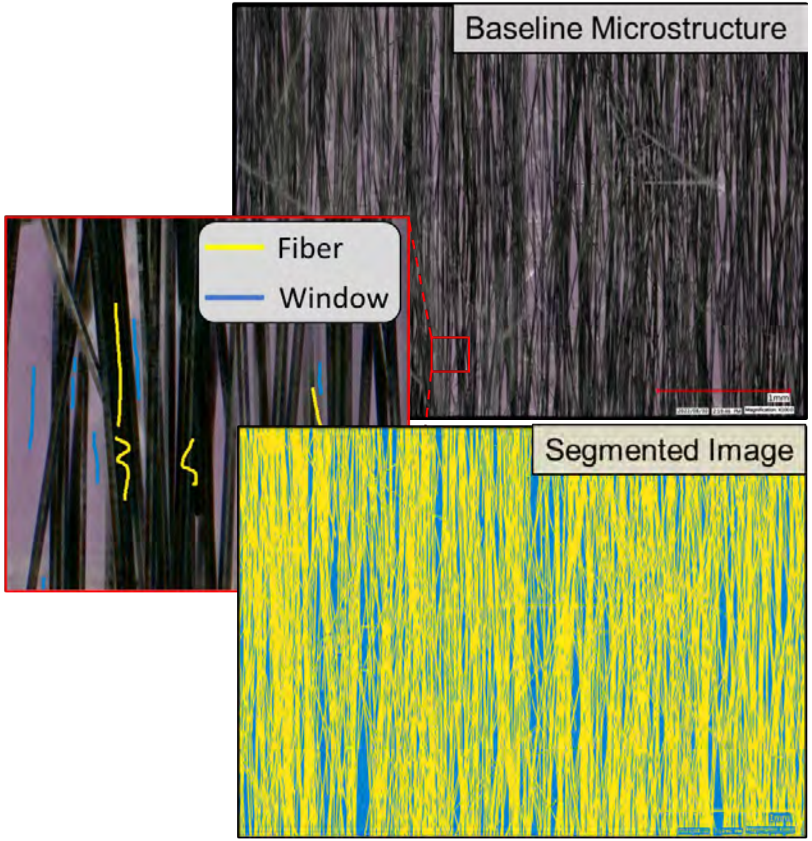
$$f_s = 45 \text{ Hz}$$

$$v_B = 2.75mm/s$$

$\lambda^* \approx 0.03–0.06$ mm

TuFF Microstructure Quantification by ML Image Processing

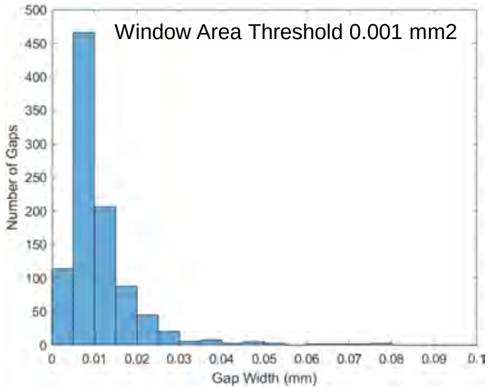
- TuFF Sheet Microstructure
- Machine Learning application in Image Processing
- Segmented Image: Fibers vs. Windows

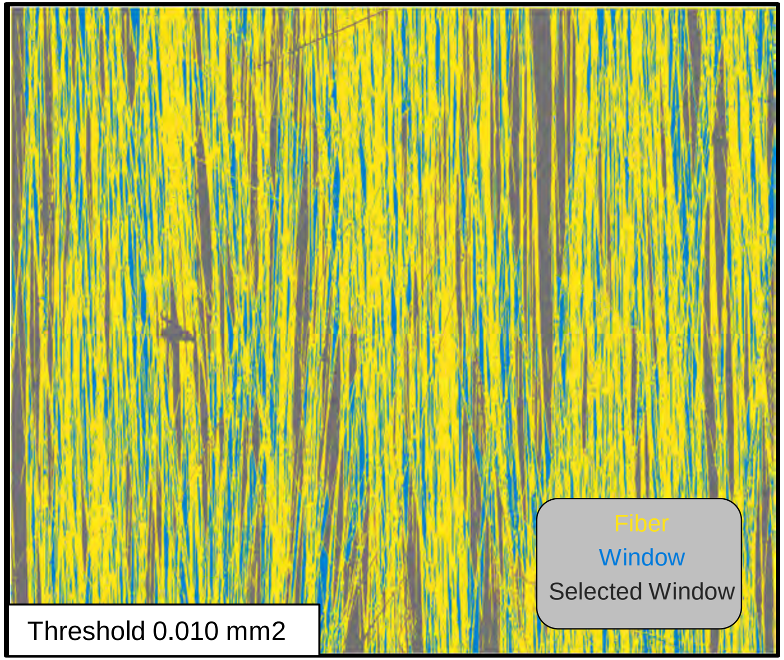


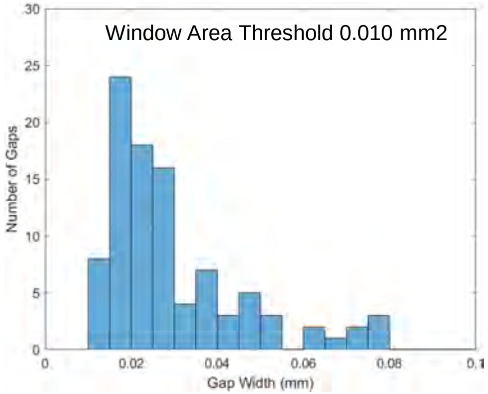
- Process segmented images on MATLAB
- Object Detection (Windows)
- Information of individual Windows
  (location, size, width, etc.)

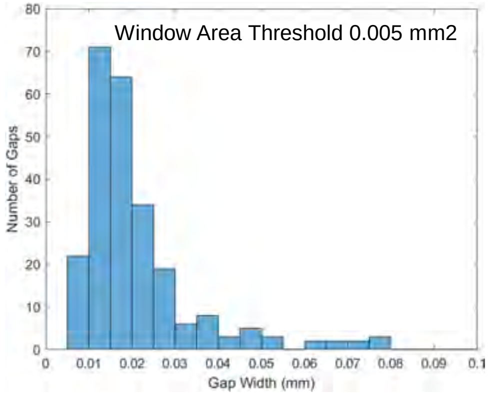
TuFF Microstructure Quantification by ML Image Processing

- Processed data
- Focus on Large Windows
- Window Width Distribution









Process Improvement – New Manufacturing Design

- Modify the manufacturing design to eliminate waves on spillway.
- Ogee Spillway:
  - ➢ Provide a control over water depth for Dam's spillway.
  - ➢ Formulated by US Army Corps.
- Downstream Curve Formulation (Ogee Spillway)

$$x^n = k{H_d}^{n-1}y$$

$$Q = CL{H_d}^{1.5}$$

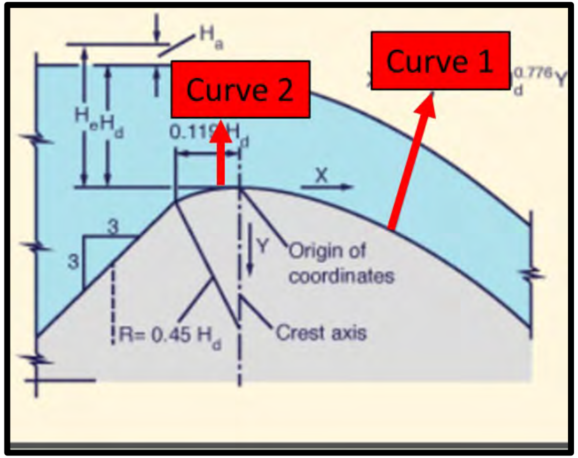
Approach Angle (Degree)	n	k
90	1.85	2
71	1.836	1.936
56	1.81	1.939
45	1.776	1.873

k, n: Design parameters based on the approach angle.

H_d: Head.

Q: Flow rate.

L: Width of spillway.



Process Improvement – New Manufacturing Design

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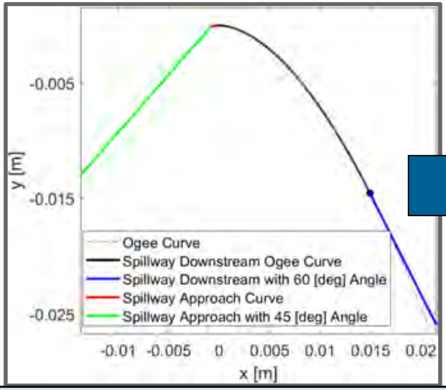
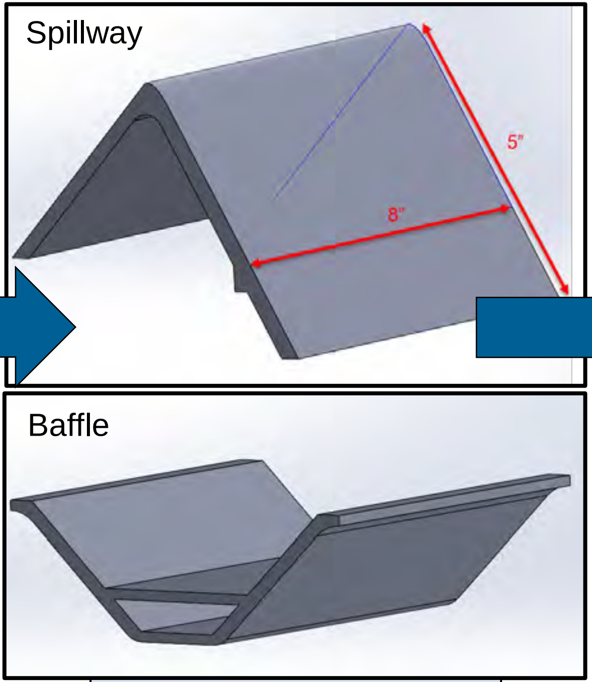
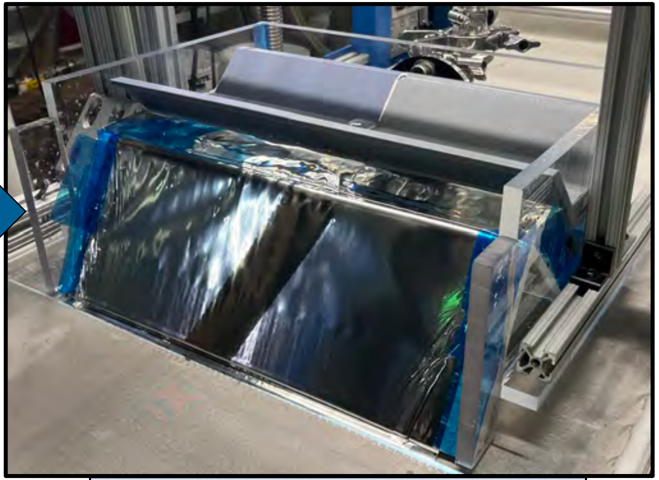
- Automated Design (in MATLAB) based on the Flow Thickness and Flow Rate.
- 3D Printed by PLA.



Curve Formulation in MATLAB



3D Model for Prototyping



Fabricated setup mounted on the TuFF manufacturing line

Results – Wave Reduction

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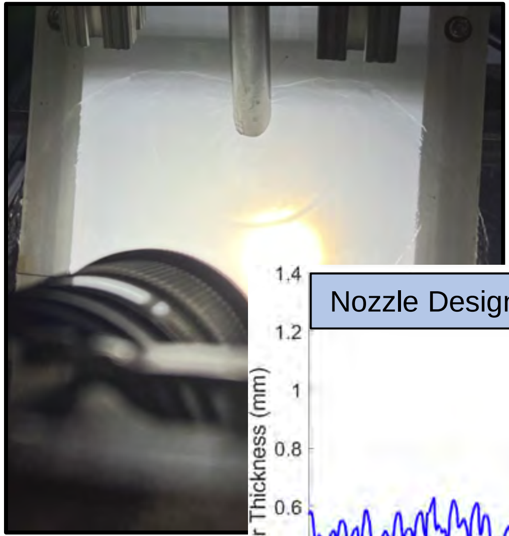
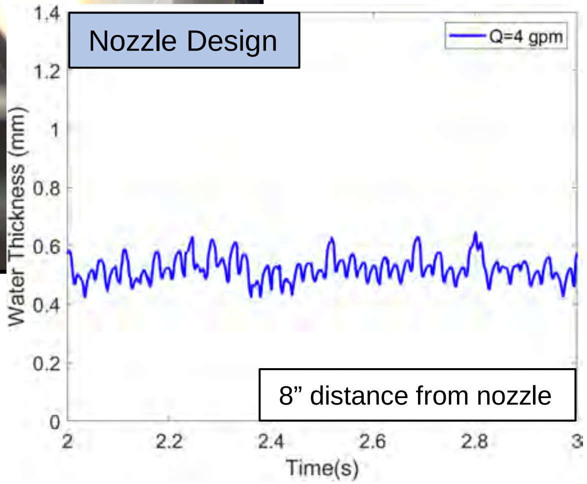
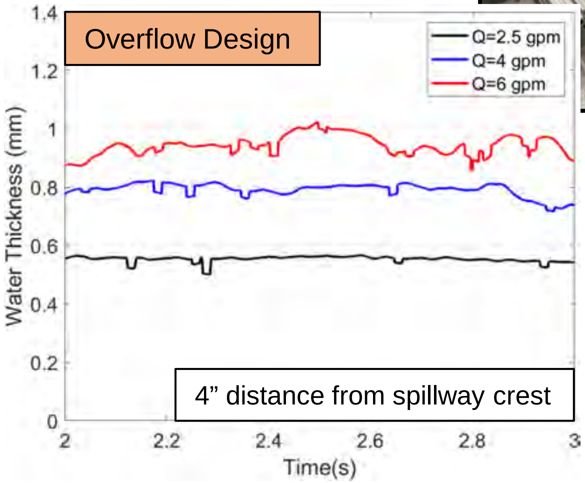
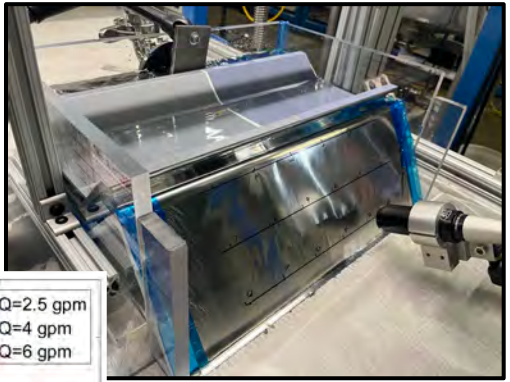
- Significant wave reduction by the new design.
- Wave amplitude reduced by 2-4 fold.

Design	Normalized Flow Rate	Water Thickness (mm)	
		Average	Standard Deviation
Nozzle	1.0	0.523	0.0418
Overflow Spillway	1.3	0.958	0.023
	1.0	0.782	0.019
	0.5	0.552	0.011









Results – TuFF Microstructure Comparison

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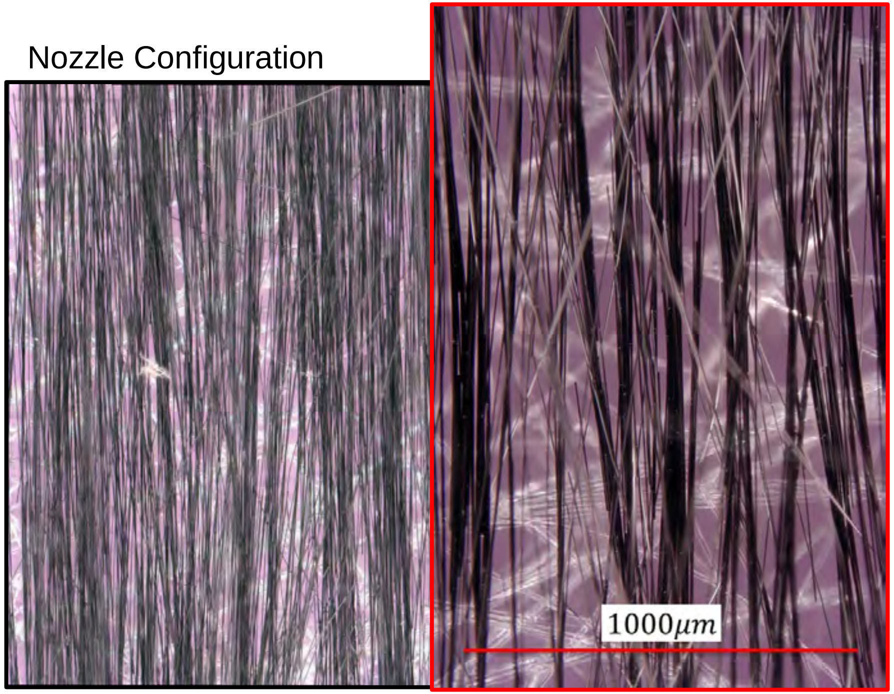
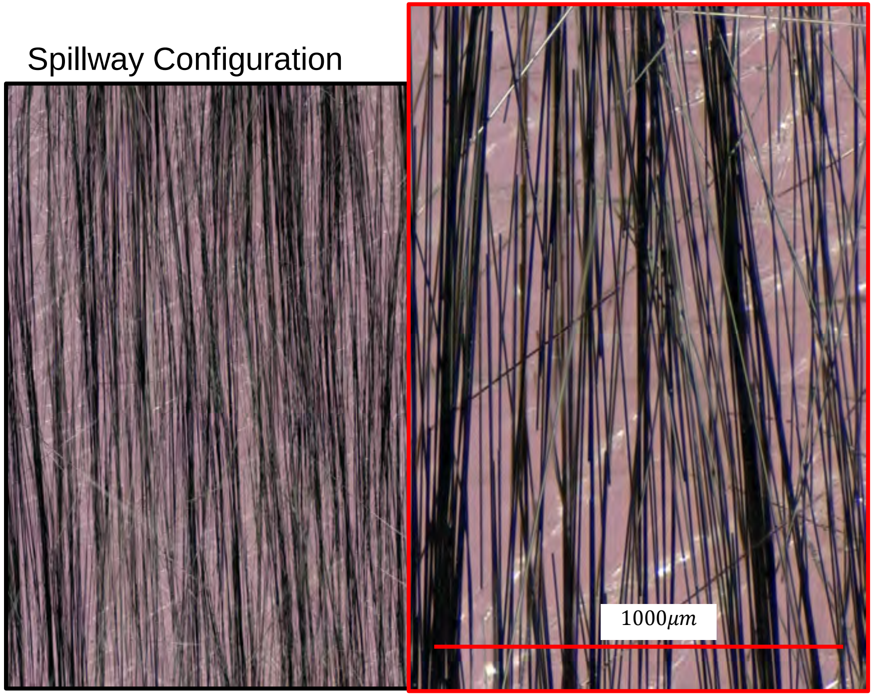
- Visual Comparison

Nozzle Configuration



Areal Weight = 7.5 gsm

Spillway Configuration



Areal Weight = 6.1 gsm

Results – TuFF Microstructure Comparison

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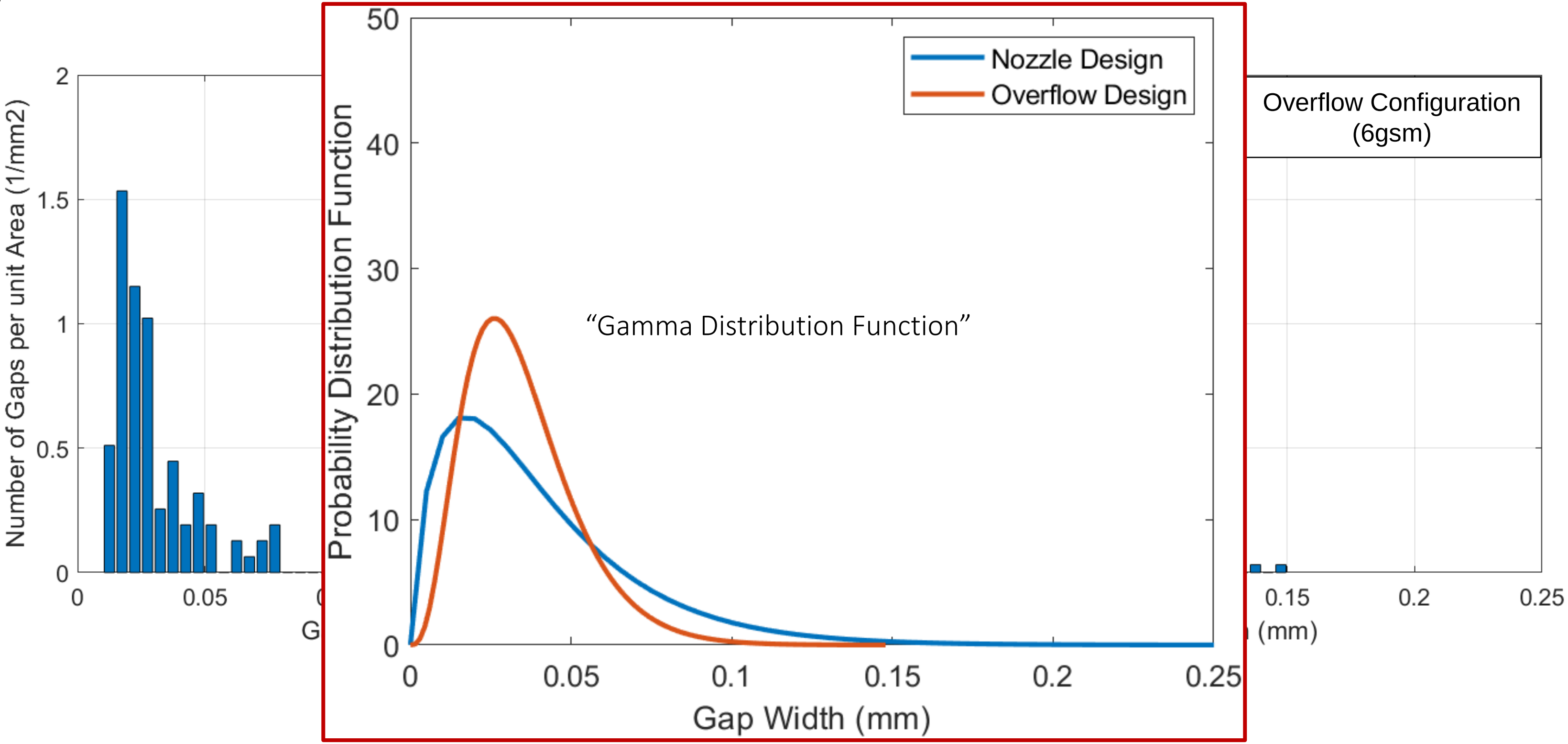
- Quantitative Comparison
- Gap Threshold 0.010mm2

Eliminated waves by new spillway reduces gap windows width



Overflow Configuration (6gsm)

Results – TuFF Microstructure Comparison (Fiber Alignment)

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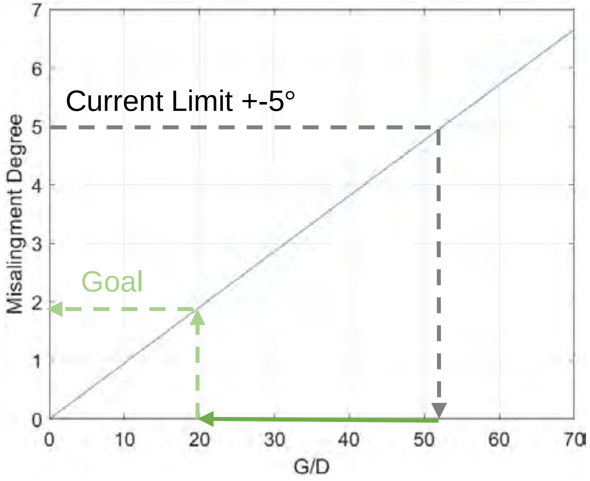
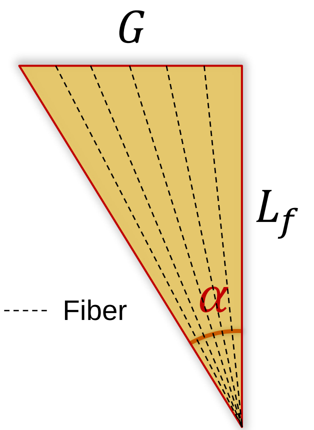
- Current alignment limitation: 95% fibers aligned ± 5°
- Describe each window by a triangle.

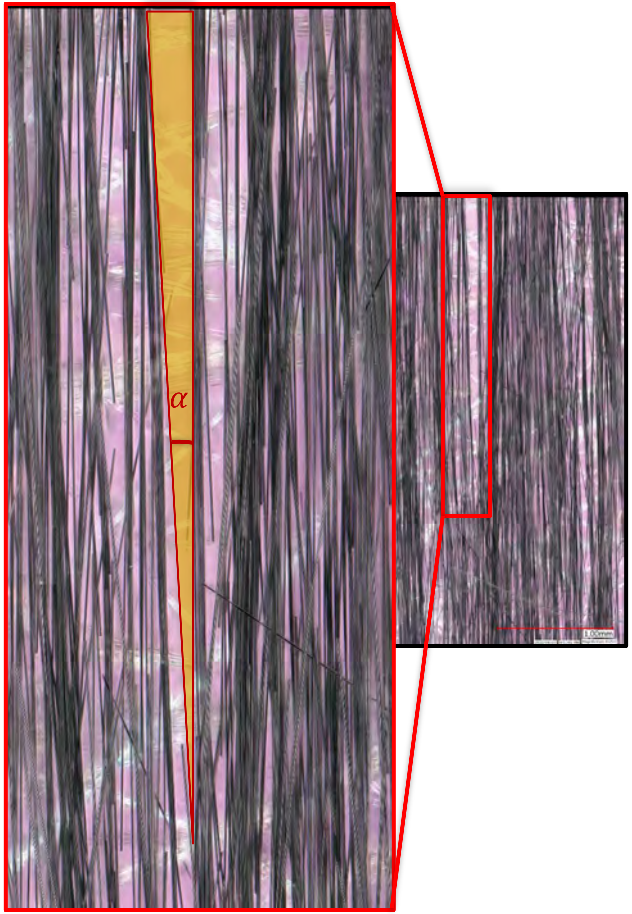
$$\alpha = \tan^{-1}\left(\frac{G}{L_f}\right)$$

- α : Fibers Misalignment Threshold





G: Window Gap Width
L_f: Fiber Length



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Conclusions

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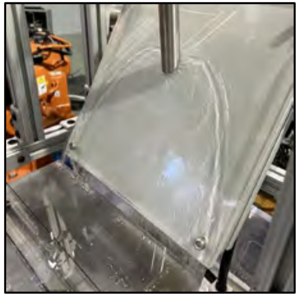
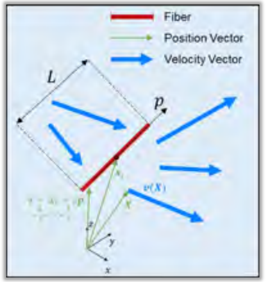
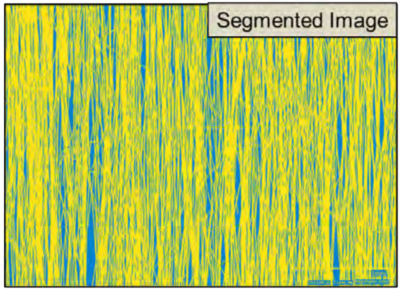
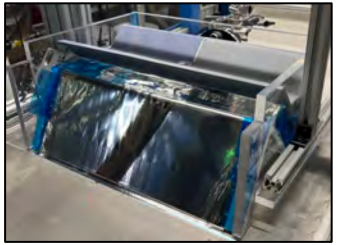
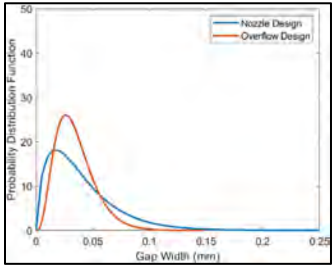
- Benchmarked the current alignment process.
  - o Process characterization
  - o Quantitative analysis of TuFF microstructure.
- Proposed a physics-based model to predict fiber orientation within thin film of water.
- Hypothesis the origin of large window gaps.
- Designed, fabricated a new scalable spillway.
- The Ogee overflow design minimizes spillway wave amplitudes.
- Wave reduction on the spillway effectively closes large windows.
- Aligning fibers with reduced window width leads to
  1) TuFF preforms with higher fiber alignment.
  2) Thin ply composites with fewer layers and lower areal weight.

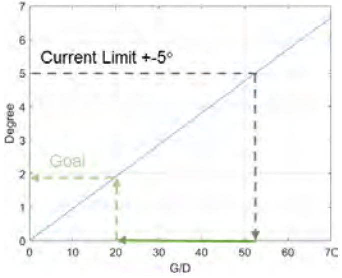












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