# U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – GROUND VEHICLE SYSTEMS CENTER

## Analysis of Micromixers to Minimize Scaling Effects on Reverse Osmosis Membranes

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Force Projection Technology

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# Overview

**I. Membrane Fouling**

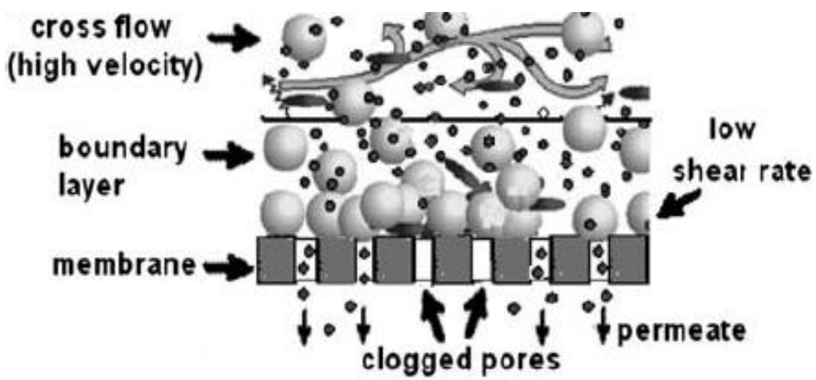
**II. Research Aims**

A. CFD modeling

B. Direct Print Micromixers

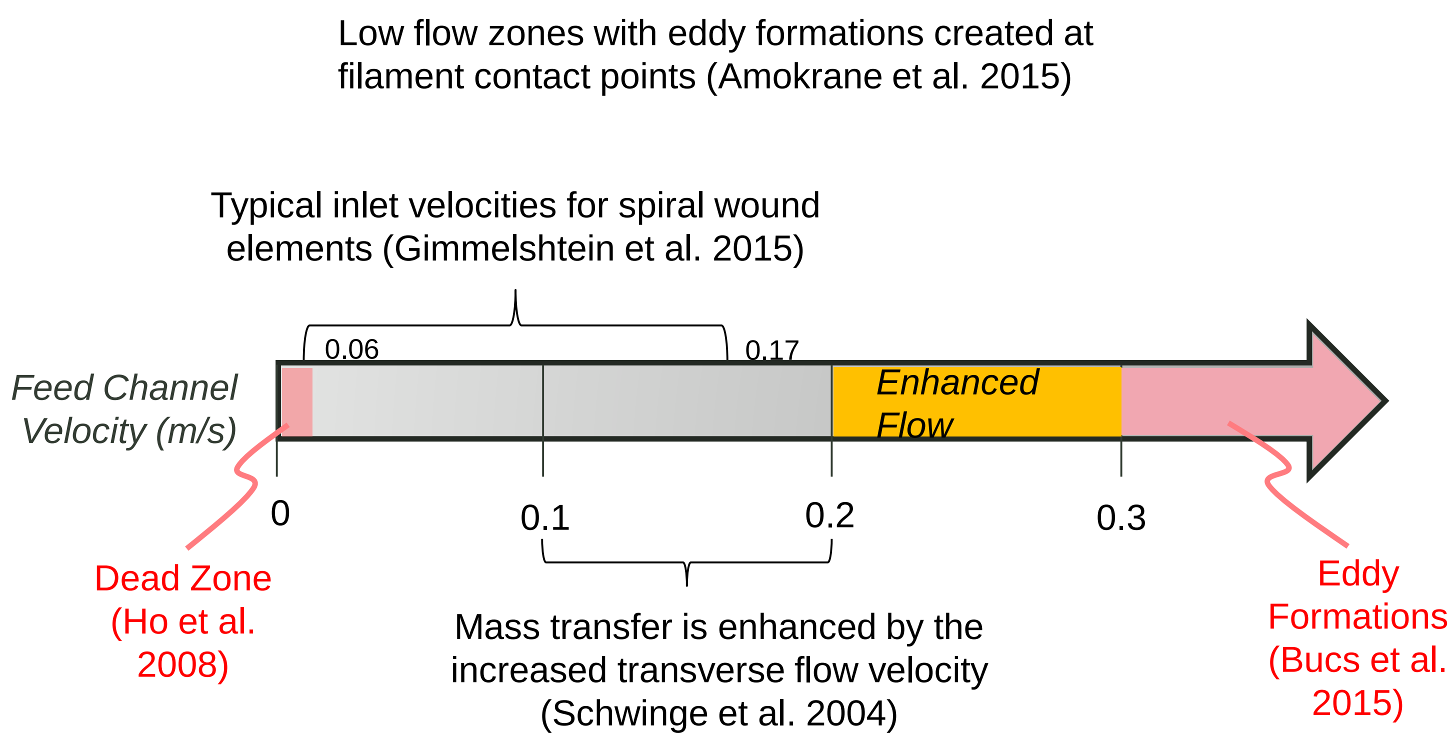
# Membrane fouling

(TARDEC 1998)




(Feng et al. 2006)

# Feed channel velocities




Defined Velocity Zones (inlet velocity 0.104 m/s):

| | |
|---|---|
| 0 – 0.1 m/s | no/low flow zone (or dead zone) |
| 0.1 – 0.2 m/s | unimproved zone |
| 0.2 – 0.3 m/s | enhanced zone |
| > 0.3 m/s | non-recirculating zone |

# Research Aim 1

**Hypothesis 1:** Optimized microstructure design and patterning will maximize the area of enhanced velocity *(0.2 – 0.3 m/s)* and minimize velocities associated with fouling (<0.1 m/s,  >0.3 m/s).

# Experimental design - COMSOL

Equation 1 $\nabla u = 0$ Continuity

Equation 2 $\rho u * \nabla u + \nabla p = \eta \nabla^2 u$ Navier-Stokes

($\rho$ is density ($kg/m^3$), u is the velocity vector (m/s), $\eta$ the viscosity (Ns/m) and p is pressure (Pa))

Model conditions:
Inlet velocity set to 0.104 m/s
Outlet pressure set to 20.7 bar
Microstructures and side walls were defined as no slip

# Experimental design - parameters

**Variables evaluated:**

Angle (A)

- 60, 90, and 120 degrees

Pattern

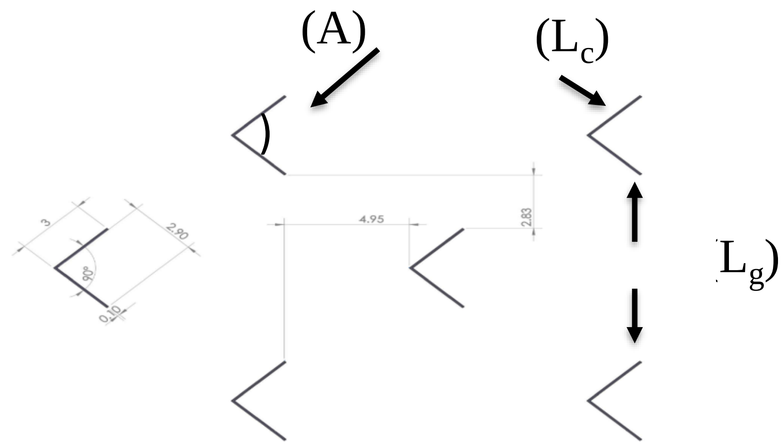
- Offset and continuous

Gap Length ($L_g$) between chevrons

- 0.75 mm, 5.75 mm, and 10.75 mm

Chevron Length ($L_c$) of chevron

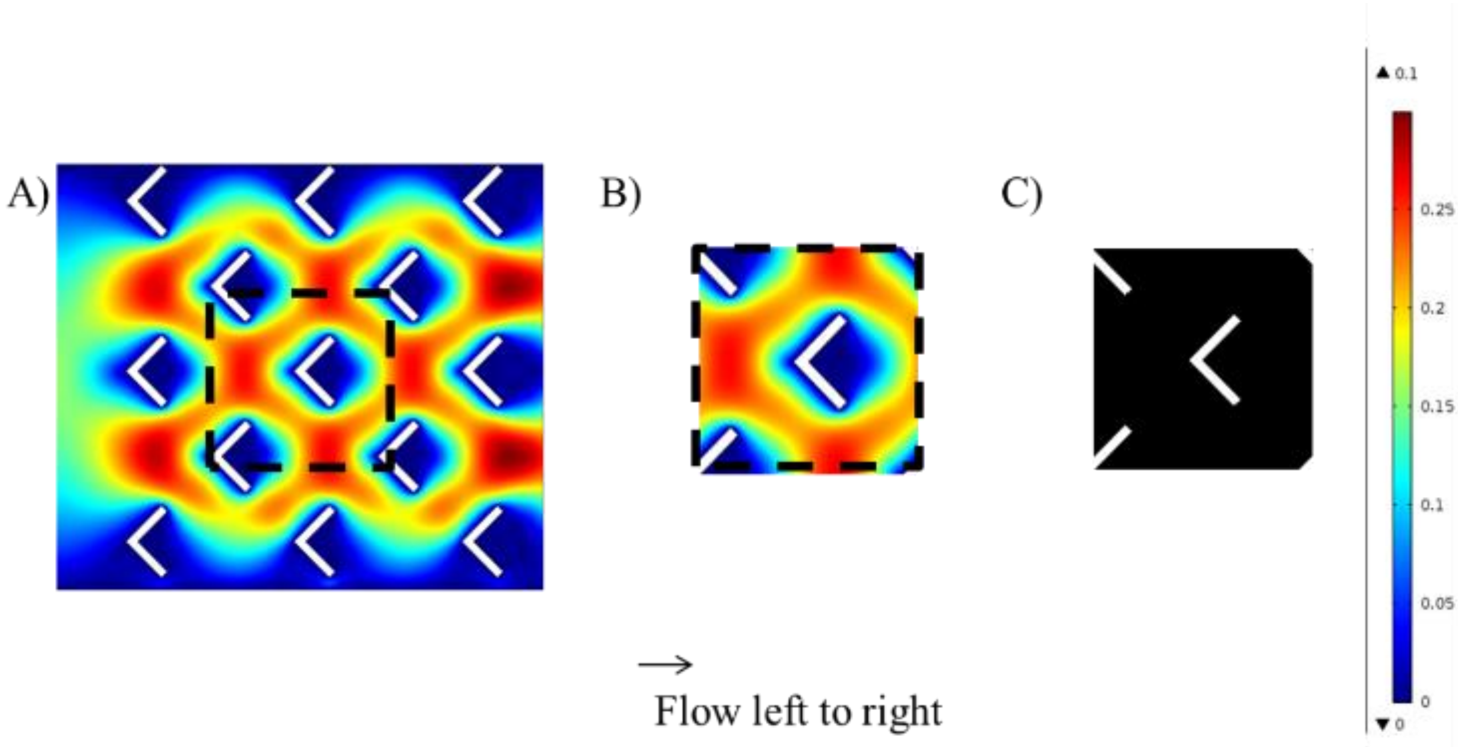
- 3 mm, 4mm, and 5 mm




Base micromixer:

- A = 90 degree chevron
- offset pattern
- $L_c$= 3mm chevron lengths
- Width of chevron (W) = 0.01 mm
- $L_g$ = 5.75 mm gap

# Unit area of quantification

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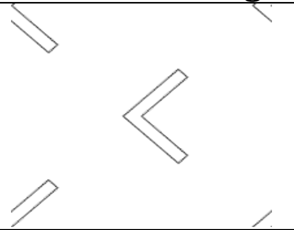
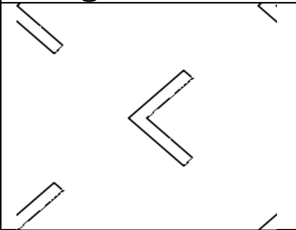
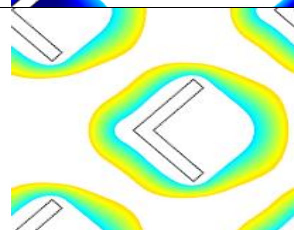
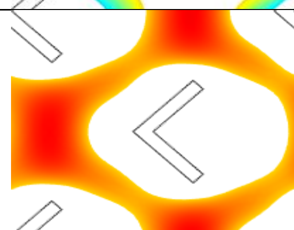
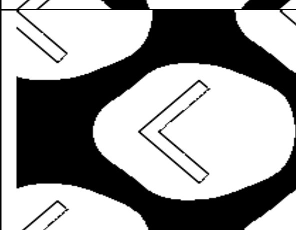
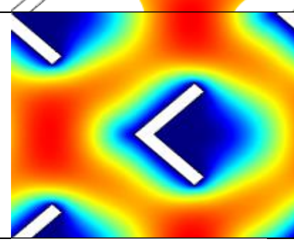
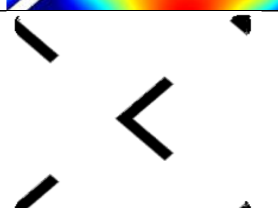
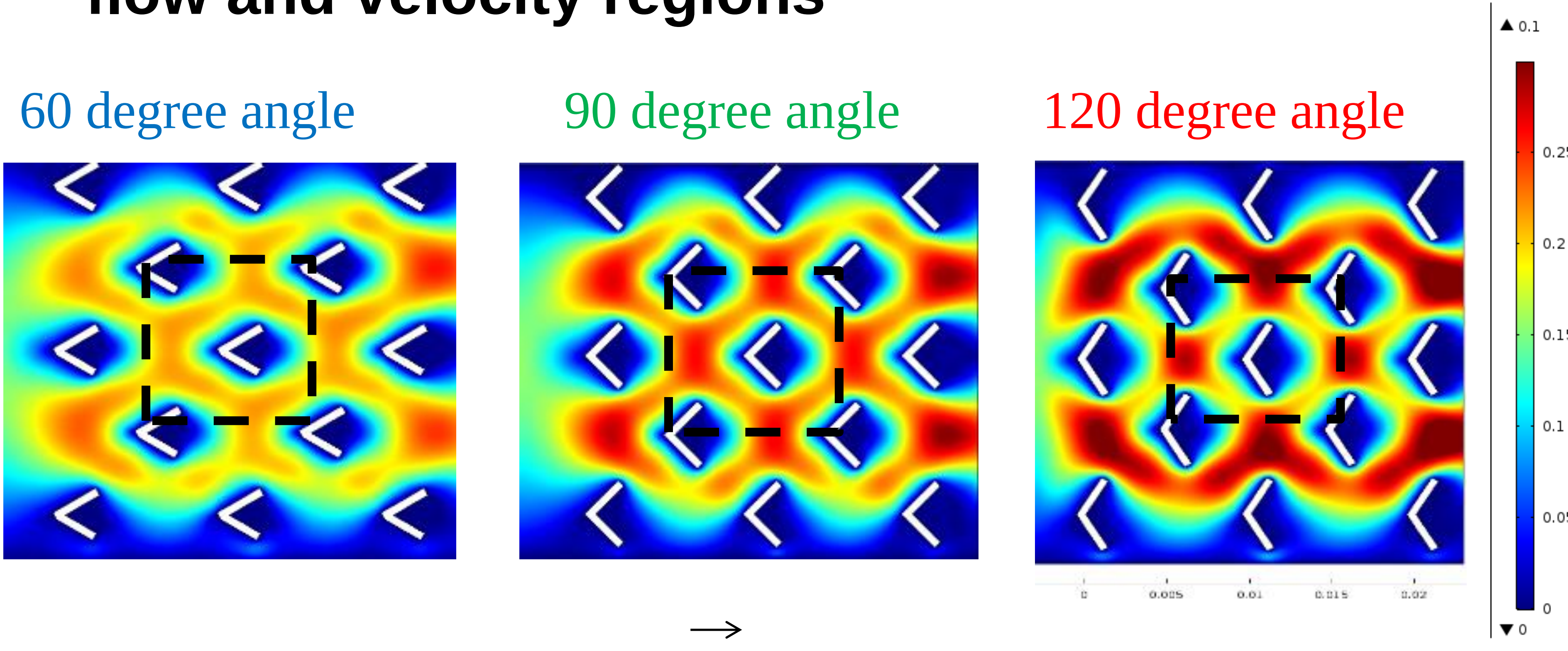
# Percent area calculation for the 90 degree angle

| Range | COMSOL image | ImageJ | % Area | Pixel |
|---|---|---|---|---|
| No flow |  |  | 1.6 | 232 |
| 0-0.1 m/s |  |  | 23.5 – 1.6 = 21.9 | 9455 – 232 = 9223 |
| 0.1–0.2 m/s |  |  | 32.8 – 1.6 = 31.2 | 13394 – 232 = 13162 |
| 0.2 – 0.3 m/s |  |  | 40.8 – 1.6 = 39.2 | 16491 – 232 = 16259 |
| All velocities |  |  | 95.4 – 1.6 = 93.7 | 38332 – 232 = 38100 |
| Chevron only |  |  | 6.3 | 2159 |

# Angle influences the amount of open channel flow and velocity regions

60 degree angle | 90 degree angle | 120 degree angle

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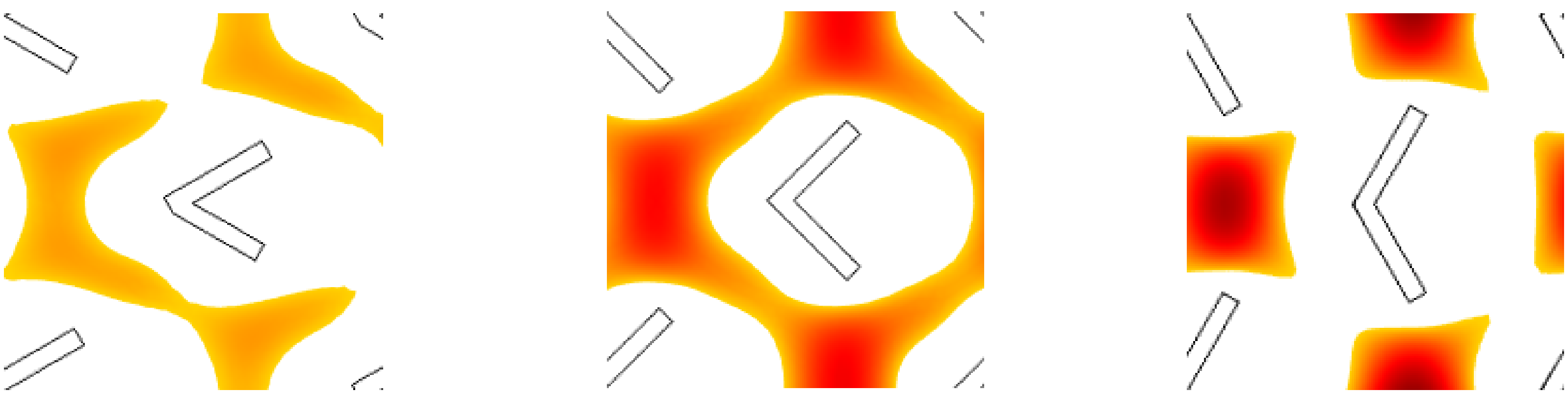
Flow left to right

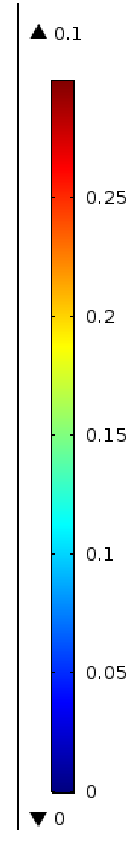
# The 90 degree geometry showed maximum coverage of enhanced flow conditions

60 degree angle - 25.6%

90 degree angle – 39.2%

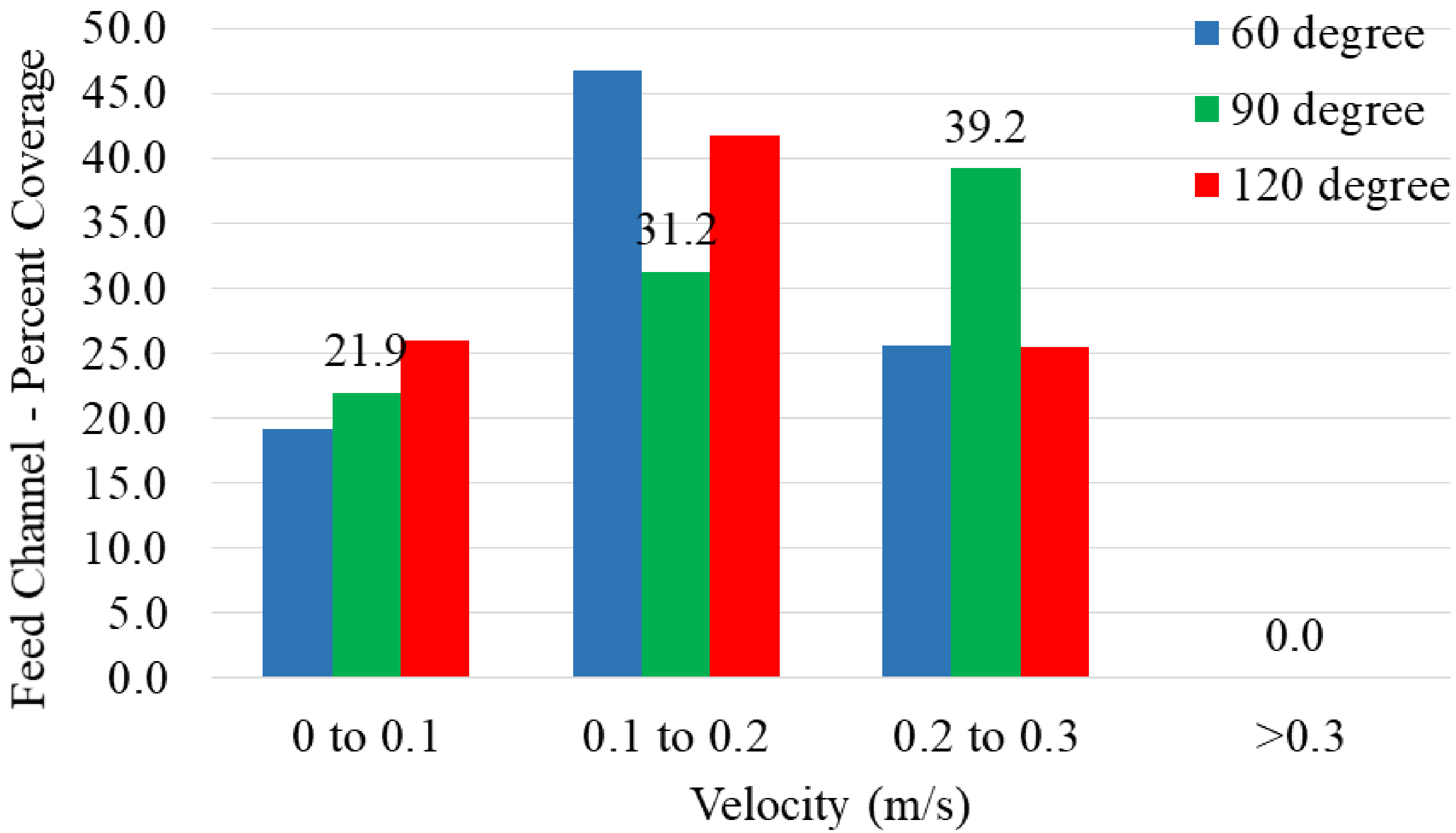
120 degree angle – 25.4%






Areas shown enhanced zone (0.2-0.3 m/s)

# 90 degree geometry provides optimal conditions across all flow velocities




*Offset base pattern: 3mm chevron length, and 5.75 mm gap*

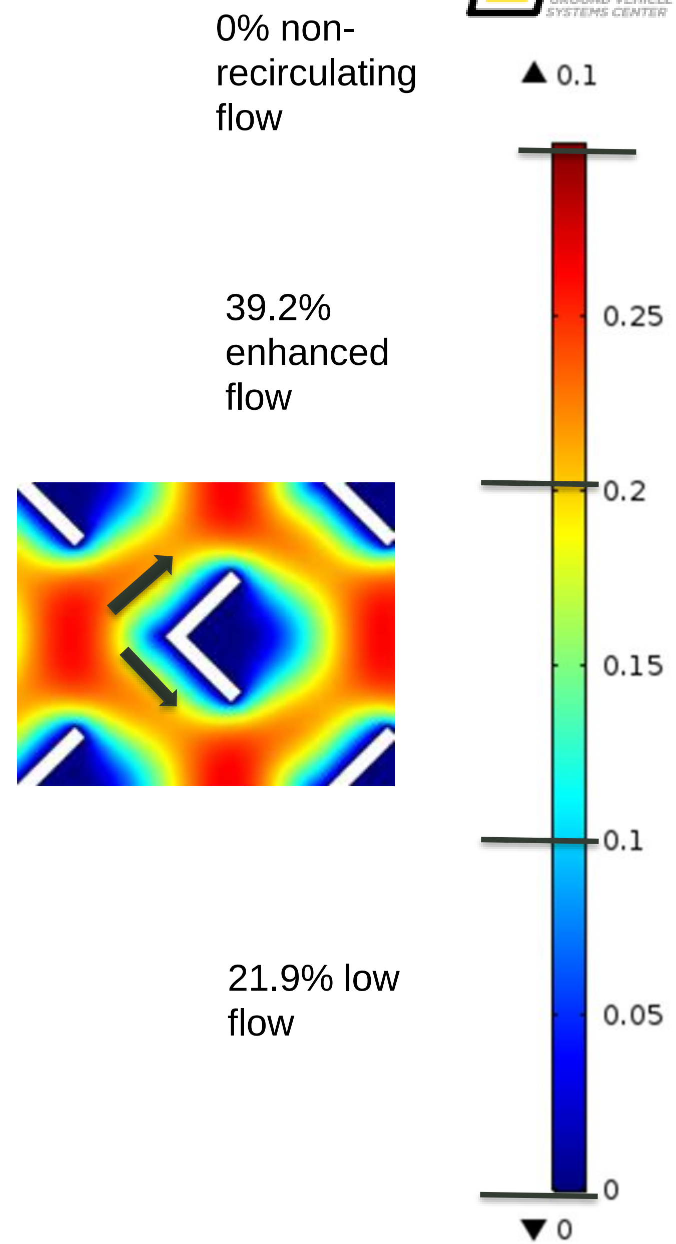
# Optimal design was 90 degree geometry with offset pattern

| | Velocity Profile (m/s) | | | | |
|---|---|---|---|---|---|
| | No/low flow zone 0 to 0.1 | Unimproved zone 0.1 to 0.2 | Enhanced zone 0.2 to 0.3 | Non-recirculating zone >0.3 | Sum of Fouling Zones 0 to 0.1 and > .3 |
| 60 degree offset | 19.2 | 46.7 | 25.6 | 0.0 | 19.2 |
| 90 degree offset | 21.9 | 31.2 | 39.2 | 0.0 | 21.9 |
| 120 degree offset | 26.0 | 41.7 | 25.4 | 0.0 | 26.0 |
| 60 degree continuous | 31.9 | 50.9 | 15.3 | 0.0 | 31.9 |
| 90 degree continuous | 37.7 | 35.5 | 24.0 | 0.0 | 37.7 |
| 120 degree continuous | 38.9 | 26.7 | 29.6 | 3.5 | 42.4 |
| Gap 0.75 mm | 33.4 | 31.0 | 9.5 | 9.1 | 42.5 |
| Gap 10.75 mm | 21.1 | 47.7 | 25.2 | 0.0 | 21.1 |
| 4 mm length | 24.2 | 27.6 | 35.7 | 4.0 | 32.2 |
| 5mm length | 25.8 | 18.2 | 24.3 | 23.6 | 49.4 |

# Research Aim 1: Conclusions

**Hypothesis 1:** Optimized microstructure design and patterning will maximize the area of enhanced velocity *(0.2 – 0.3 m/s)* and minimize velocities associated with fouling (<0.1 m/s,  >0.3 m/s).

- **Angle: 90 degree chevron**
- **Pattern: Offset**
- **Gap Length: 5.75mm**
- **Chevron Length: 3mm**



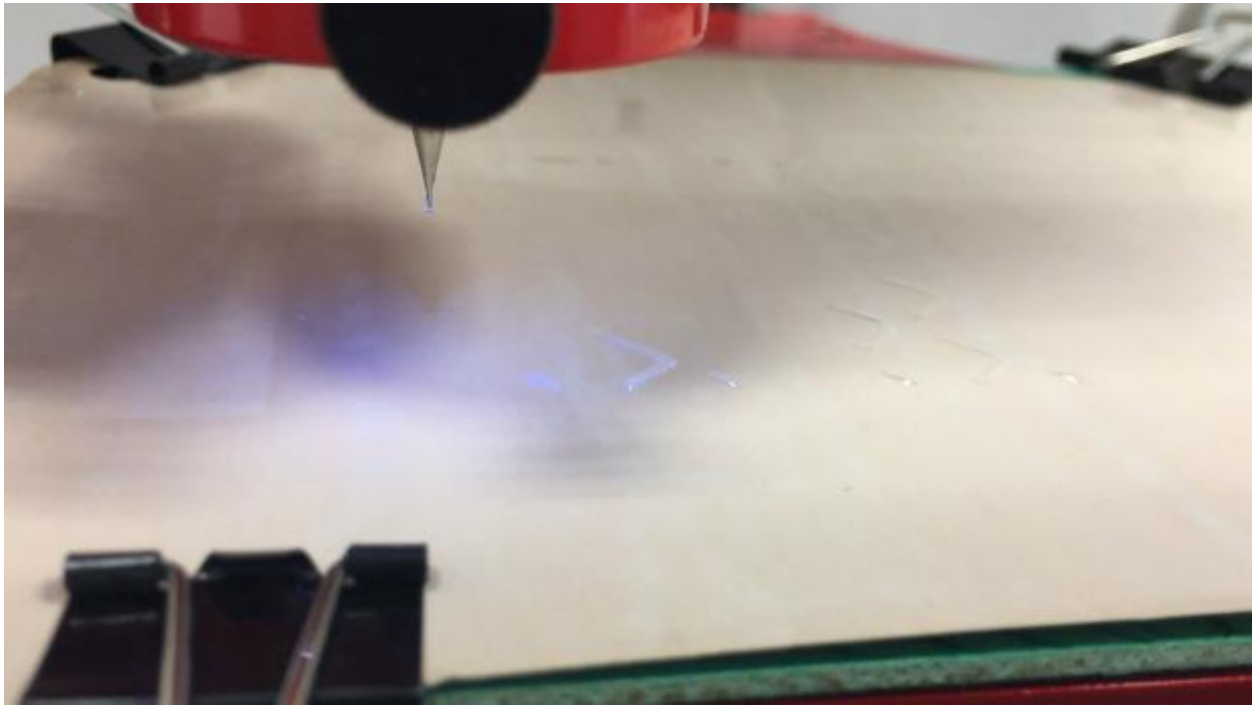
# Research Aim 2

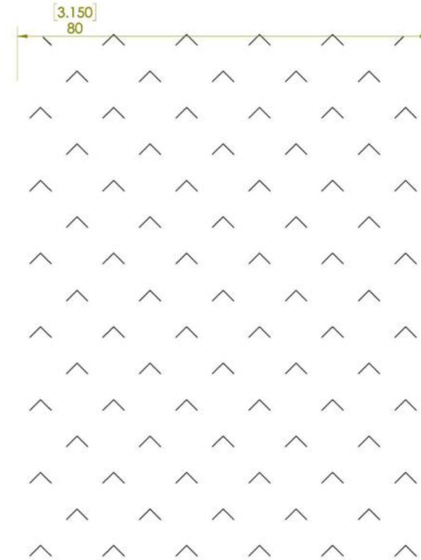
3-Dimensional printing of micromixers onto a membrane and fluorescent beads to experimentally validate modeling

# Printing Directly on the Membrane

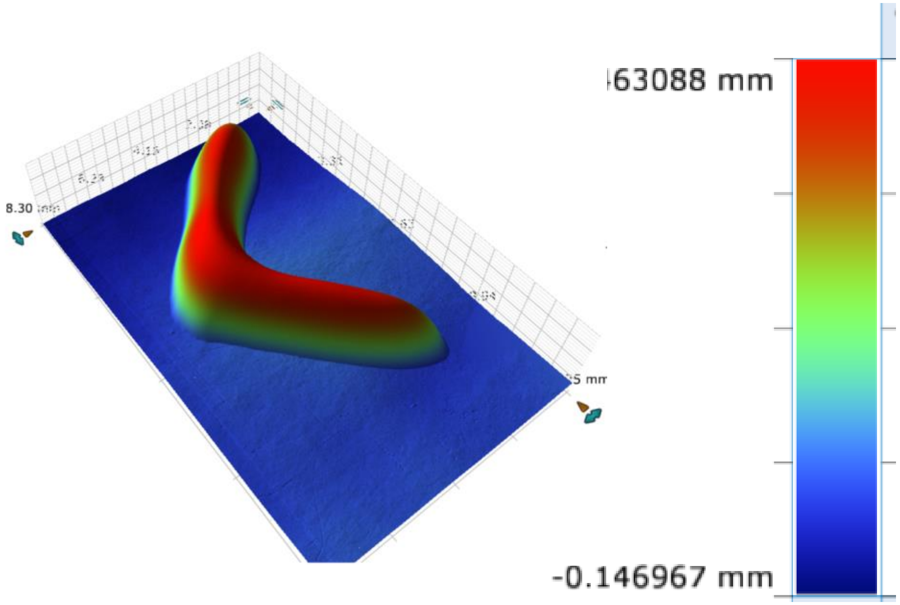
Modified 3D Printer:

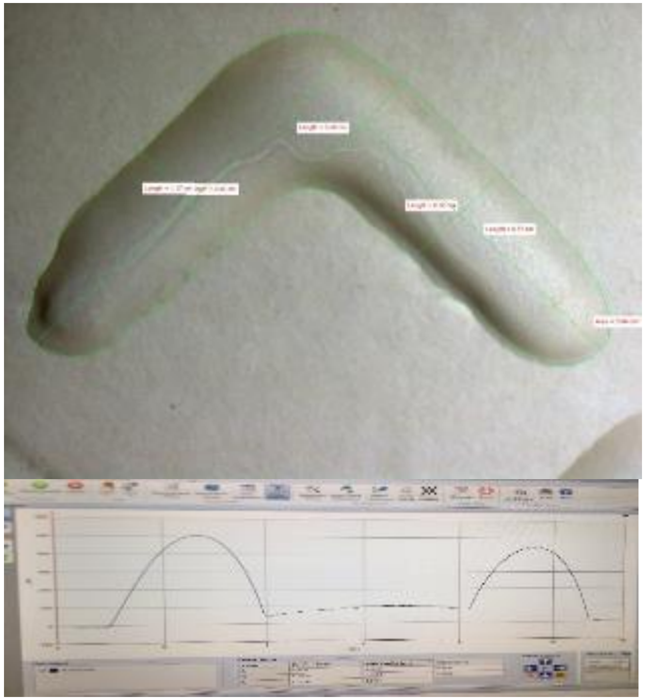
UV curable epoxy, UV15TK (Masterbond)

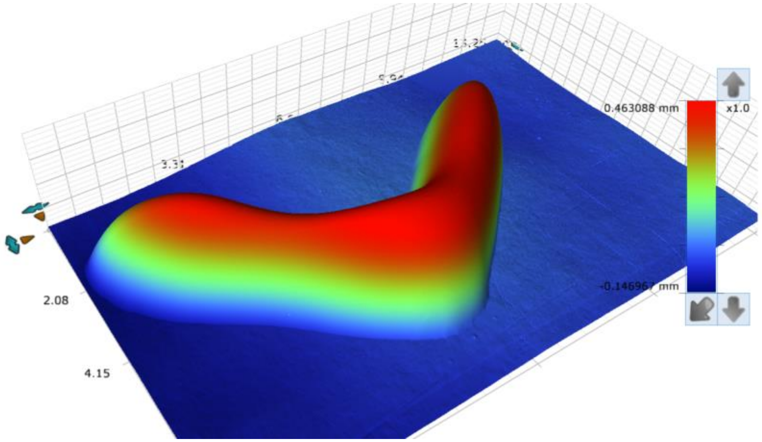




# Individual chevron characterized



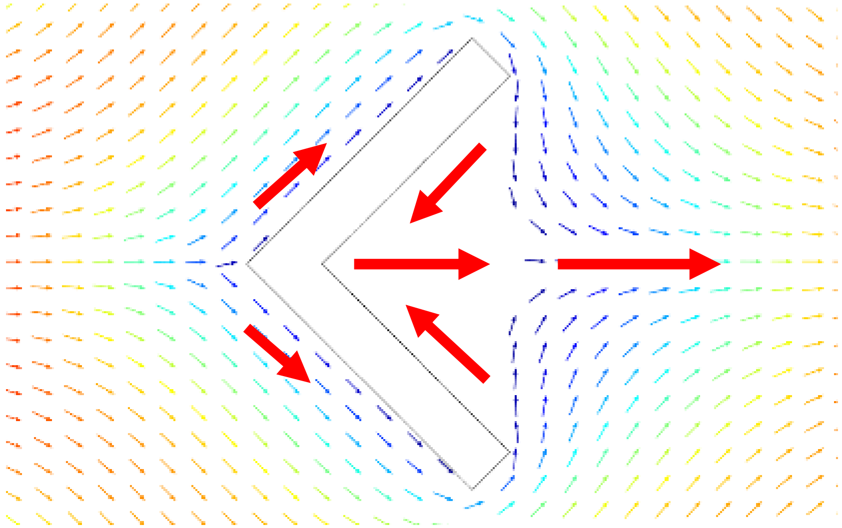






**500 micron height**

# Fluorescence imaging of 2µm green beads was used to support model results

Forward flow



Flow left to right

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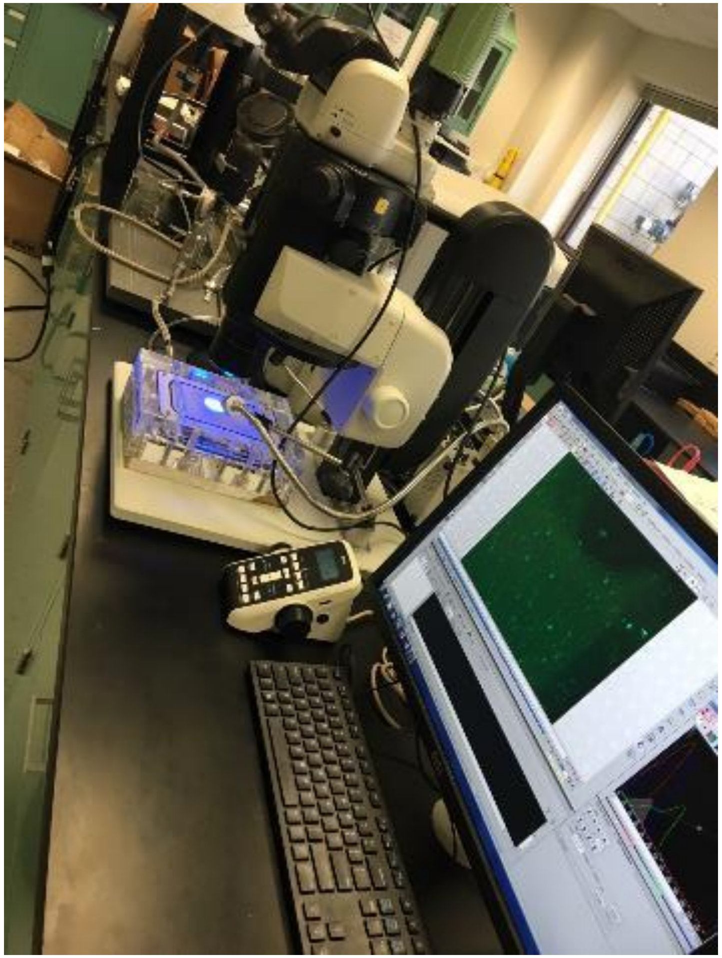
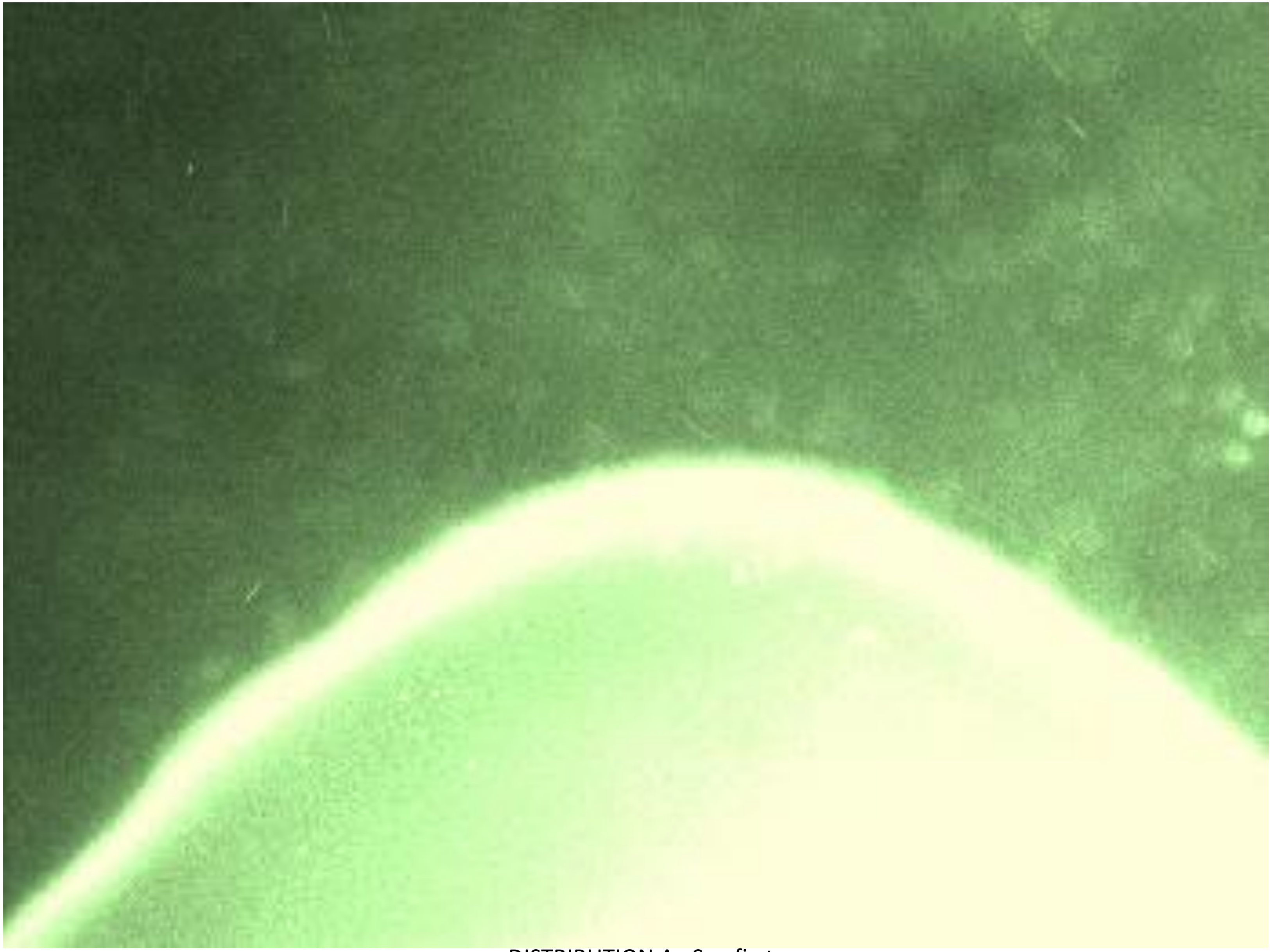
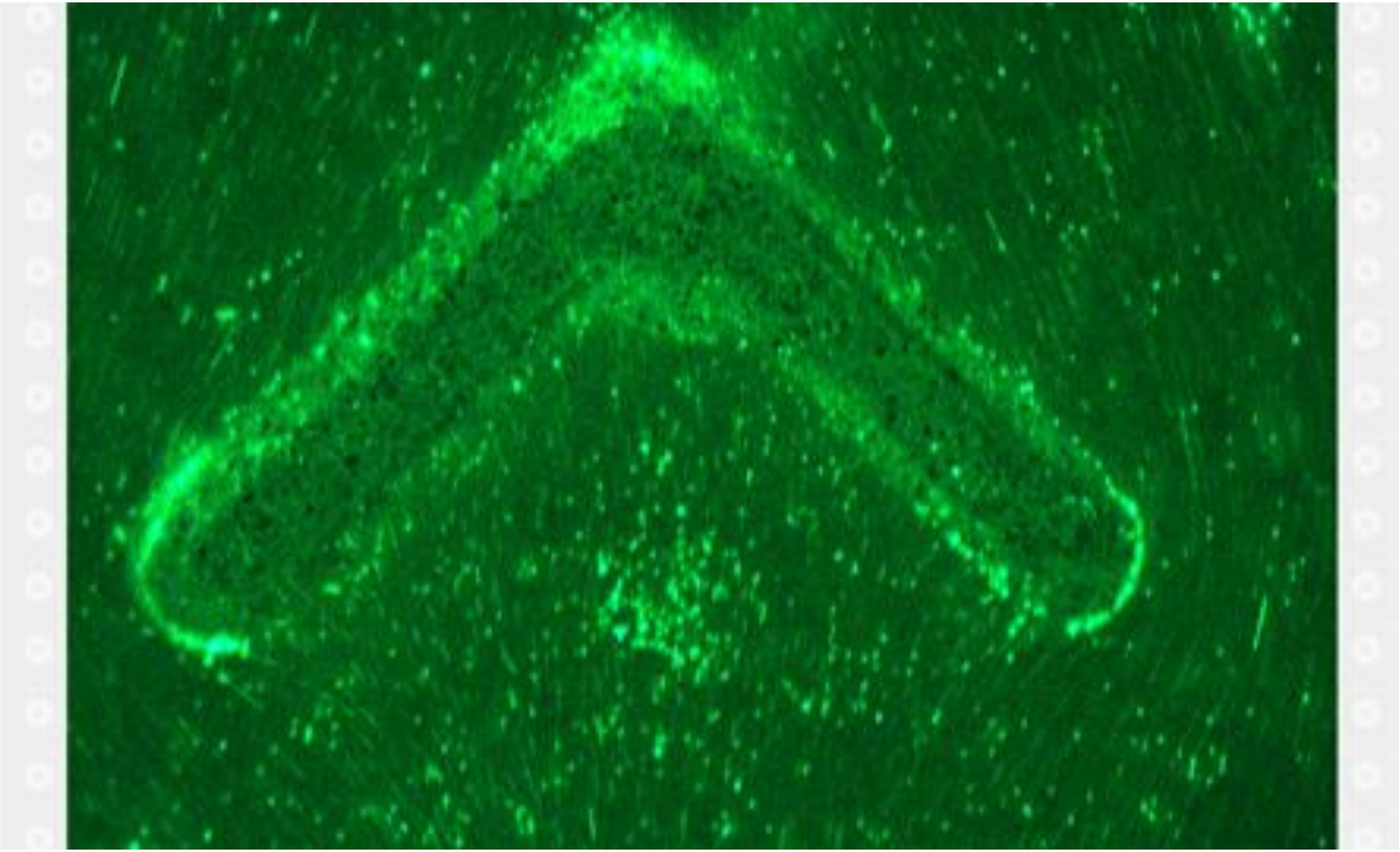


# Visual flow profile at front of chevron

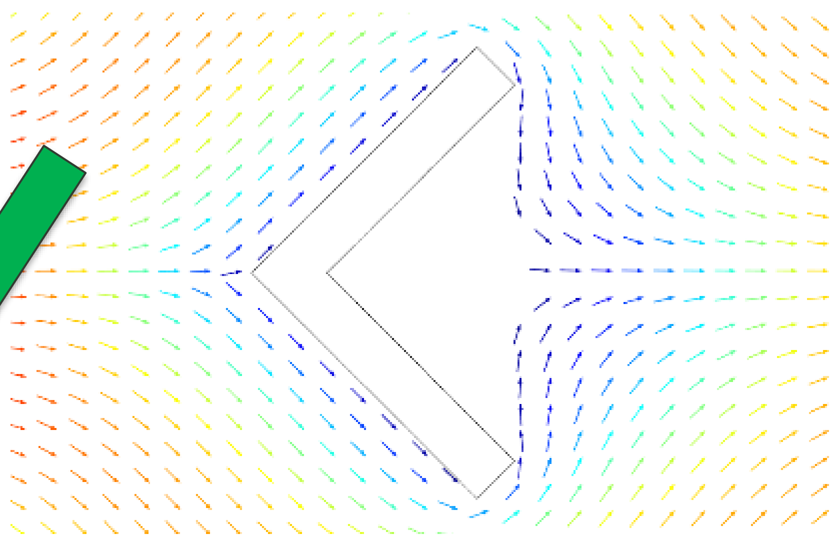


# VISUAL FLOW PROFILE OF CHEVRON



# Research Aim 2: Conclusions

- Successfully printed on the membrane surface without intrinsic properties of membrane being damaged



- Visual observations were consistent with fluid flow profile from computational modeling

# QUESTIONS ?