# Developing a Microfluidic Nozzle to Generate Water Sheet Jets for Cooling Sharp Leading Edges


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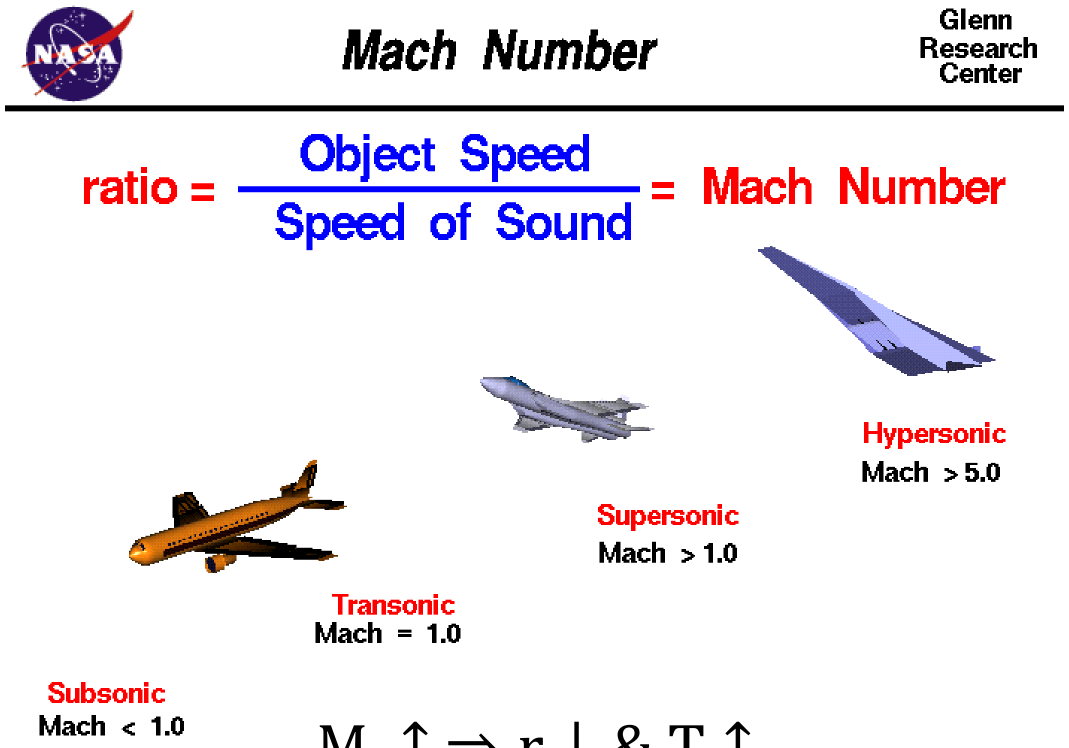
**MSc Research seminar**
**Under the supervision of Asst. Prof. Alexandros Terzis**

Thermo Fluids & Interfaces Lab

DEPARTMENT OF AEROSPACE ENGINEERING | TECHNION Israel Institute of Technology

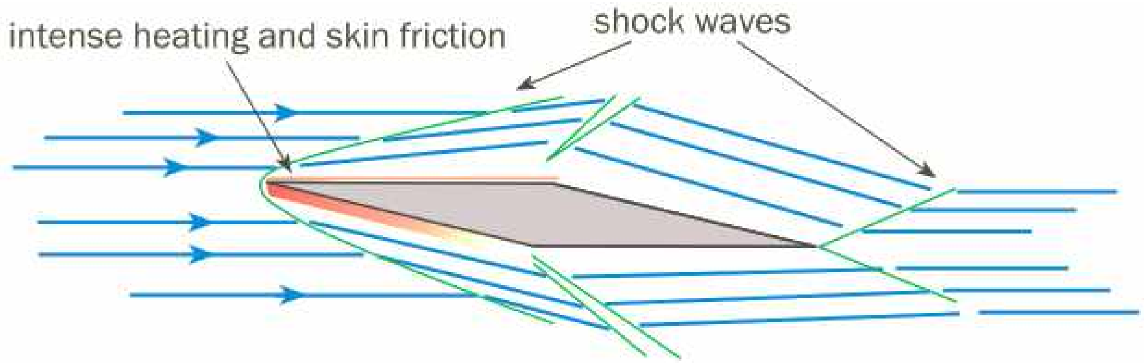
# Hypersonic flight and aerodynamic heating




$$M \uparrow \Rightarrow r \downarrow \,\&\, T \uparrow$$

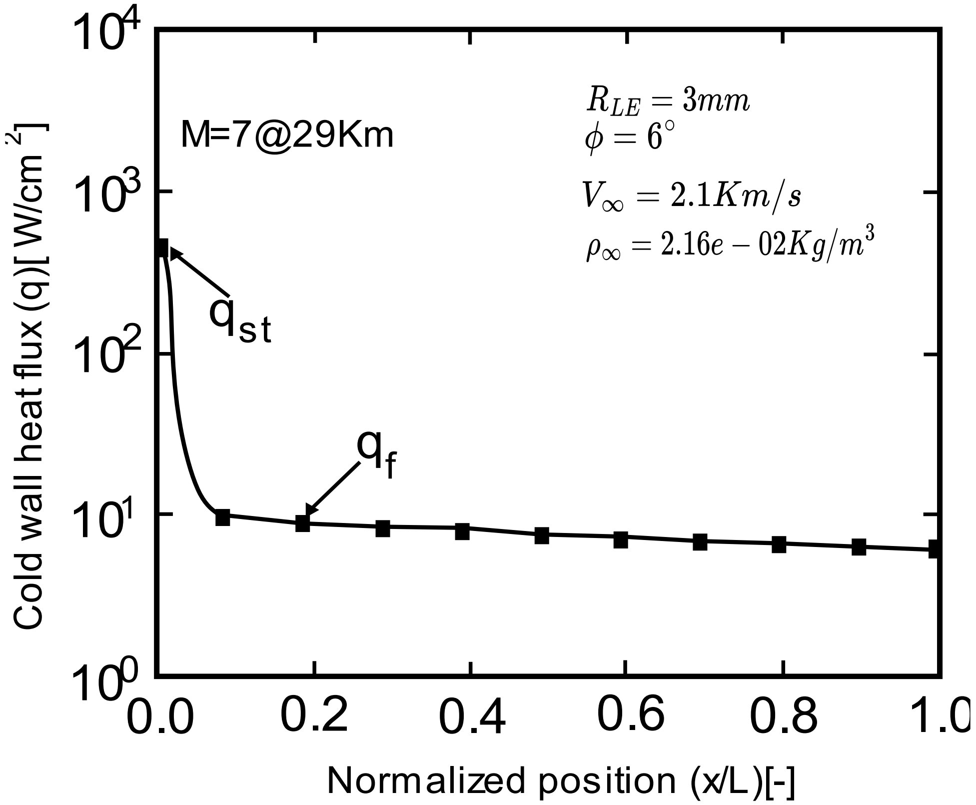
$$T_o = T\left(1 + \frac{\gamma - 1}{2} M^2\right)$$

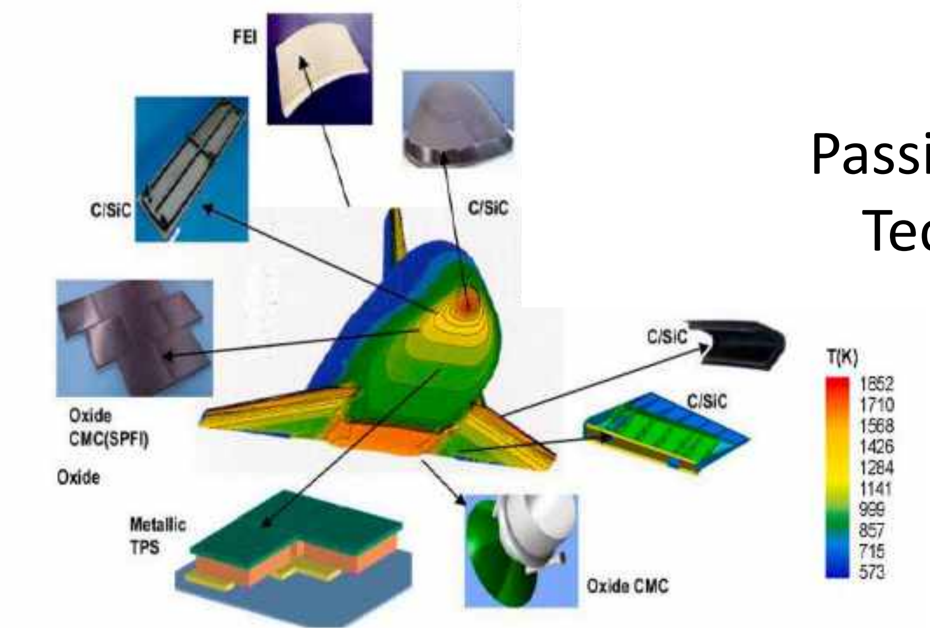
- Intensified flow phenomena
  - Viscous interaction
  - High temperature



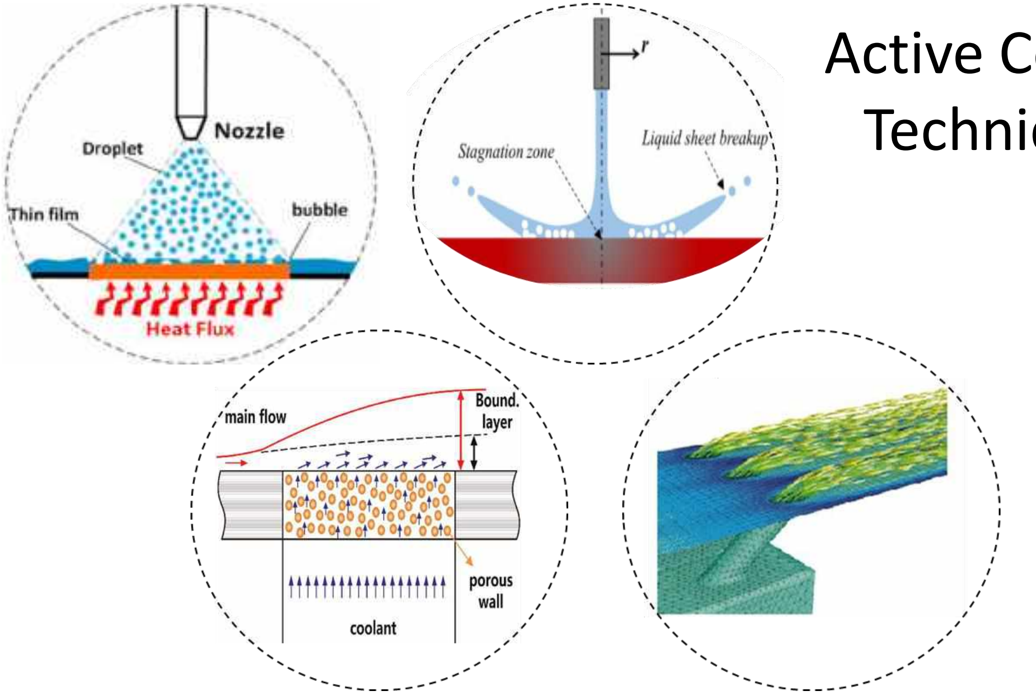

- $\uparrow$Aerodynamic heating$\rightarrow\downarrow$ L/D

# Aerodynamic heating on LE



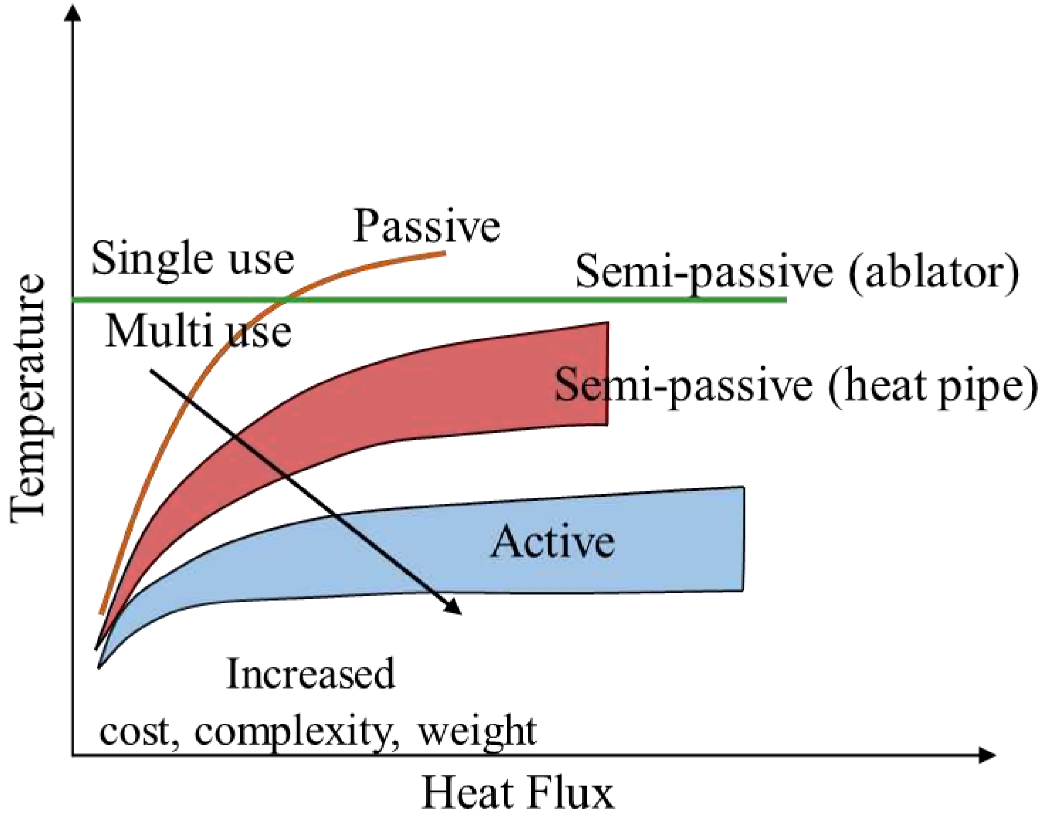



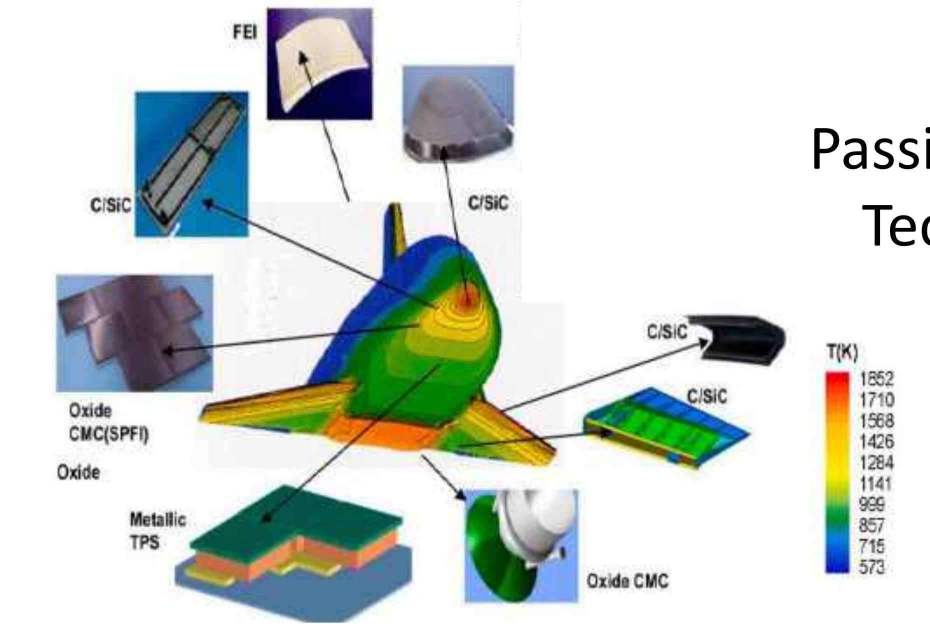

Passive Cooling Techniques




Active Cooling Techniques

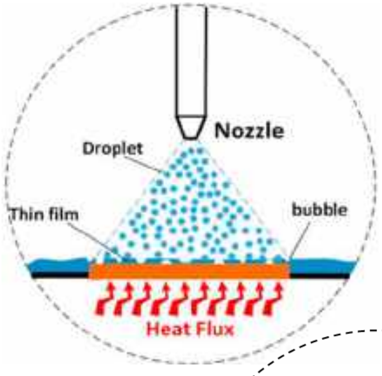
# Aerodynamic heating on LE

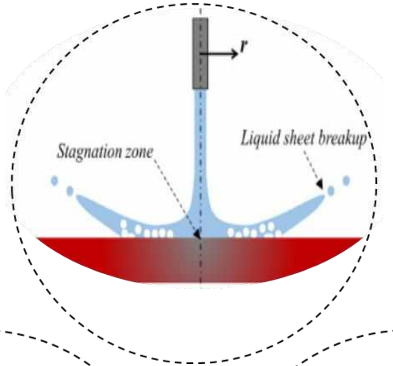


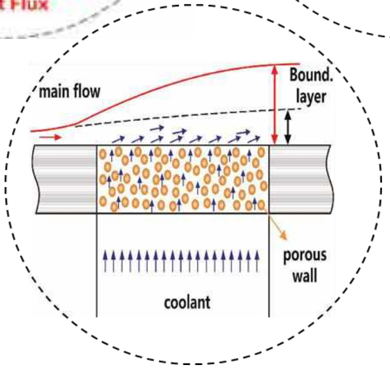



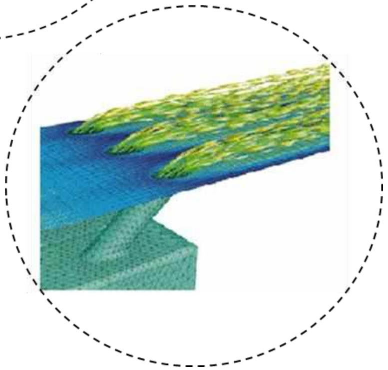

Passive Cooling Techniques

Active Cooling Techniques



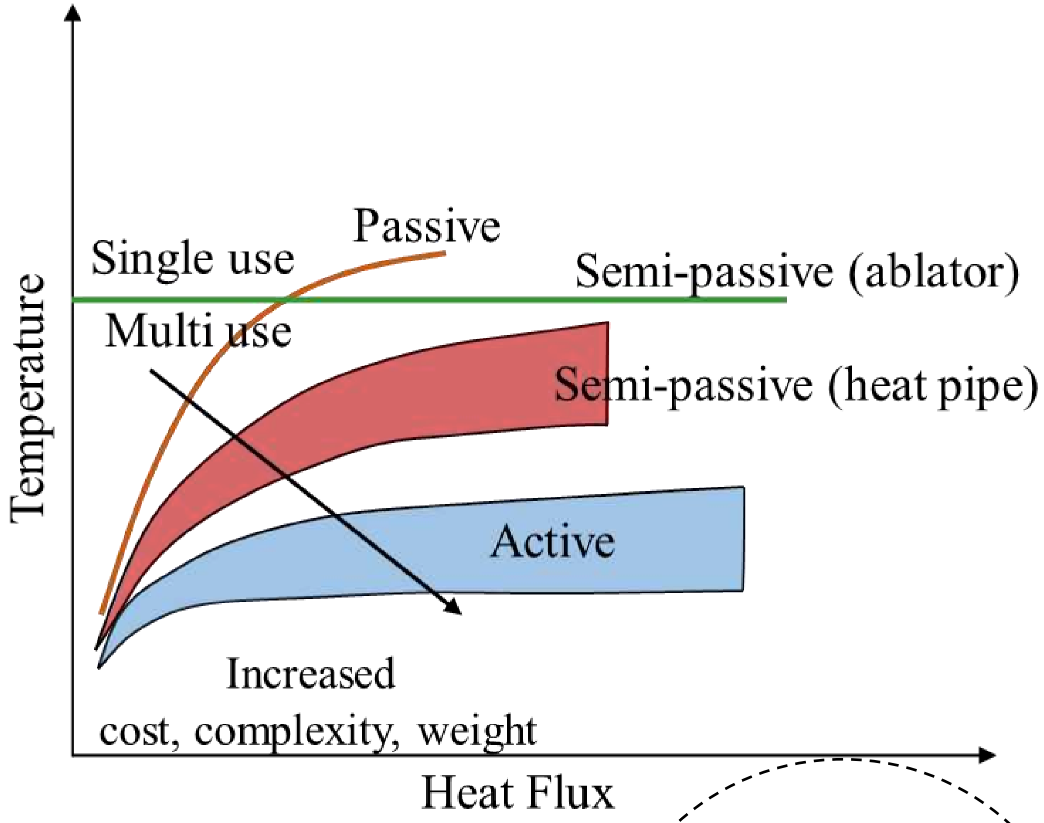



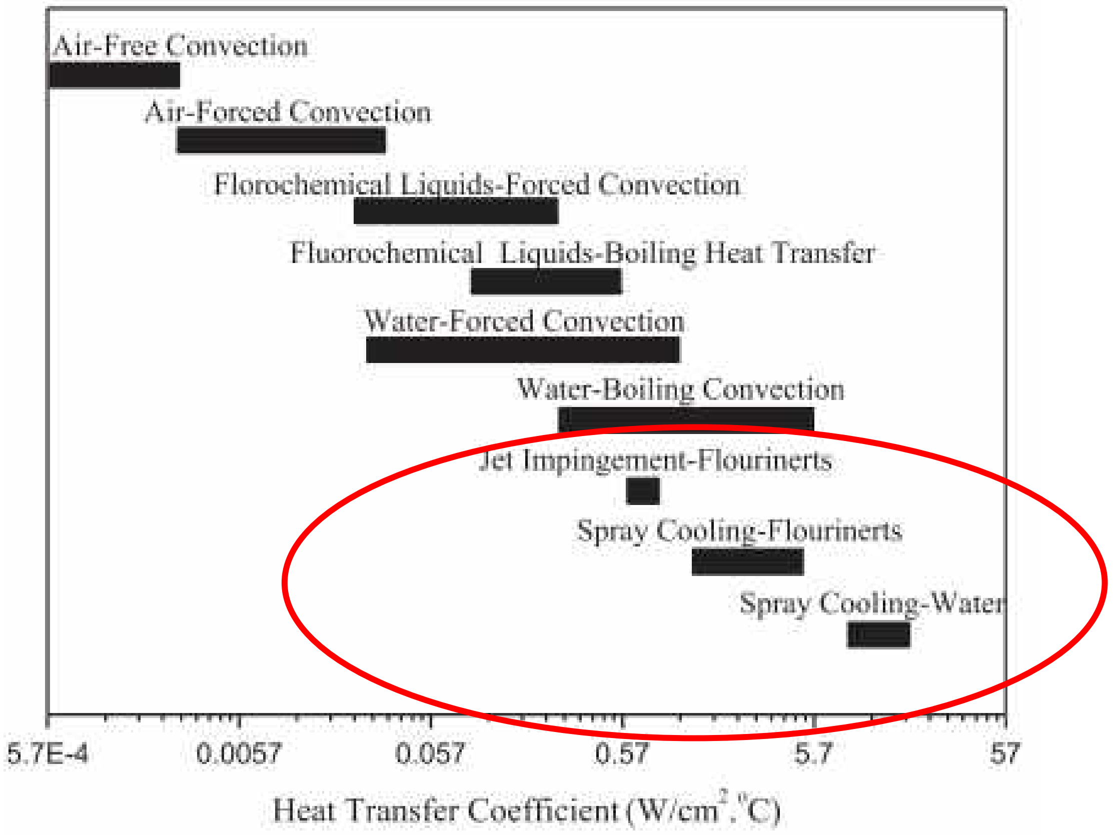



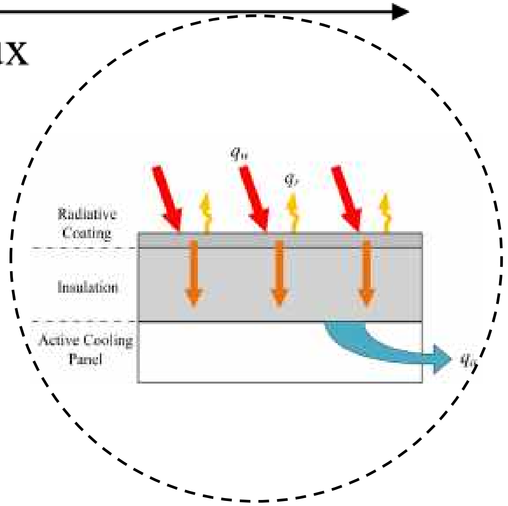
- Sustainable solution
- Effective handling of high T and q”
- Active-Passive combination

# Aerodynamic heating on LE




Hybrid Method




**Challenges:**

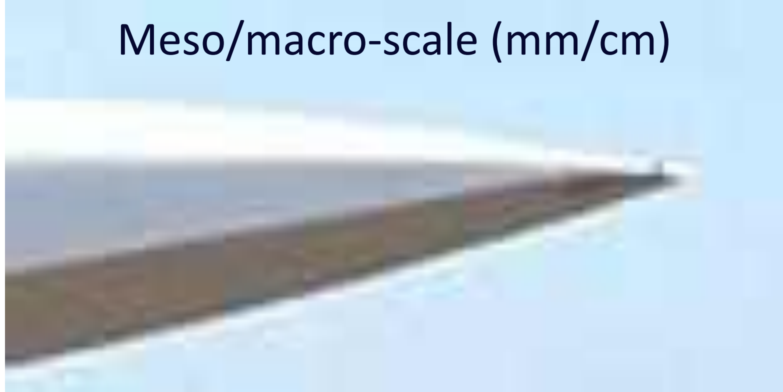
- Confined LE (1-3 mm radii)
- Extreme thermal loads
- Insufficient Passive TPS

# MSc Research Objective & Methodology

**Motivation**: Make hypersonic flights feasible

- Maintain aerodynamic efficiency
- Effectively manage extreme thermal loads

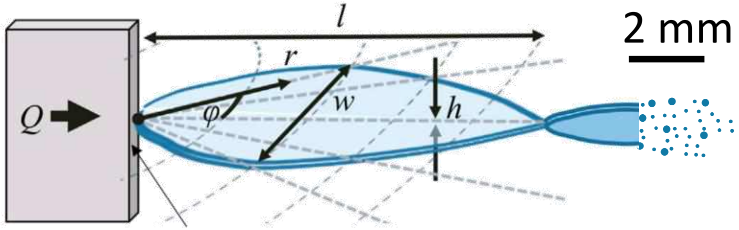

**Objective**: Develop an internal active cooling system for sharp and slender leading edges




**Methods**: Parametrically design and develop a microfluidic device for liquid sheet/spray cooling to characterize the:

- Dynamics of liquid sheets
- Jet & spray breakup

Micro/meso-scale (µm/mm)




Nozzle Exit | Primary Sheet | Secondary Sheet/spray

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# Presentation Outline

1. Introduction
2. **Liquid sheets**
3. Experimental Methods
4. Numerical Methods
5. Results
6. Summary and Conclusions

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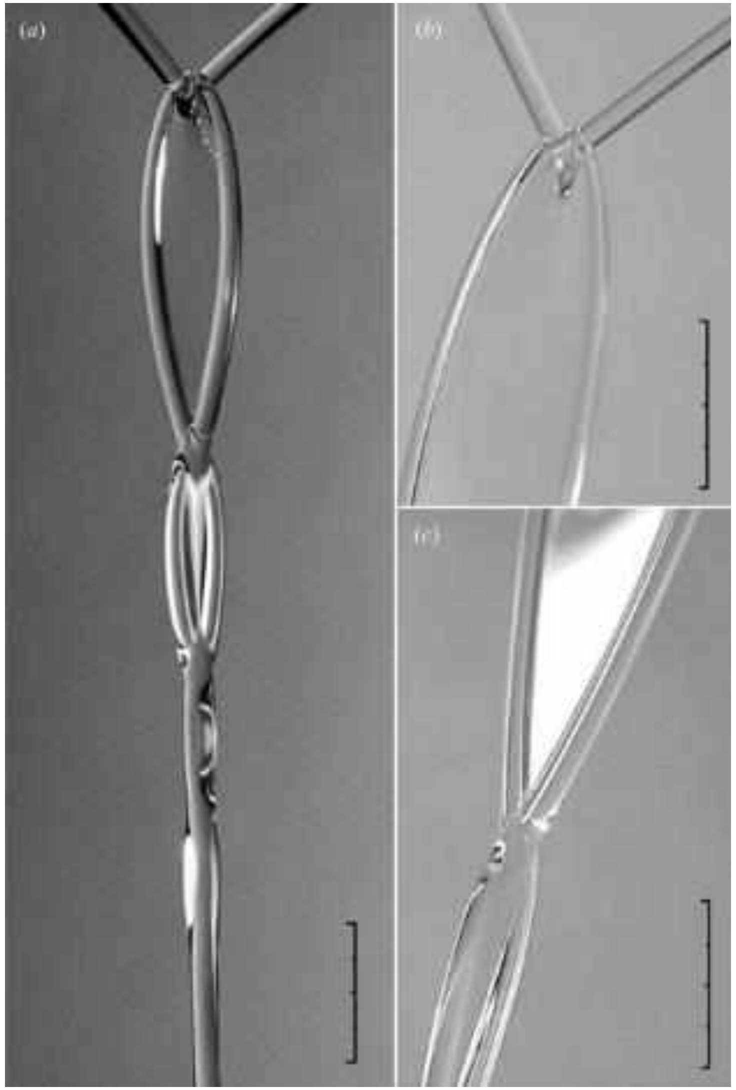
# Liquid sheet formation

- Collision of two identical, high Re & coplanar jets at an oblique angle
- Dynamics dominated by surface tension & inertia
- Liquid sheet generation perpendicular to the plane of incidence
- Leaf-shaped links, formed in mutually orthogonal planes

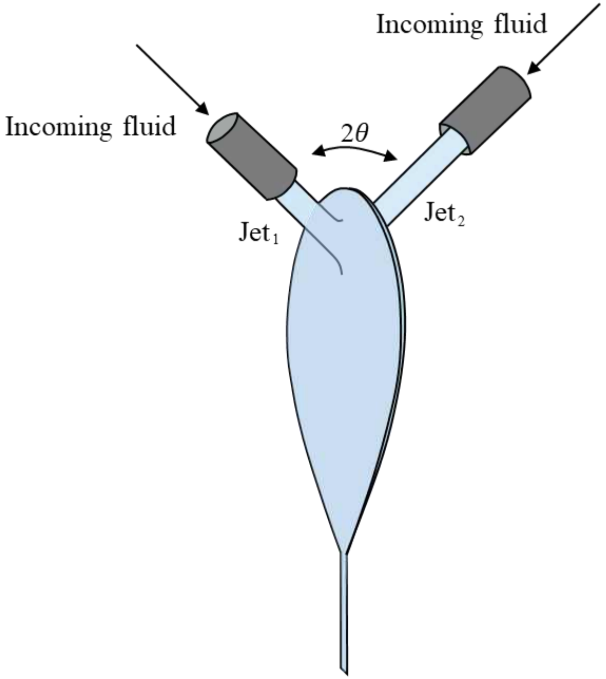


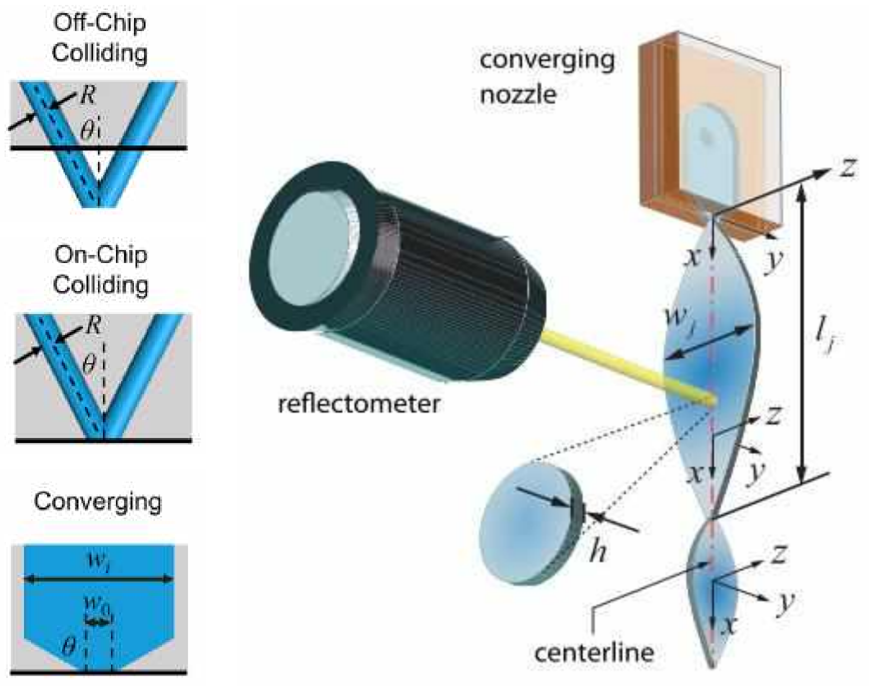
A fluid chain resulting from the collision of a pair of identical laminar jets of a glycerol–water solution. Scale bar: 1cm

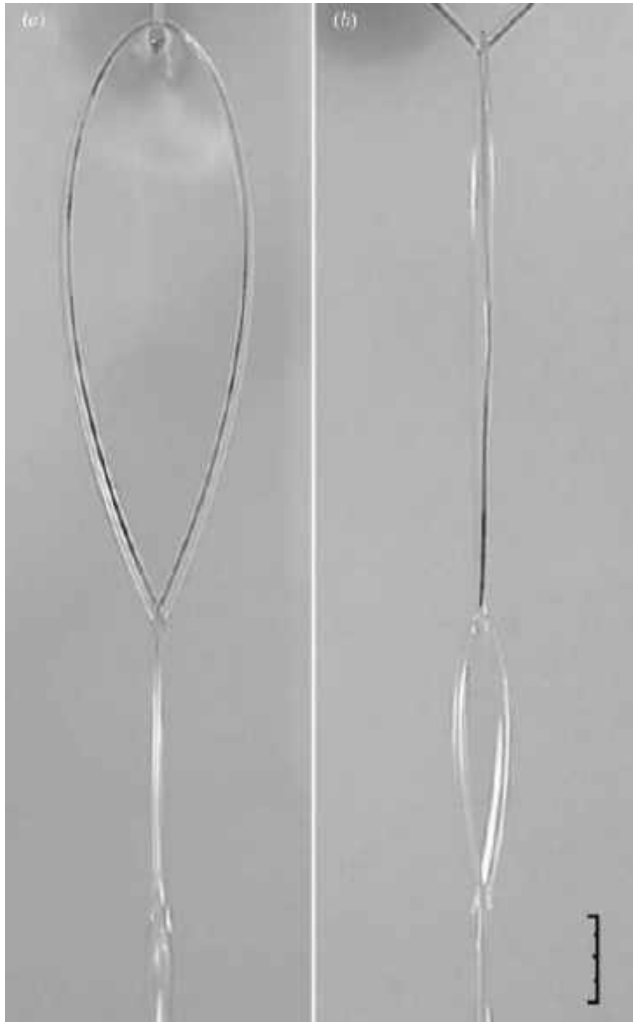
# Liquid sheet generation

- Impinging jets approach
  - Instabilities due to jet collision
  - Higher sensitivity to external perturbations
  - Jet misalignment

- In-chip flow-channels approach



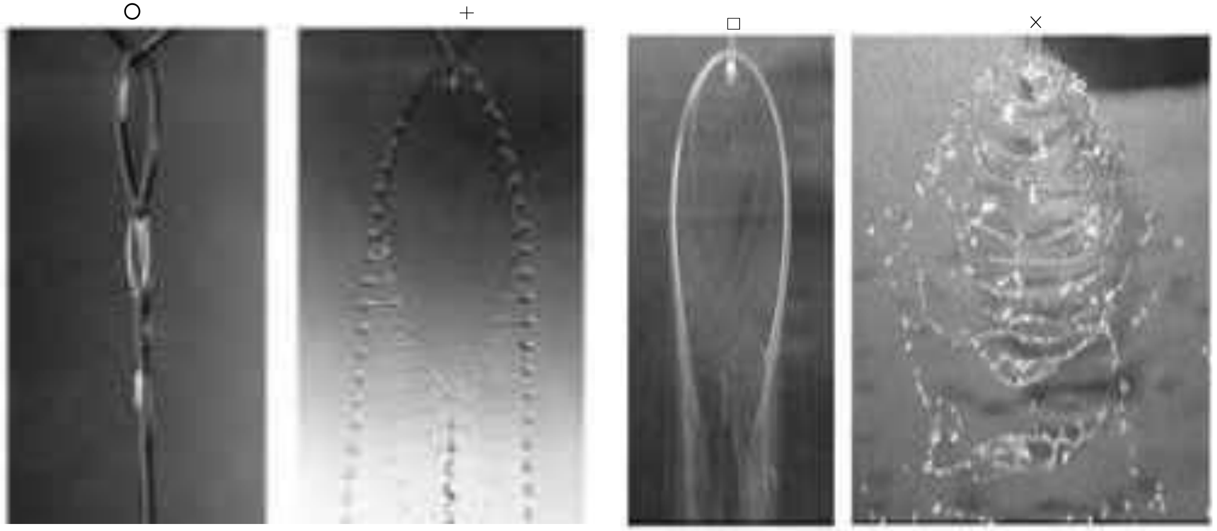
Front & side views of the fluid chain resulting from the collision of a pair of identical laminar jets[10]

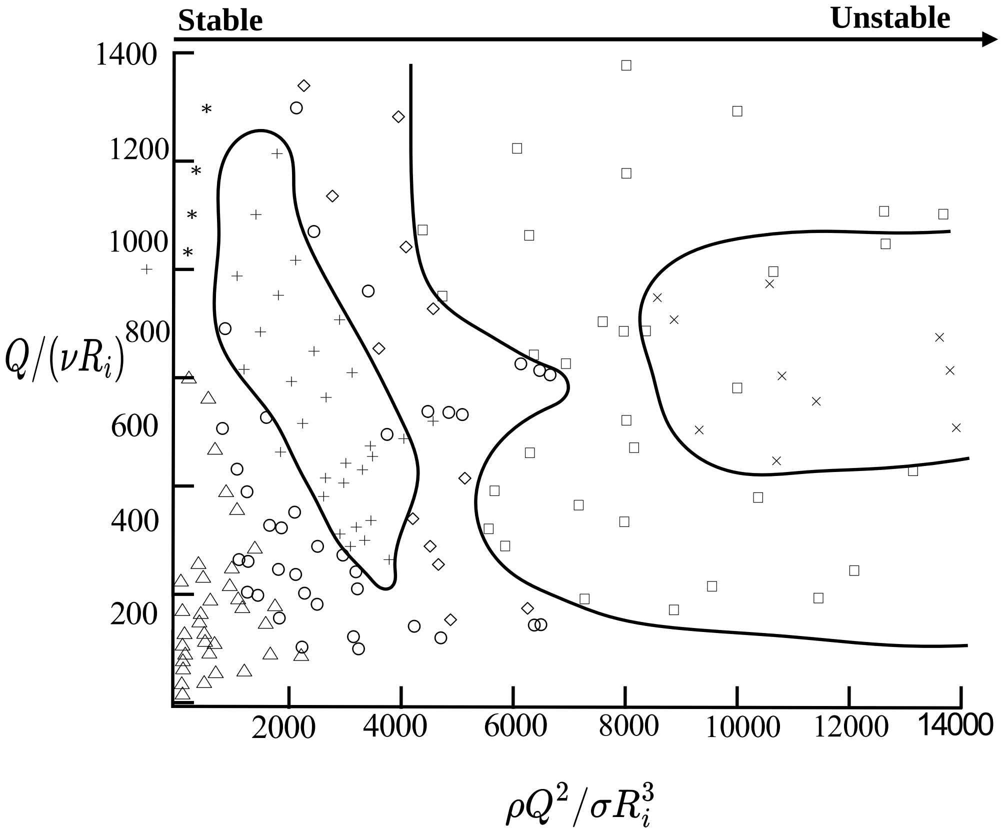
# Liquid sheet morphology

- Dynamics described by Reynolds (Re) & Weber (We) numbers

$$\mathrm{Re} = \frac{Q}{\nu R_j} \quad \& \quad \mathrm{We} = \frac{\rho Q^2}{\sigma R_j^3}$$

| Symbol | Behaviour |
|---|---|
| △ | Oscillating streams |
| ⋆ | Sheets with disintegrating rims |
| ∘ | Fluid chains |
| + | Fish-bones |
| ◇ | Spluttering chains |
| □ | Disintegrating sheets |
| × | Violent flapping |



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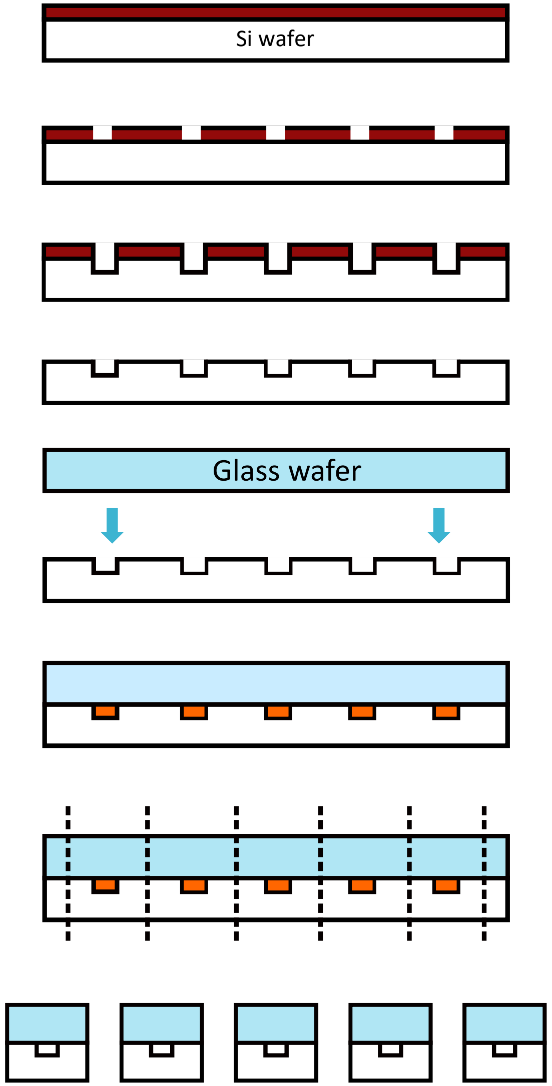
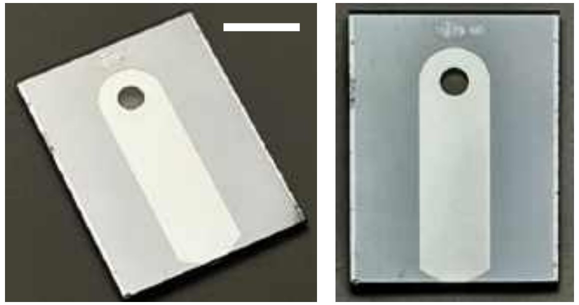
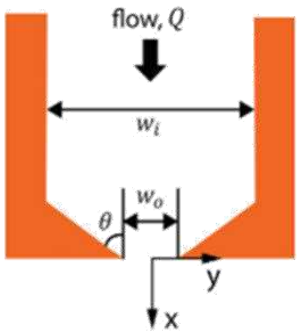
# Nozzle chips fabrication

1) Spin coat photoresist
2) Expose mask geometry and develop
3) Deep Reactive Ion Etching
4) Strip photoresist
5) Wafer alignment & Anodic bonding
6) Channel filling with wax
7) Dicing
8) Polishing



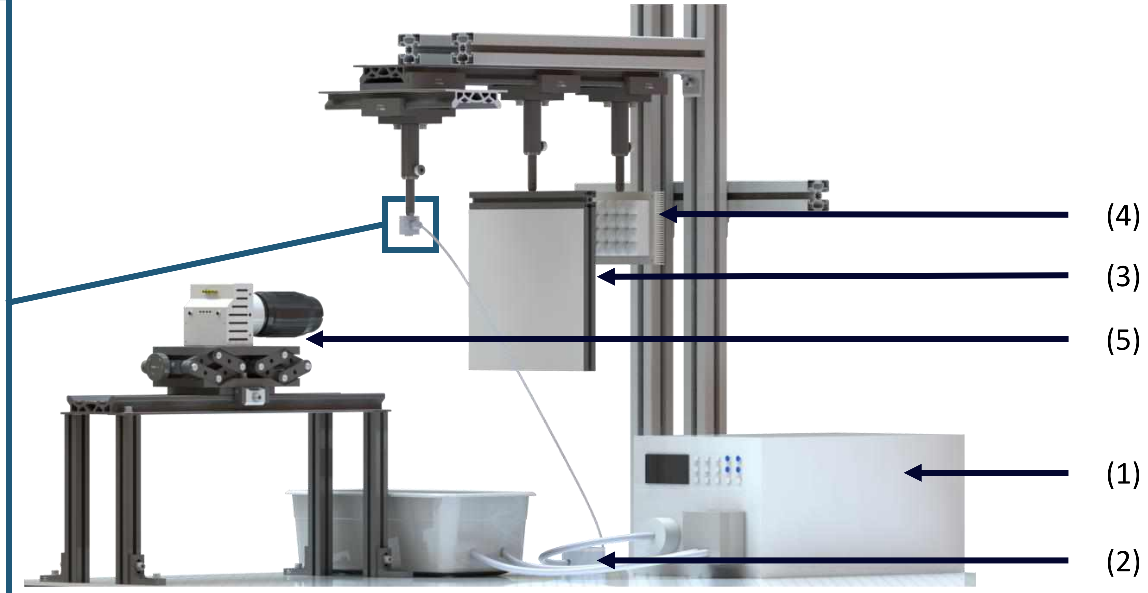



Scale bar: 5 mm




| | | | |
|---|---|---|---|
| Nozzle thickness | $t$ | μm | 50-150 |
| Outlet width | $w_o$ | μm | 250-1000 |
| Nozzle angle | $\vartheta$ | deg | 40-80 |
| Flow rate | $Q$ | ml/min | 20-100 |

# Shadowgraph Imaging setup


- HPLC dosing unit (1) with external pulse dampener (2) for DI water flow
- Backlight-diffused illumination (3 & 4) for shadowgraph imaging (5)
- 100 kHz framerate with 8.93 µs exposure time
- 70 µm/px optical magnification

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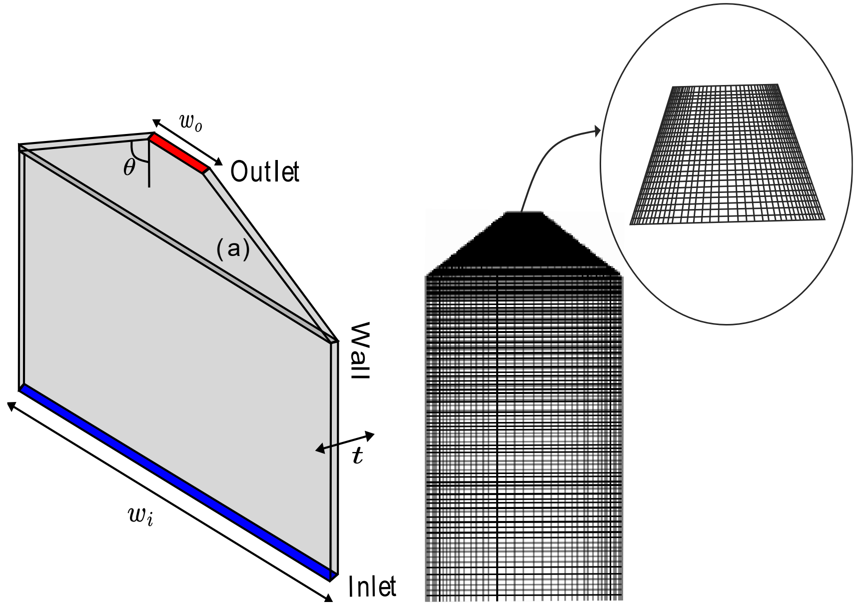
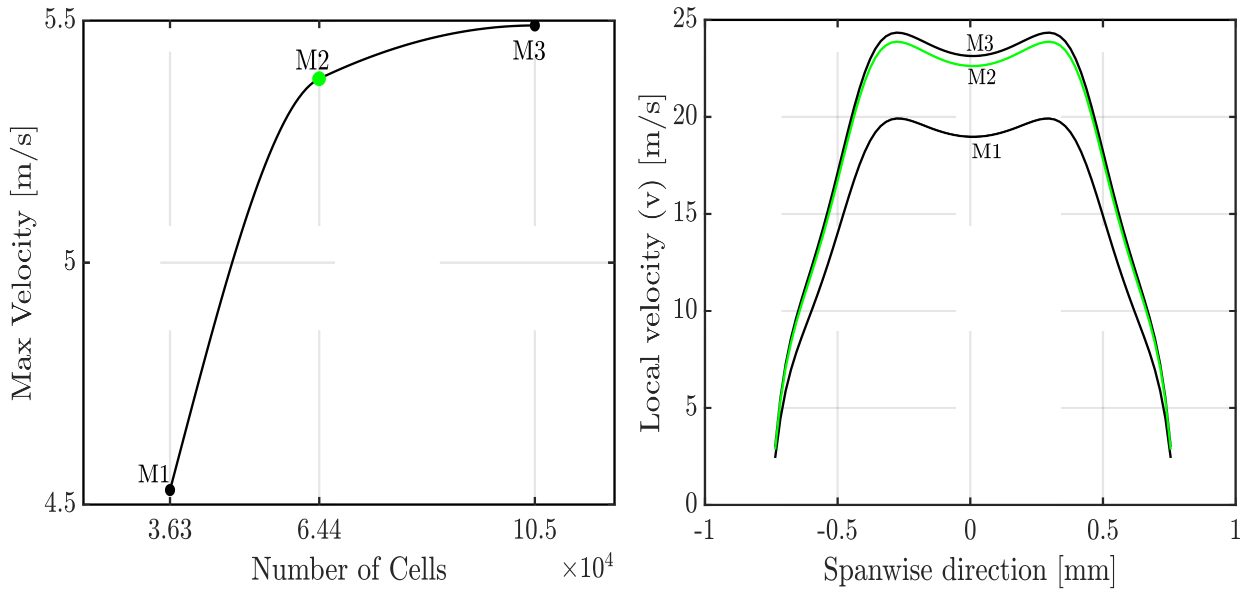
# Numerical simulation configuration

- ANSYS Fluent 2022 R1
- Grid Independence study
  - Longitudinal velocity profile evaluation
  - Outlet width - $w_o$ = 900 μm
  - Inlet width - $w_i$ = 4950 μm
  - Nozzle thickness- t = 60 μm
  - Nozzle angle - θ = 60°



# Numerical setup and validation

- ANSYS Fluent 2022 R1
- Steady, incompressible and laminar solver
- Residuals criterion: $10^{-6}$
- Validation with PIV measurements

$E_{mc}=\phi_m - \phi_c = 3.97$

$E_{mf}= \phi_f - \phi_m = 0.47$

r = 1.6

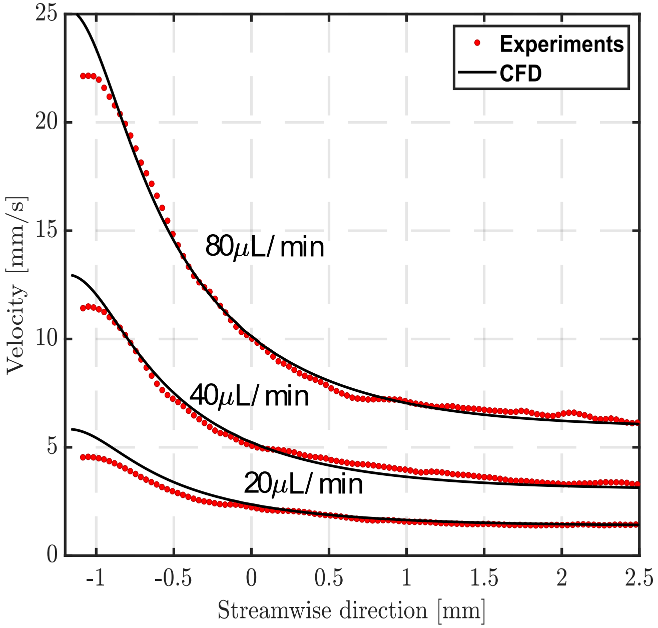
r: Grid refinement ratio

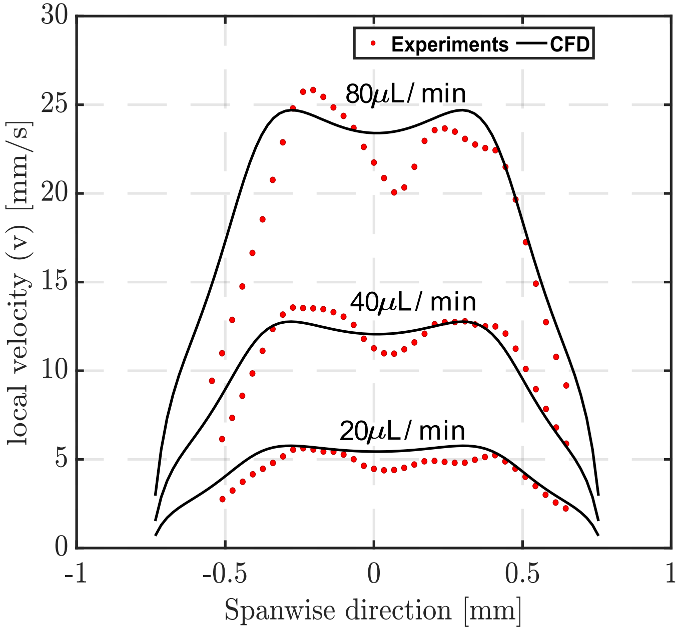
$$p=\frac{\ln\left(\frac{E_{mc}}{E_{mf}}\right)}{\ln(r)} = 4.54$$

p: Order of convergence

Grid Convergence Index (GCI)

$$GCI = \frac{E_{mf}}{E_f}\left(\frac{r^p}{r^p-1}\right) = \mathbf{1.135<5\%}$$



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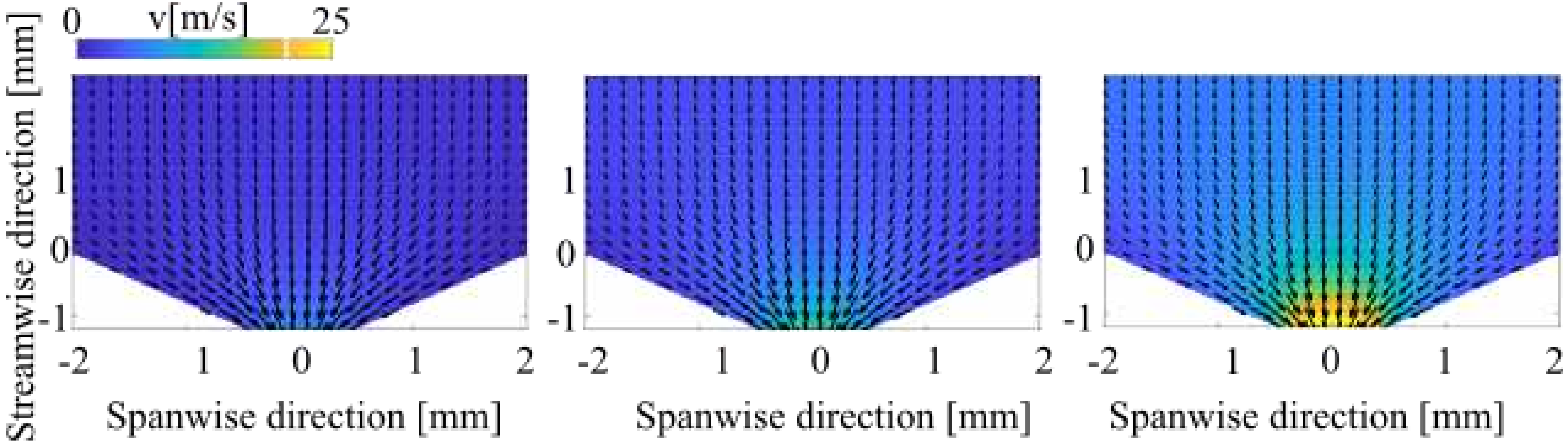
# Nozzle velocity field-CFD

- Similar velocity field characteristics
- Laminar flow despite high Re
- No indications of flow non-uniformities & present disturbances

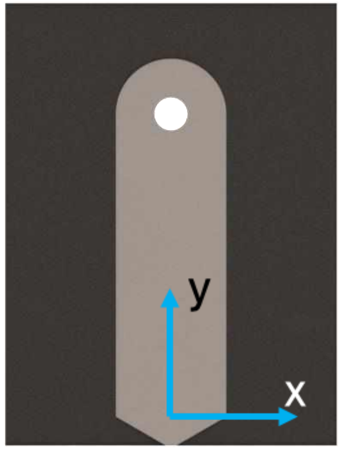


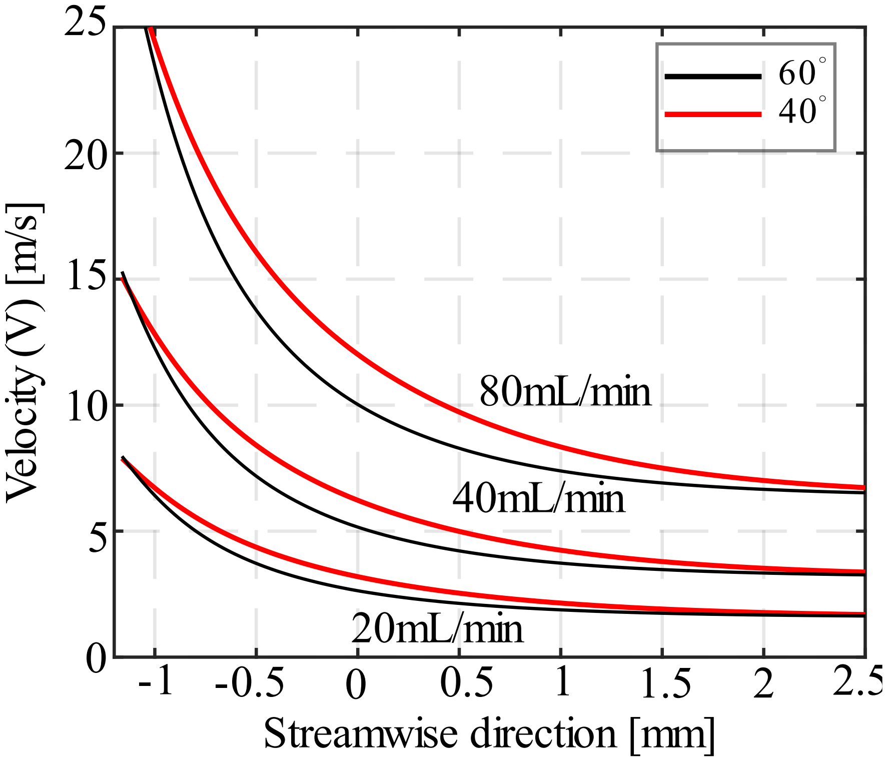

(a) (b) (c)

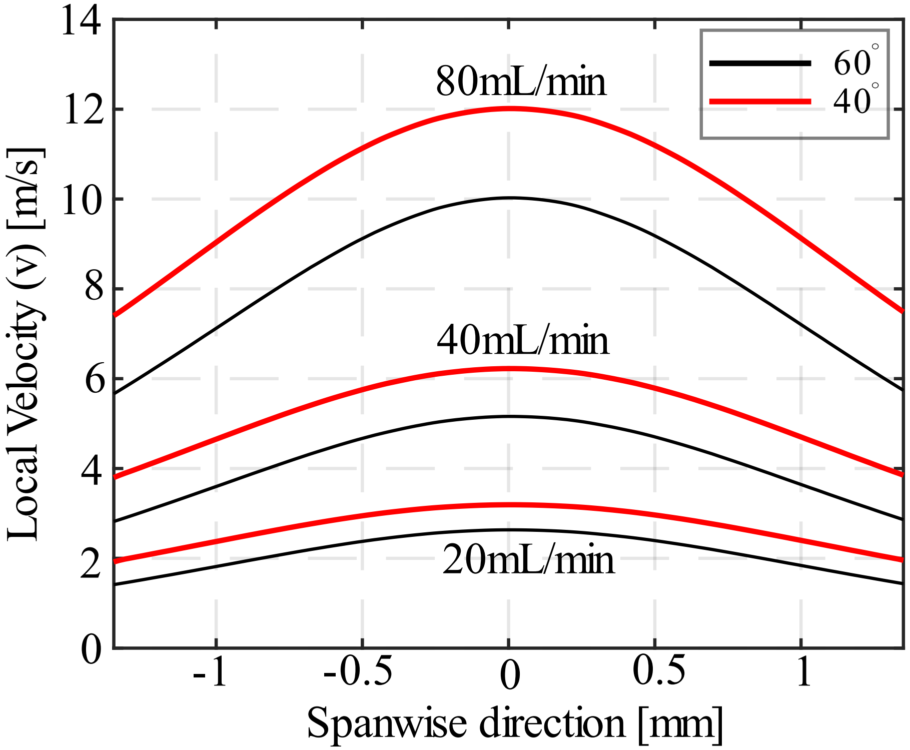
Comparison of longitudinal velocity contours and vector plots in the nozzle for varying flowrate (*Q* ) of a) 20mL/min, b) 40mL/min, c) 80mL/min

# Nozzle velocity field - CFD

- Parametric investigation of nozzle angle θ  variation effects
- Inversely analogous dependency between nozzle angle θ and the velocity field in the nozzle
- Exit velocity dependent only on outlet dimensions

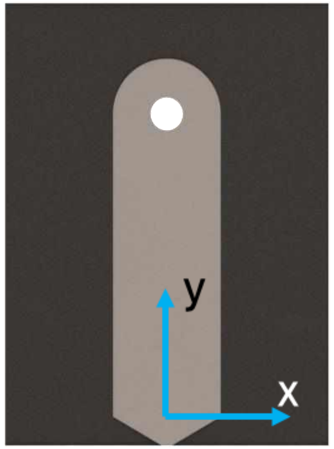


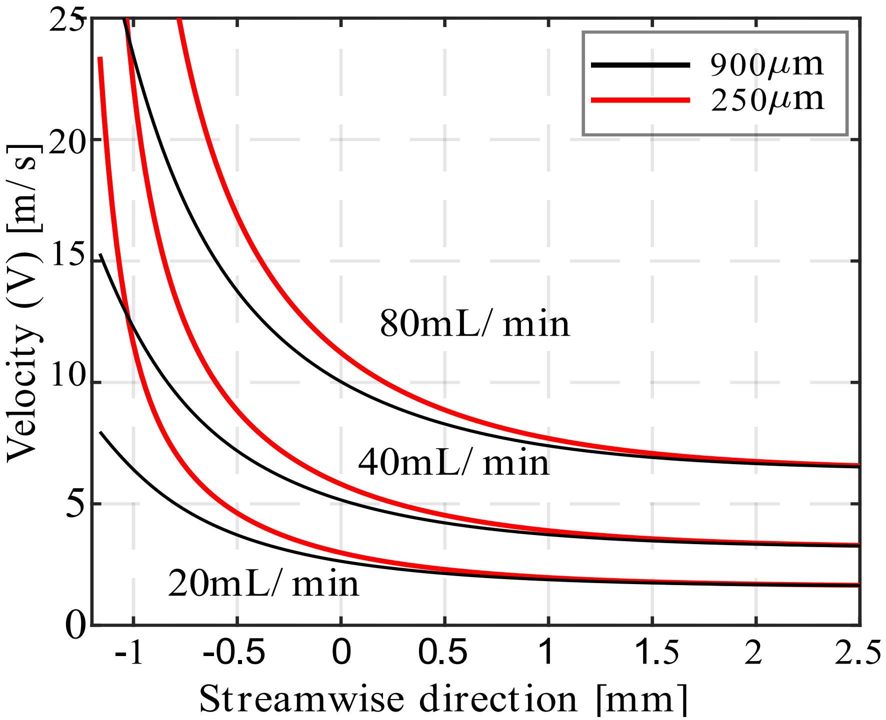



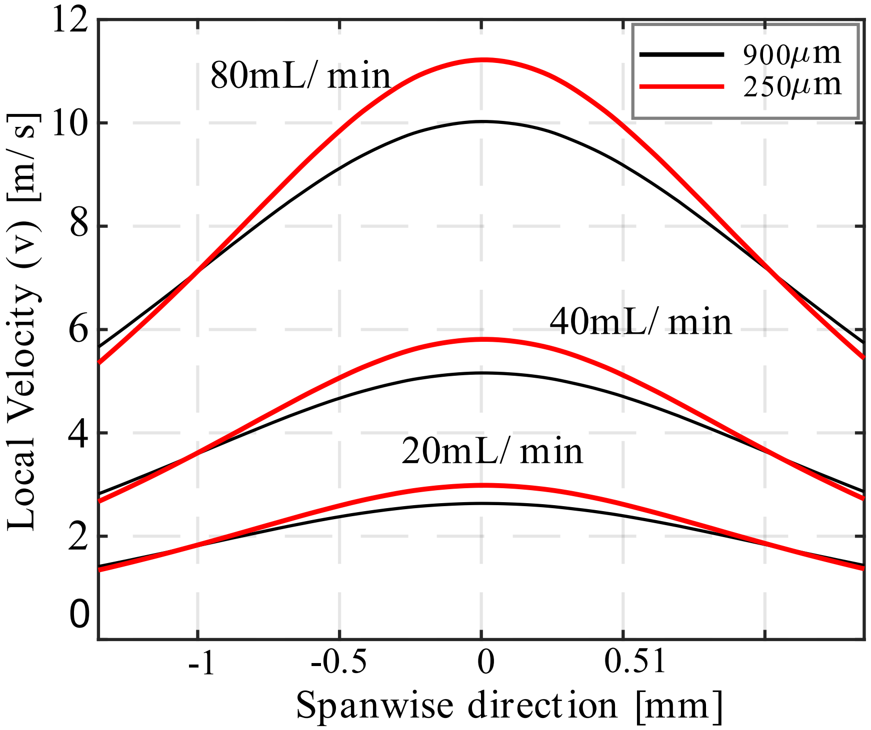



# Nozzle velocity field - CFD

- Parametric investigation of outlet width $w_o$ variation effects
- Inversely analogous dependency between outlet width $w_o$ and the velocity field
- Augmented exit velocity due to smaller outlet cross-sectional area



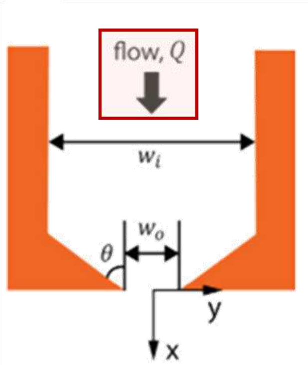



# Effect of Q-variation on sheet dynamics

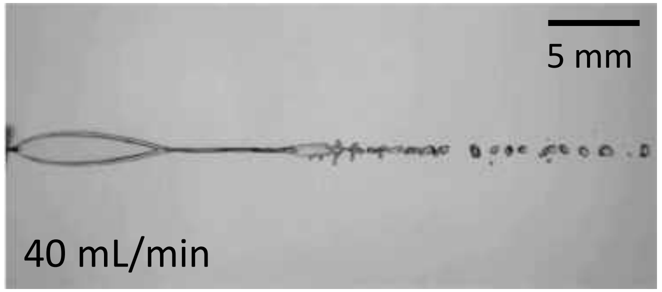
- Nozzle geometry
  - $w_o$ = 750 µm, θ = 40° and t = 100 µm
- Video playback speed – 1650 times slower

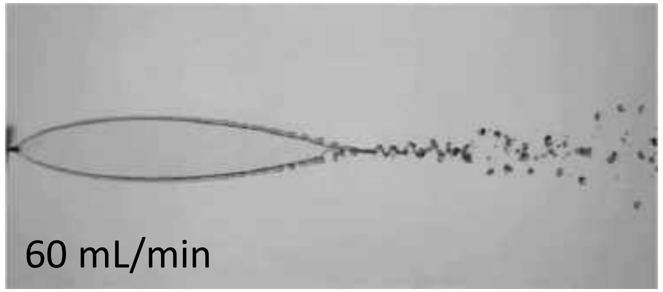
- Gradual rim thickness change
- Increasing length and width
- Decreasing number of links
- Rim breakup before the link's apex

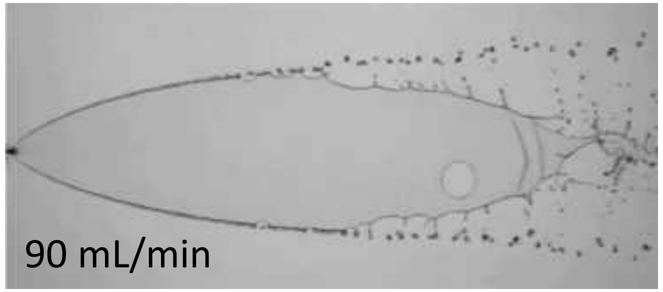



- Literature quantification of flowrate effects on liquid sheet size

$$\{l_s, w_s\}(Q) \sim We \cdot Ca^m$$



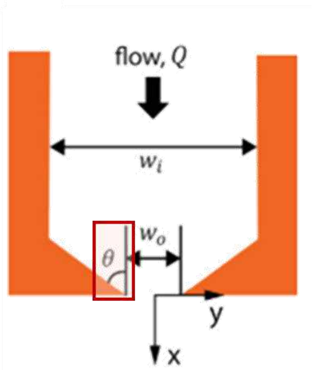



# Effect of θ-variation on sheet dynamics

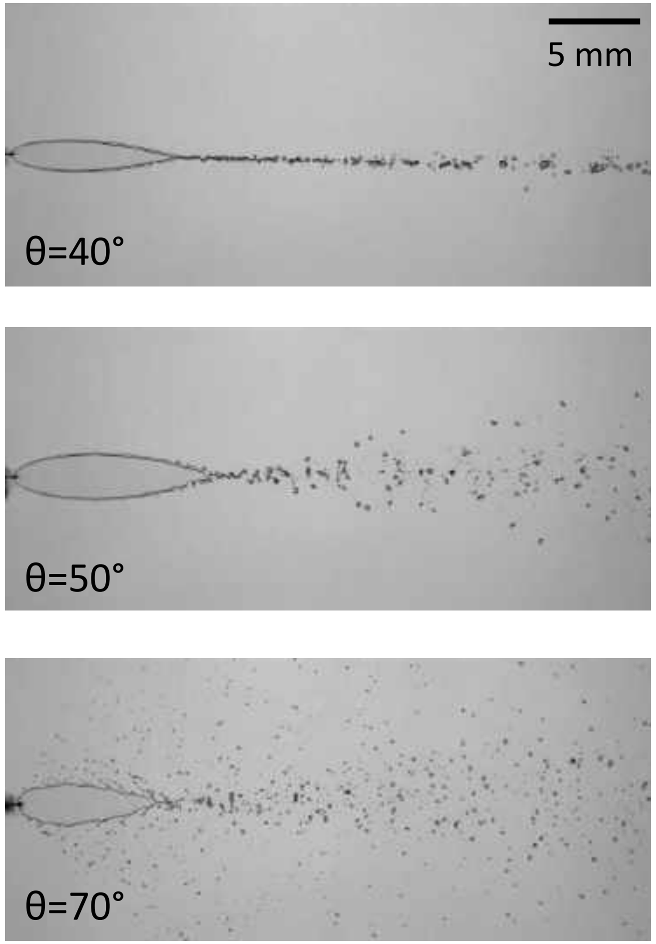
- Nozzle geometry and flow conditions
  - $w_o$ = 750 µm, Q=30 mL/min and t = 100 µm
- Video playback speed – 1100 times slower

- Length and width fluctuation
- Max sheet size at $\theta \approx 55°$
- Rim instability propagation with θ↑
- Drop shedding from rims at $\theta \geq 70°$




- Literature quantification of nozzle angle effects on liquid sheet size

$$\{l_s, w_s\}(\theta) \sim [1+\cot(0.67\theta)]^{-n}$$

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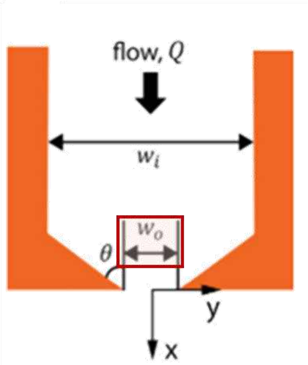
# Effect of $w_o$-variation on sheet dynamics

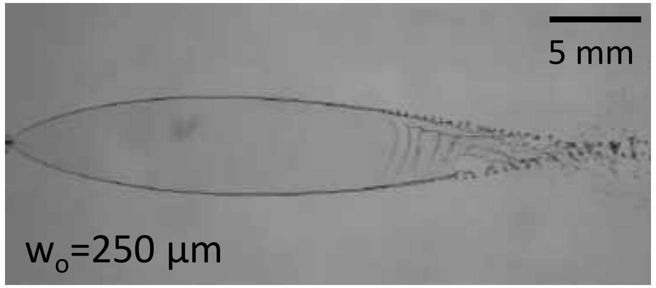
- Nozzle geometry and flow conditions
  - $\theta = 60°$, Q=60 mL/min and t = 150 µm
- Video playback speed – 1100 times slower

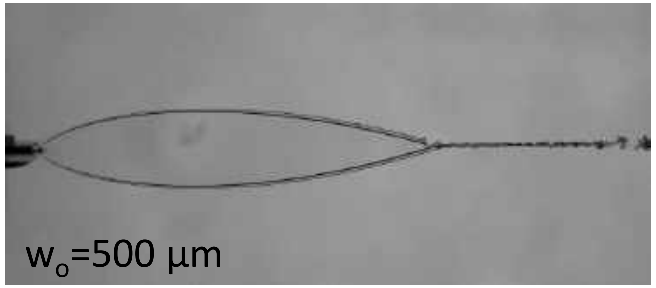
- $A_{ex}$ increase and $V_{ex}$ decrease
- Length and width decrease
- Instability damping & Breakup delay
- Shift from spray to jet breakup

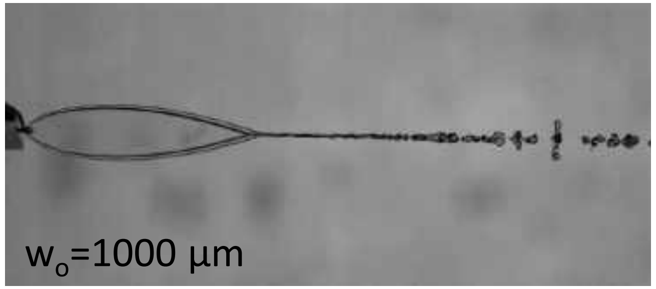



- Literature quantification of outlet width effects on liquid sheet size

$$\{l_s, w_s\}(w_o) \sim (1+1.5\alpha^2)^{-n}$$

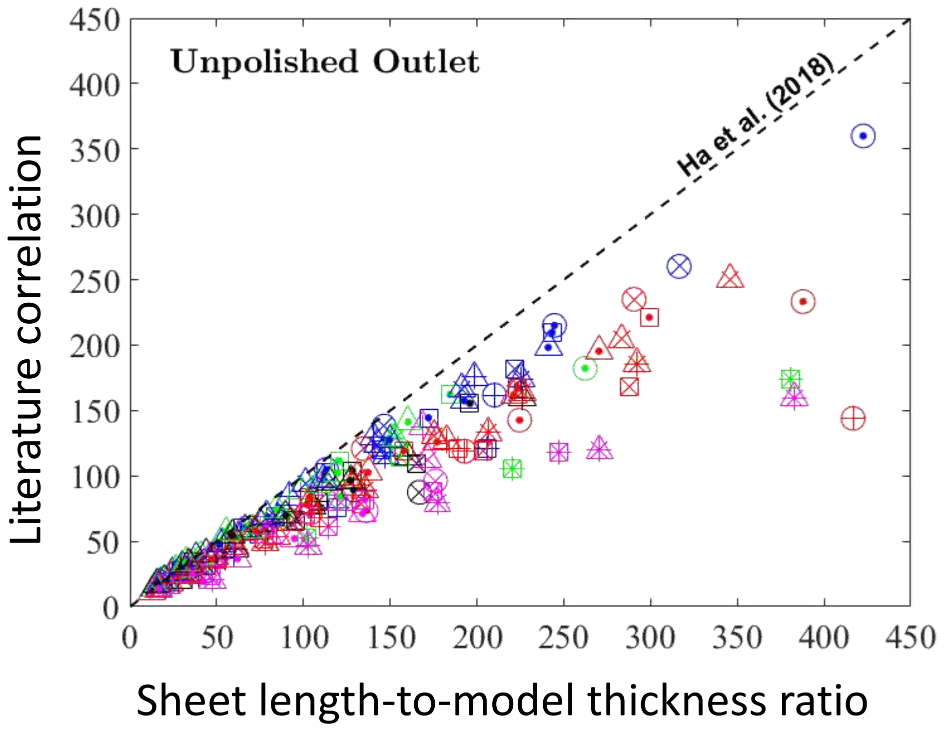


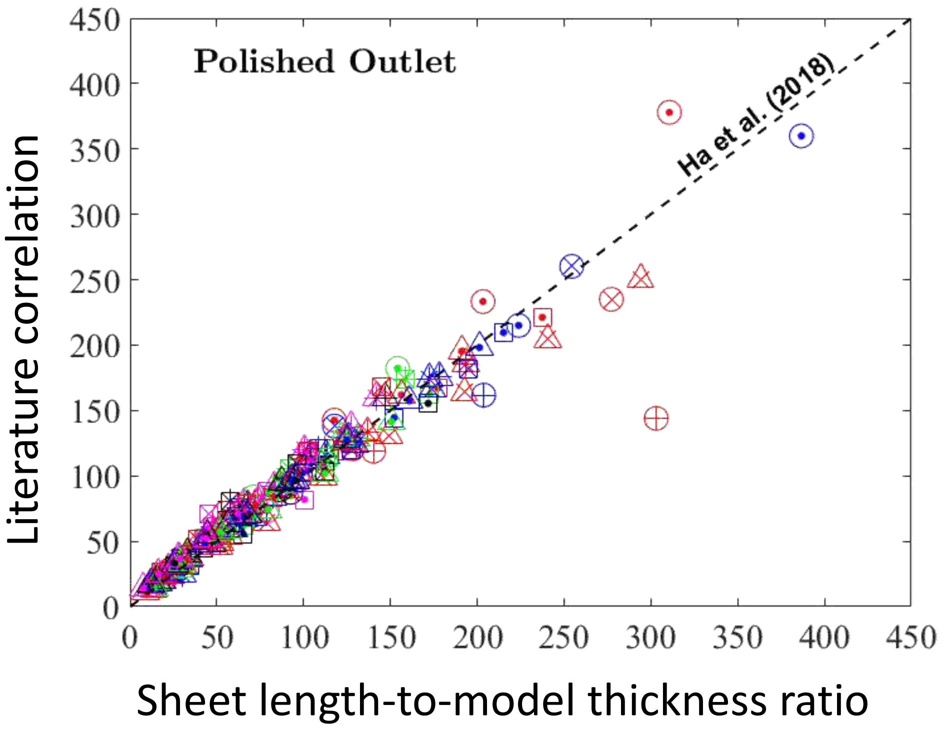



# Outlet polishing effects on sheet length

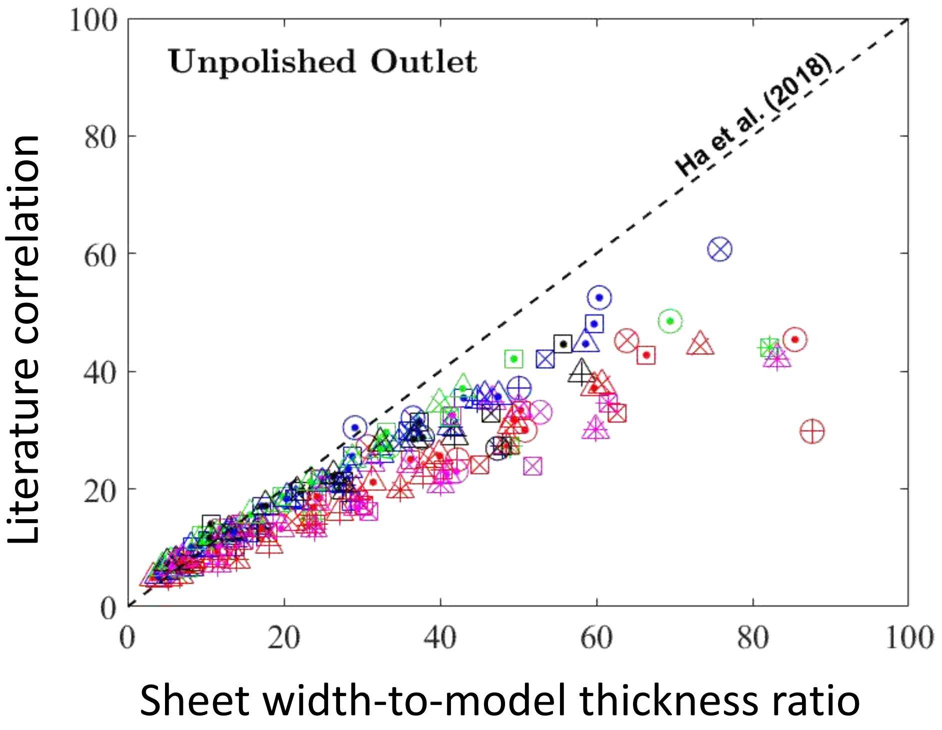
$$l_s/t = 0.23We \cdot Ca^{-0.1}(1+1.5\alpha^2)^{-0.5}[1+\cot(0.67\theta)]^{-0.5}$$

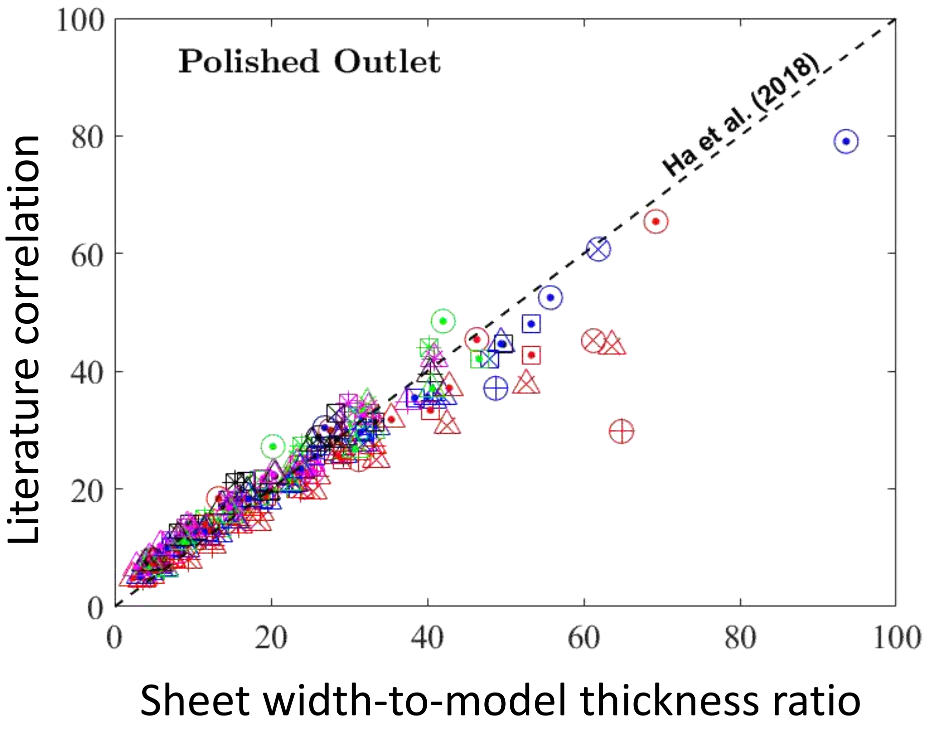


# Outlet polishing effects on sheet width

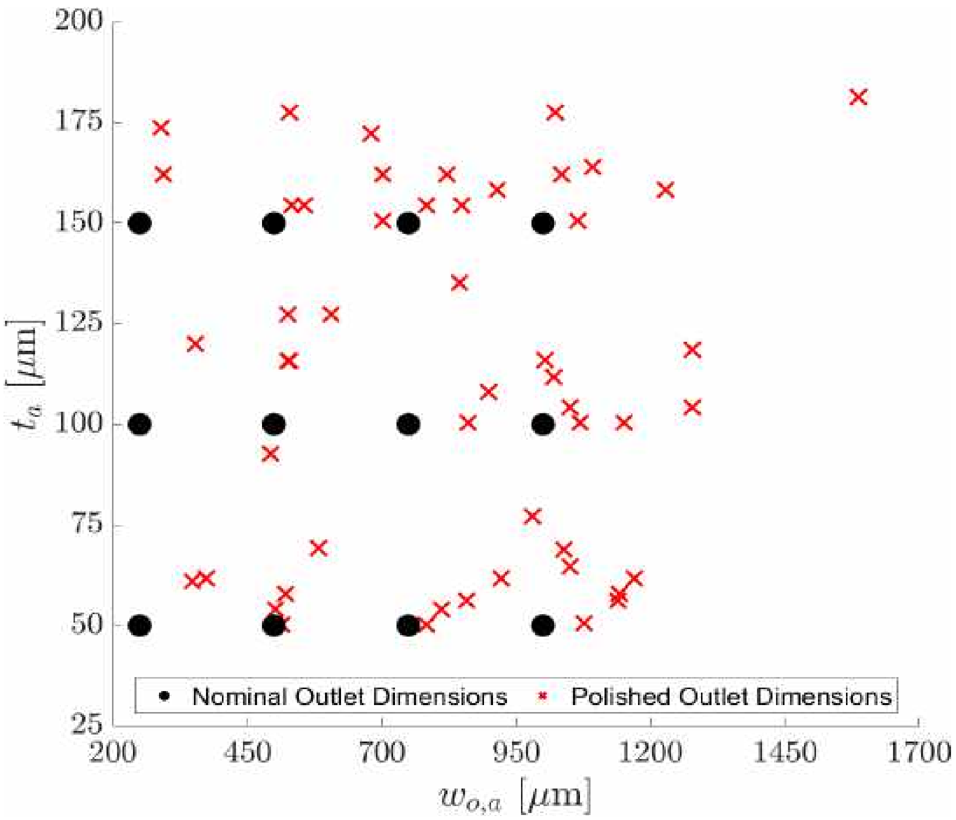
$$w_s/t = 0.074We \cdot Ca^{-0.2}(1+1.5\alpha^2)^{-1}[1+\cot(0.67\theta)]^{-1}$$

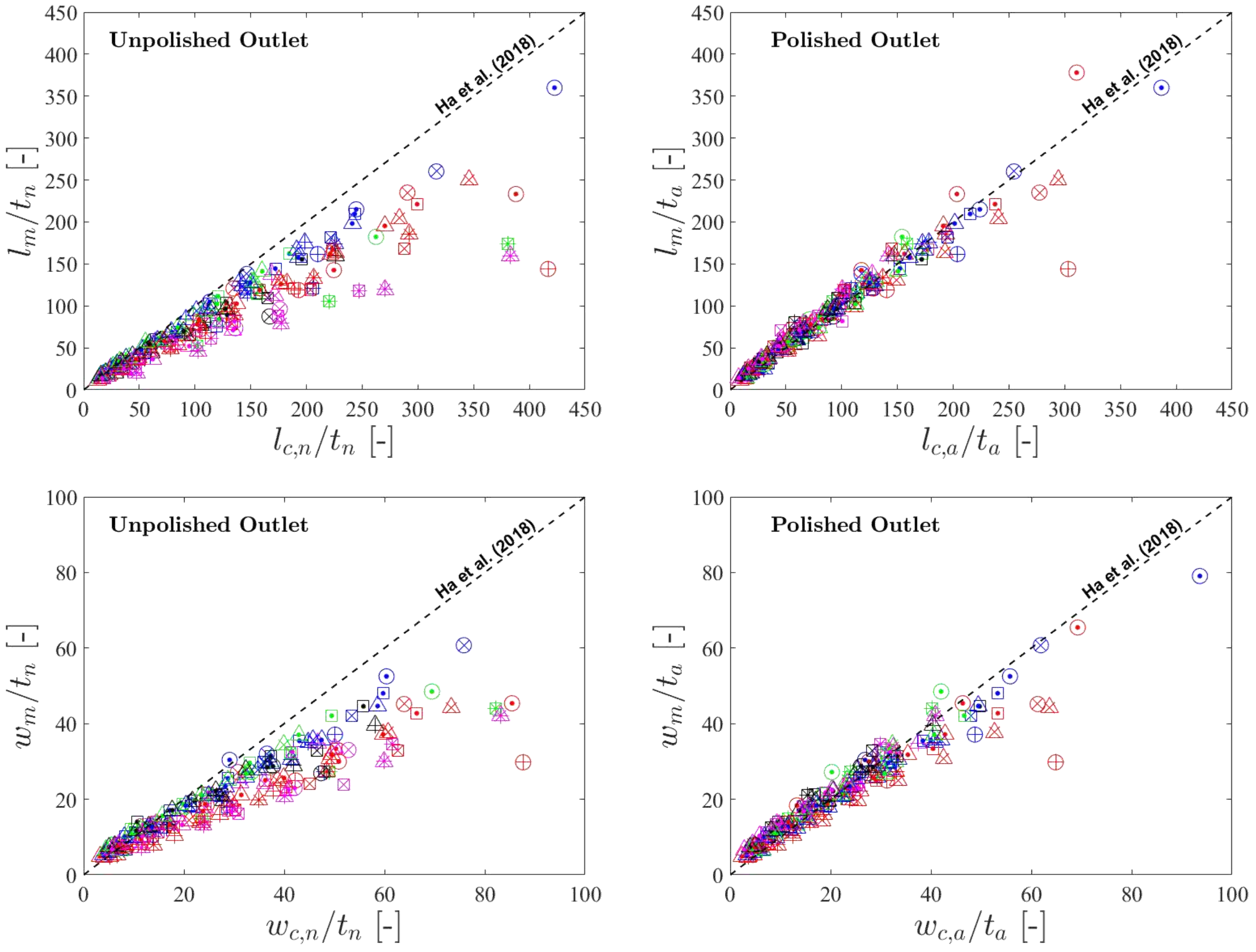


# Design point shift due to polishing

- Outlet dimensions increase

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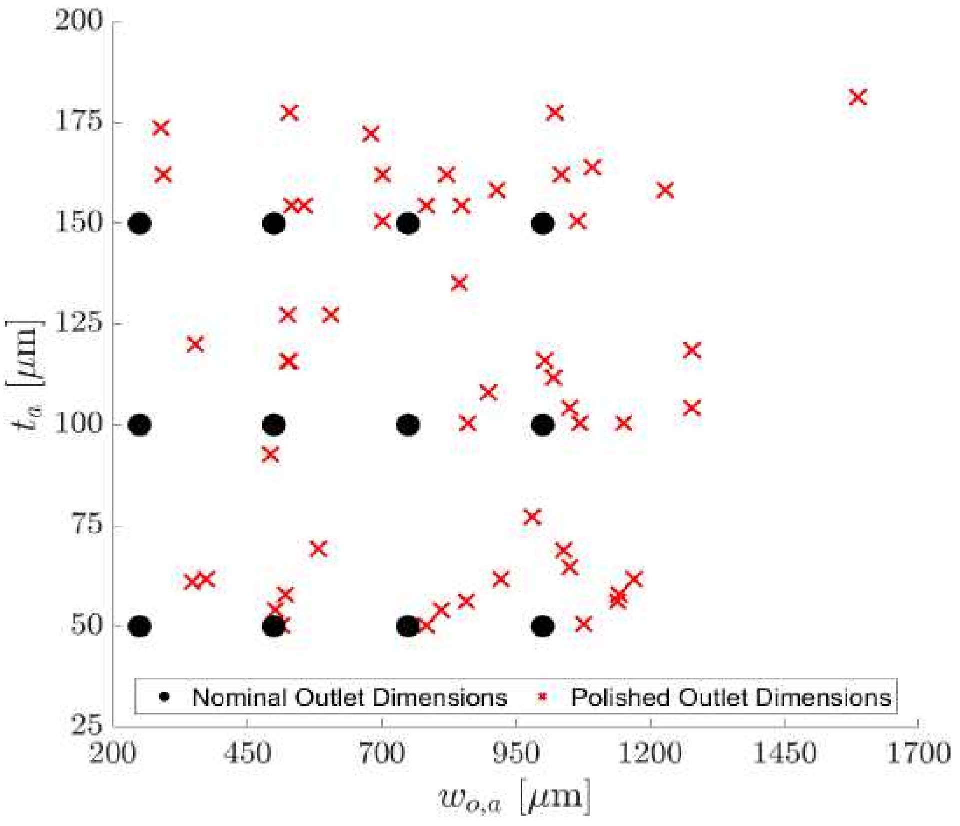
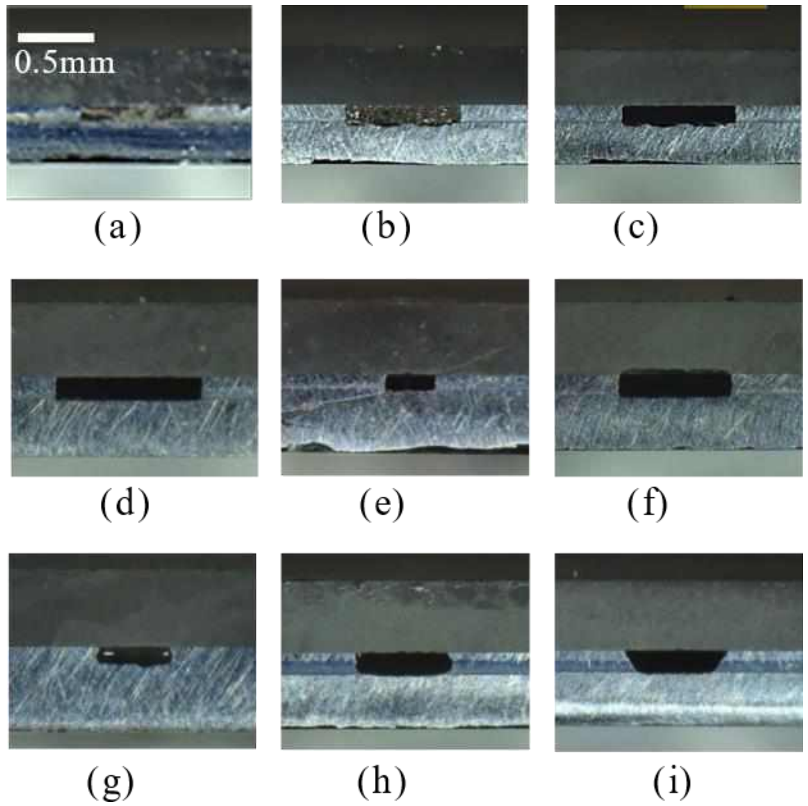
# Polishing-exposed fabrication flaws

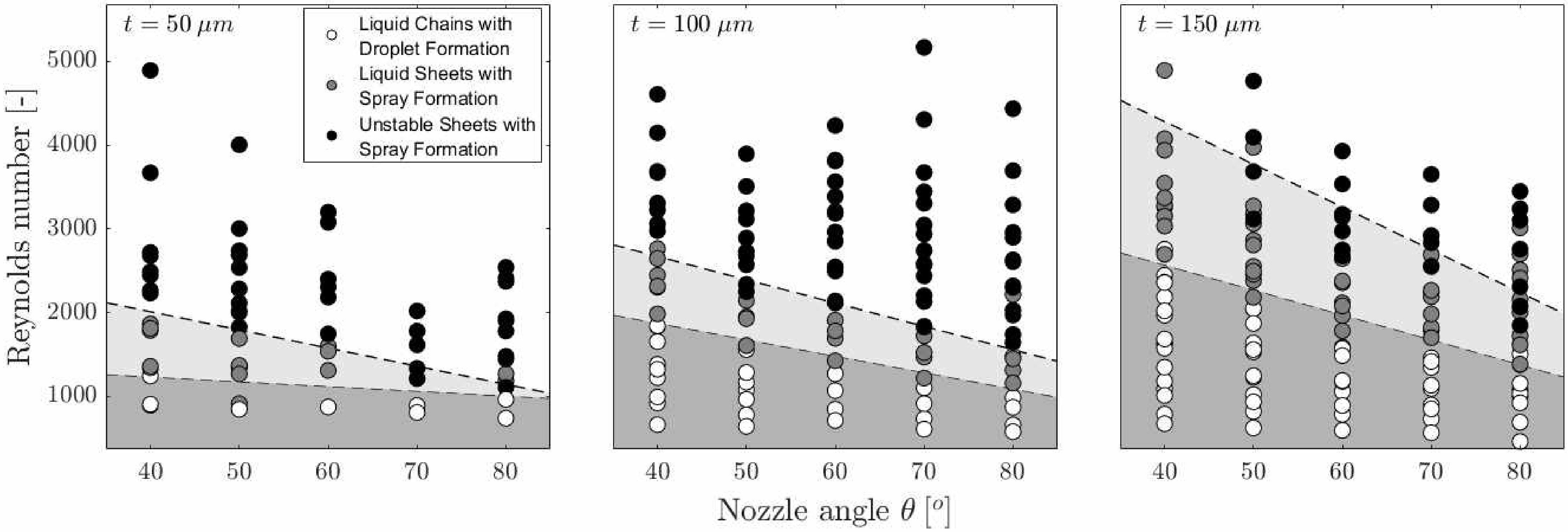
- Outlet defects - Shape deformation, Edge roughness & Wafer cracks
- Introduction of flow perturbations → Outliers presence



# Sheet-breakup regime classification

- Nozzle thickness increase delaying spray formation
- Nozzle angle increase accelerating spray formation
- Linear regime boundaries – Re = a+bθ



# Presentation Outline

1. Introduction
2. Liquid sheets
3. Experimental Methods
4. Numerical Methods
5. Results
6. **Summary and Conclusions**

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# Summary & Conclusions

- Design and development of a microfluidic device for liquid sheet generation
  - Lithographic fabrication of nozzle chips
  - Parametric study of fabrication, geometric and flow effects
- Evaluation of fabrication methods effects on sheet dynamics
- Sheet classification applying combined sheet and  breakup patterns

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# Summary & Conclusions

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  - Lithographic fabrication of nozzle chips
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- Pronounced Q- and $w_o$-effects on liquid sheet dimensions
- Nozzle angle θ controlling sheet and rim stability
  - Drop-shedding rims at higher θ
  - Transition from jet- to spray-breakup
- Critical influence of outlet polishing
  - Outlet dimensions modification
  - Sizing and stability features shift

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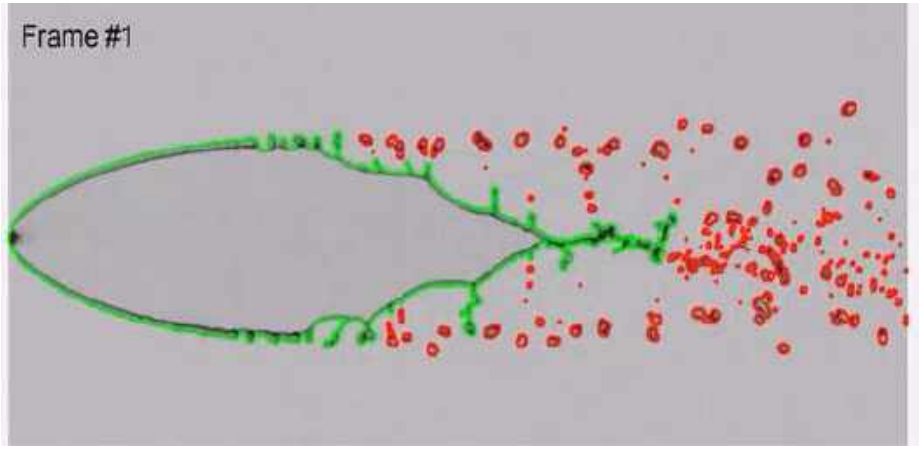
# Future Work

- Heat transfer efficiency for a flat surface using LS
- Heat transfer for a curved surface
- Study on the droplet dynamics



# Developing a Microfluidic Nozzle to Generate Water Sheet Jets for Cooling Sharp Leading Edges

**Priyanka Sinha**

**Thank you for your attention!**

**Questions?**

Thermo Fluids & Interfaces Lab

DEPARTMENT OF AEROSPACE ENGINEERING | TECHNION Israel Institute of Technology

# EFFECT ON THE THICKNESS

**For thinner sheets:**

a) Increased impingement angle

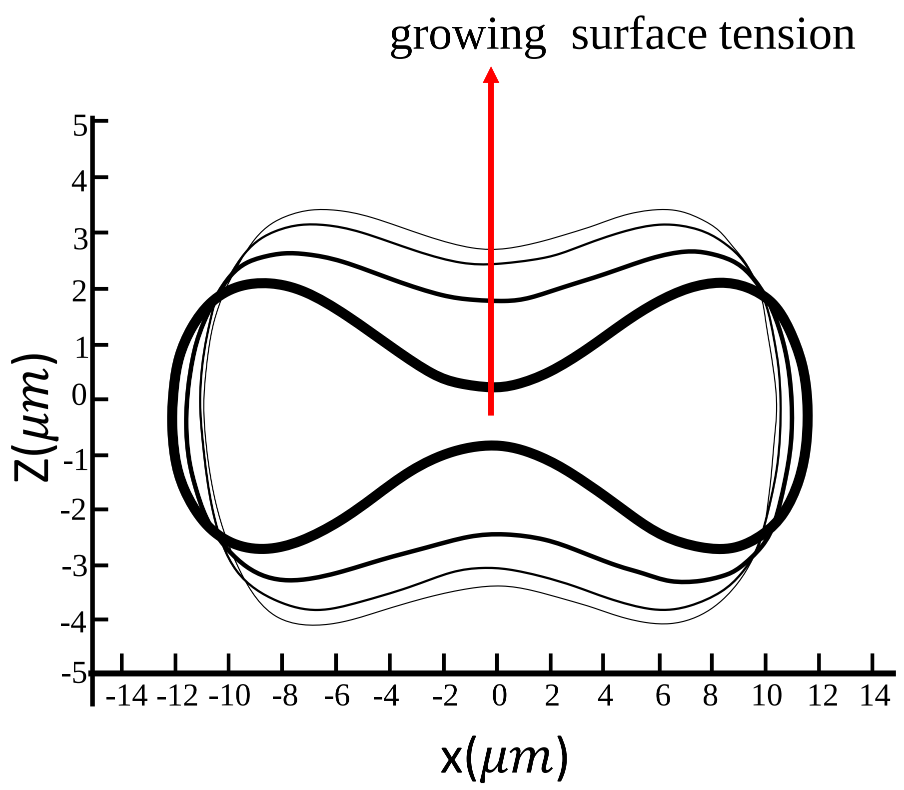
b) Working fluids

-use of solvents

c) Lower surface tension

Taylor: $h \propto 1/r$

Hasson and Peck: $\frac{hr}{R_j^2} = \frac{\sin^3(\theta)}{\{1 - \cos(\phi)\cos(\theta)\}^2}$



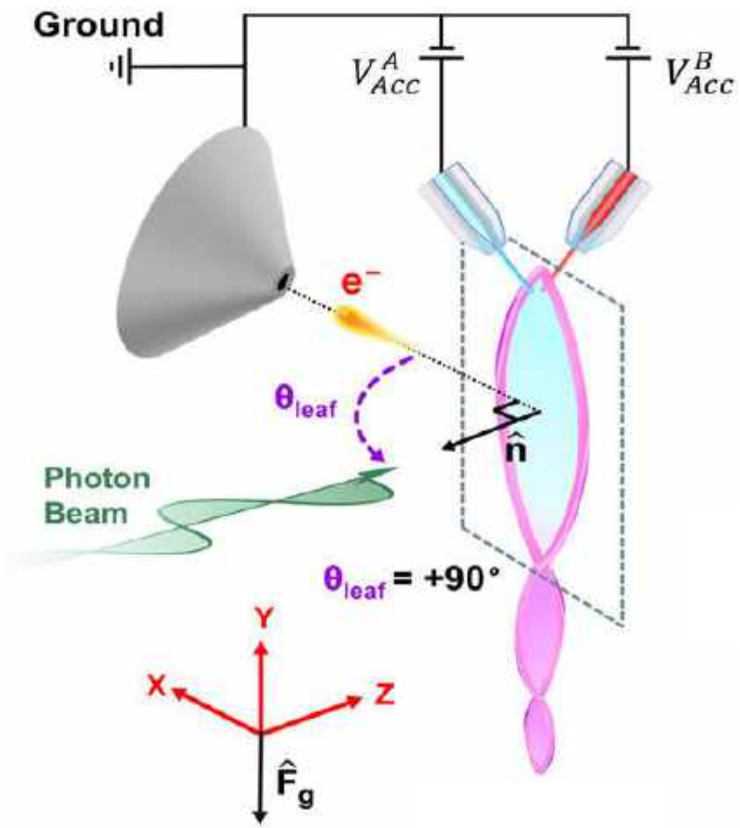

h-thickness of the sheet

r-radial distance

$\phi$-azimuthal angle

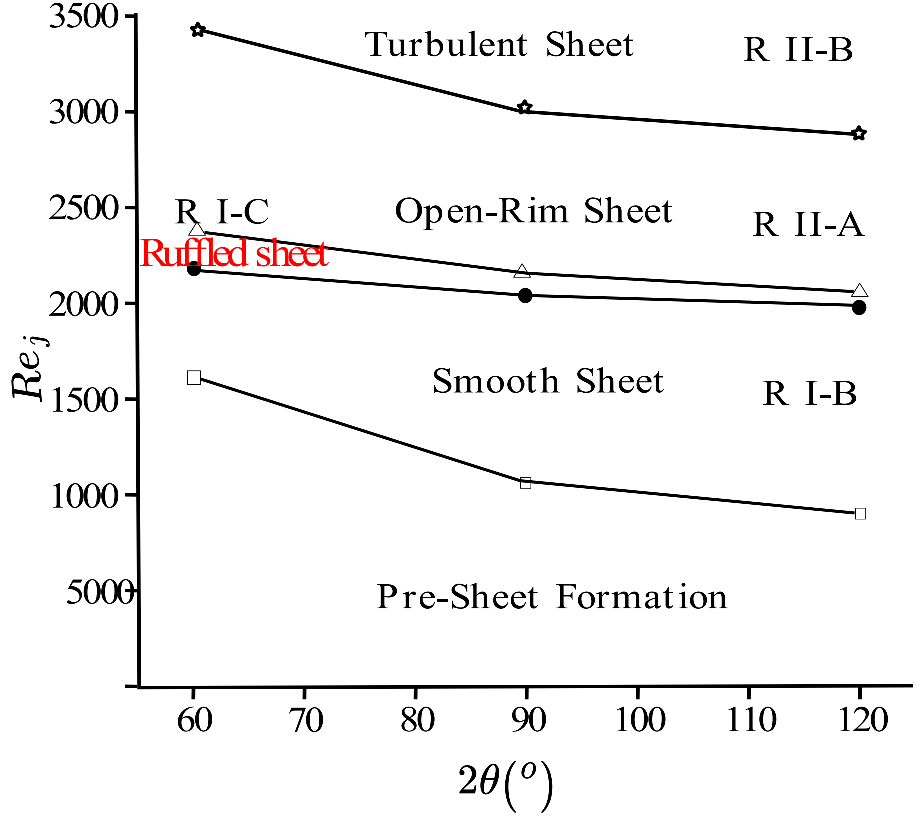
**Application of LS**

- X-ray, electron spectroscopy
- Fluid mixing in liquid propellants
- Chemical kinetics[9]

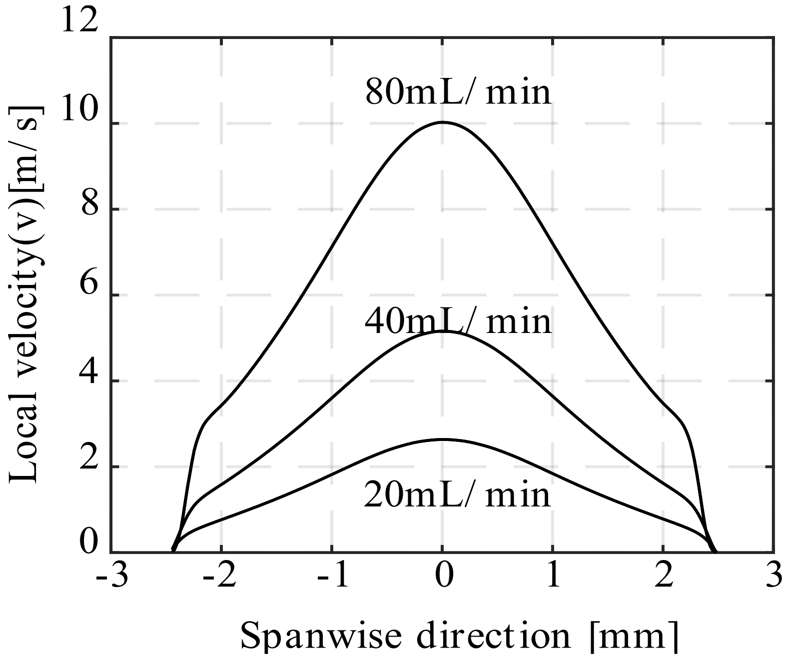


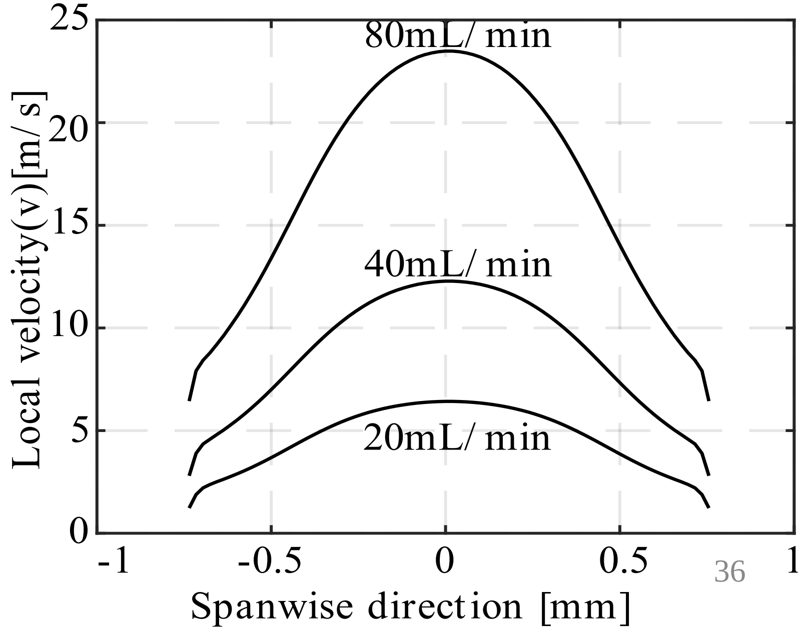

Liquid sheet used in photoelectron spectroscopy (PES)[8]

# Effect of Re on stability




# Q variation –internal flow



**CONTRIBUTING FACTORS**

Aerodynamic waves

Hydrodynamic/impact waves

**INSTABILITY PATTERN**

Open rim w/o droplets

Closed rim w/ droplets

Open rim w/ droplets

Rimless sheet

Bow-shaped ligaments

Fully developed spray

**DISINTERGATION MECHANISM**

Jet impingement

Formation of flapping sheet

Evolution of ligaments

Eventual droplet formation