Fluid Simulation Over A Rotating Disk: Momentum And Mass Transfer Across The Wafer Boundary

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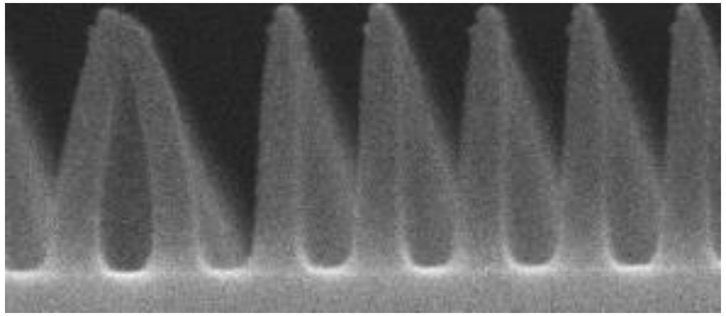
November 14-17, 2023

SCREEN Semiconductor Solutions Co., Ltd.

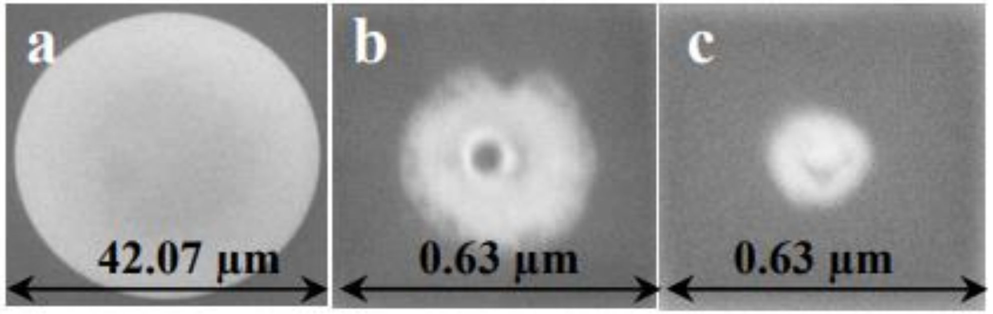
80th Anniversary

Motivations: Addressing Semiconductor Challenges with CFD

- ♦ **Precision:** Nanometer accuracy demands superior modeling.
- ♦ **Wetting Dynamics:** Simulate ideal wetting and dewetting on various wafer types.
- ♦ **Mass & Heat Transfer:** CFD insights guide advanced modeling for precise etching.
- ♦ **Sustainability:** Optimize processes for efficient water usage.
- ♦ **Large Eddy Simulation (LES) Role:** Captures turbulent and unsteady structures for our goals.



Nanometric collapse[1]



Drying marks observed on hydrophobic wafer[2]

[1]UCPSS2021, Y.Akanishi & al, “Removal of Post Etch Residue on BEOL Low-k “
[2]UCPSS2009, N.Kurumoto & al, “Relationship between Atmospheric Humidity and Watermark Formation in IPA Dry of Si wafer after HF clean”

Outlines:

- **Theoretical Background and Fundamentals:**
  - Basics of Boundary Layer Theory
  - Viscous sublayer: wall distance y+ and friction velocity u*
  - How rotation affects fluid flow near the surface
  - The role of centrifugal forces
- **Simulation set-up and Results:**
  - Liquid and flow characteristics
  - Boundary conditions and solver setting
  - RANS vs. LES: Calculation result
  - Confirmation by experimental measurement
- **Simulation data analysis:**
  - Scaling hydrodynamics numbers
  - Thickness evolution
  - Viscous sublayer thickness

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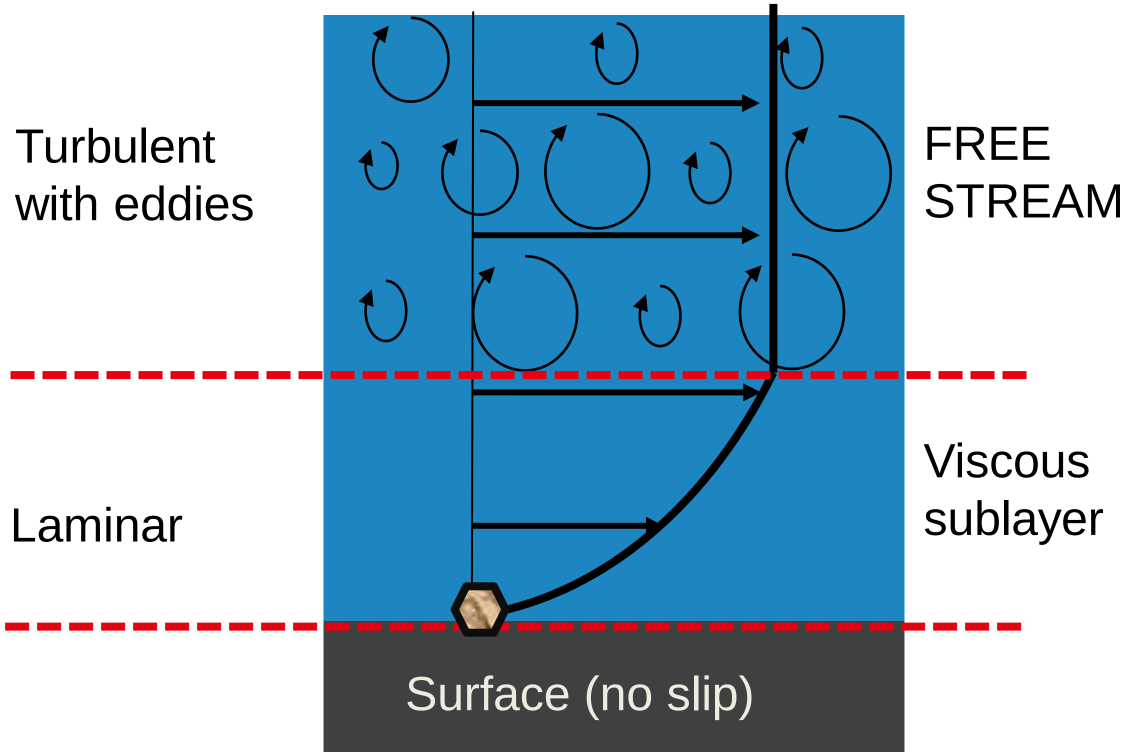
Basics of Boundary Layer Theory :

- **The viscous boundary layer is the region near a solid surface where fluid velocity changes rapidly due to viscous effects.**

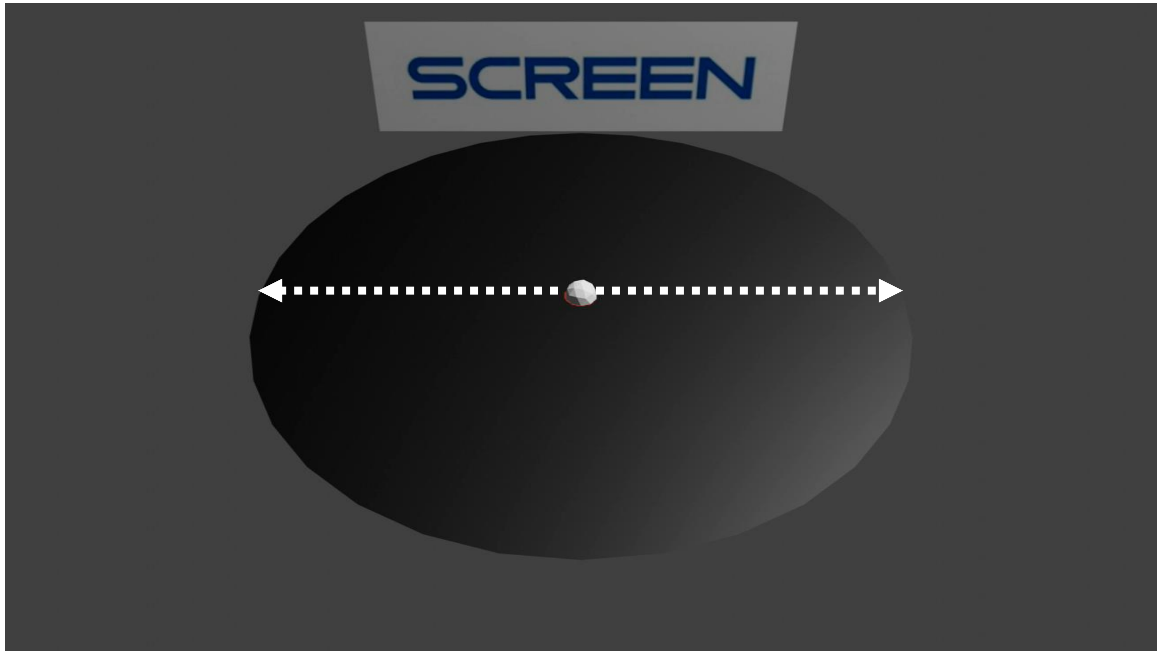


Effective rinsing requires overcoming the boundary layer. Higher flow velocities or turbulence can disrupt the layer, enhancing rinsing efficiency.

The viscous boundary layer acts as a barrier to efficient rinsing. Minimizing and Overcoming it is essential for effective cleaning.

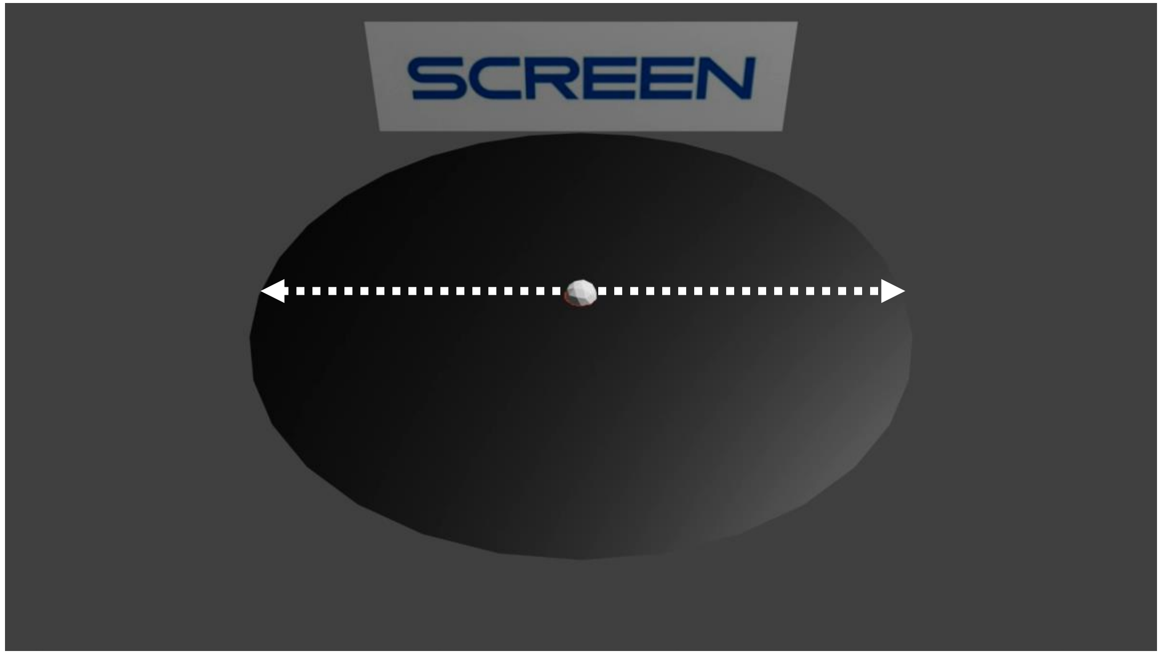
How rotation affects fluid flow near the surface:

Newtonian Referential (no rotation)



$$\sum \vec{F} = m\vec{a}$$

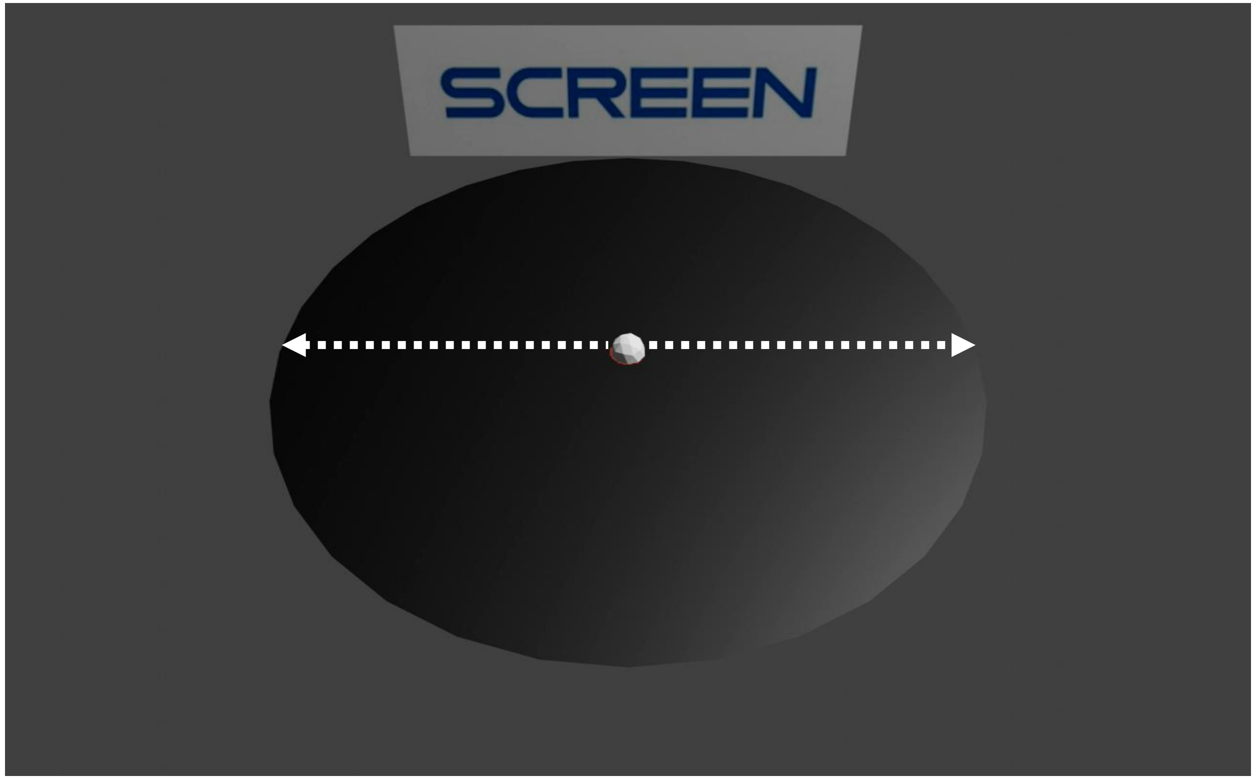
Non Newtonian: Spinning Referential



$$\sum \vec{F} = m\vec{a} - (\vec{F}_{centrifugal} + \vec{F}_{Coriolis} + \vec{F}_{Euler})$$

➔ The fictitious forces are introduced in the rotating frame to account for the non-inertial nature of the reference frame and to apply Newton's second law correctly in that context.

The role of pseudo inertial forces:



Centrifugal Force: Arises due to rotation, pushing objects outward from the rotation's center.

$$\vec{F}_{centrifugal} = m\boldsymbol{\vec{\omega}} \times \boldsymbol{\vec{\omega}} \times \boldsymbol{\vec{r}}$$

Coriolis Force: Acts on moving objects in a rotating frame, perpendicular to the motion, affecting their trajectory.

$$\vec{F}_{Coriolis} = 2m\boldsymbol{\vec{\omega}} \times \dot{\boldsymbol{\vec{r}}}$$

Euler Force: Appears when angular velocity changes, causing acceleration tangential to the rotation.

$$\vec{F}_{Euler} = m\dot{\boldsymbol{\vec{\omega}}} \times \boldsymbol{\vec{r}}$$

At constant rotation: $$\sum \vec{F} = \vec{F}_{real} + \vec{F}_{centrifugal} + \vec{F}_{Coriolis} = m\vec{a}$$

Depends on position (centrifugal) — Depends on speed (Coriolis)

➔For a particles moving outwards (towards wafer edge), trajectory is a spiral whose direction depends on the rotation and the centrifugal forces.

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Liquid and flow characteristics:

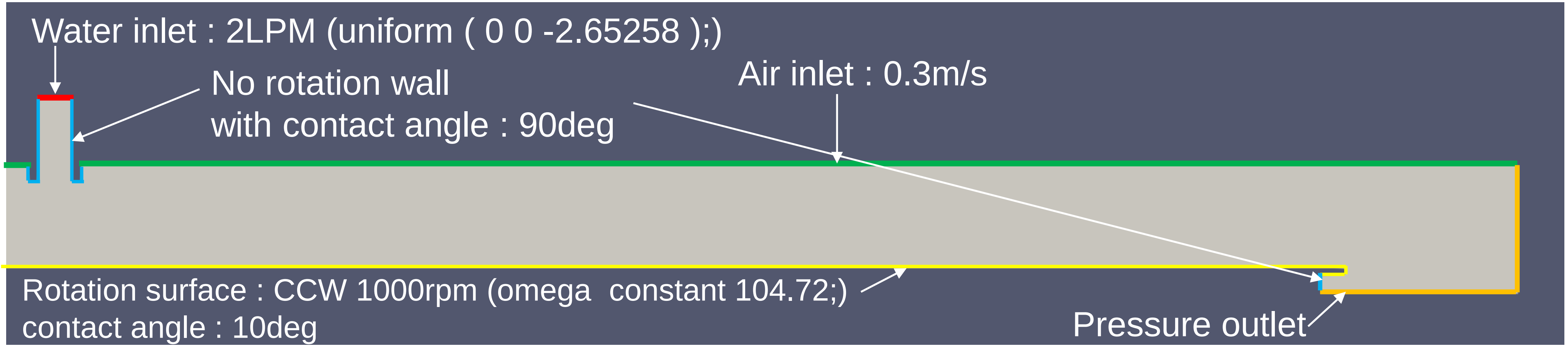
- **Liquid:**
  - Vertical dispense : Impinging jet at center (Hiemenz flowrate)
  - Few microns thin film
  - Waves: Interface air-liquid tracking
  - Viscosity/density (Newtonian)
  - Constant Flowrate

- **Surface:**
  - Constant rotation at high speed 1000rpm
  - Wetting properties (contact angle)
  - Rotating surface w/o slip

➔Goal: understand the mass transfer within the liquid from the air-liquid interface down to the boundary layer close to the surface.

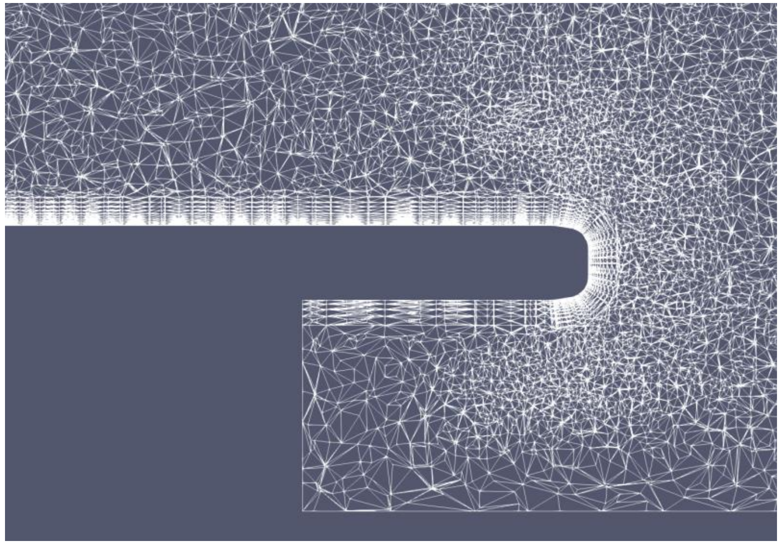
Boundary conditions and solver setting

♦ Boundary conditions

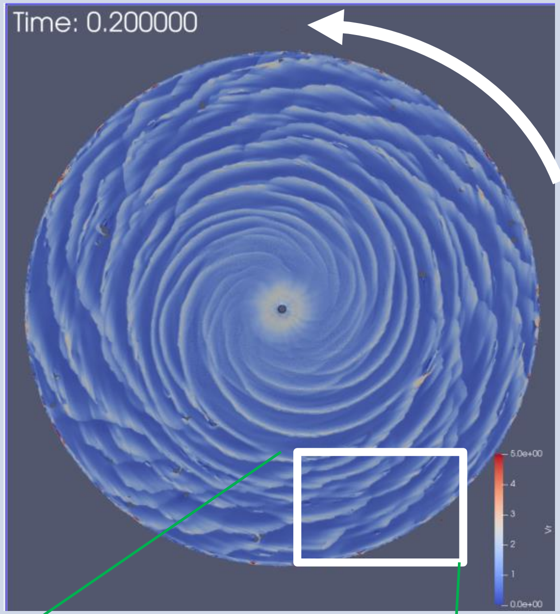
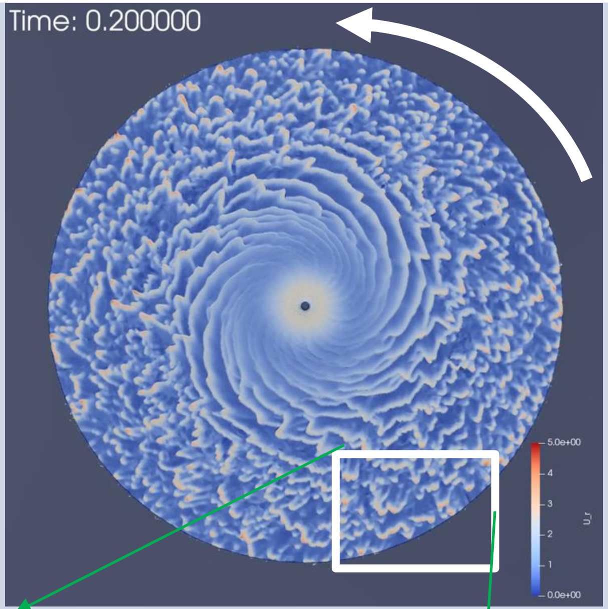
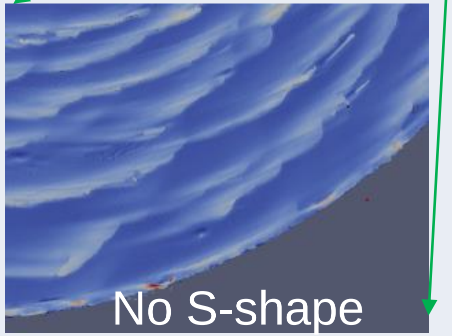
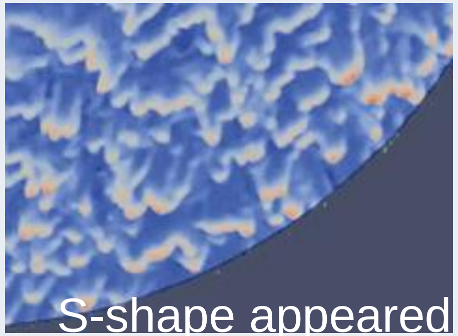


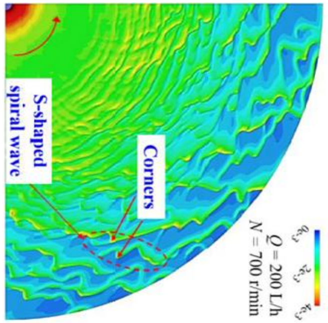
♦ Solver

- OpenFOAM v2012 (LES Smagorinsky)
- Mesh type and number :
  - Polyhedral: 26M
  - hexahedra: 85K
  - Boundary layer :
    - thickness = 300um,
    - 12layer, growth rate = 1.1



RANS vs. LES: Calculation result

	RANS	LES
Whole image with V3 at 0.2sec		
Zoom up of waves shape		
Average y+	7.54164	0.867003

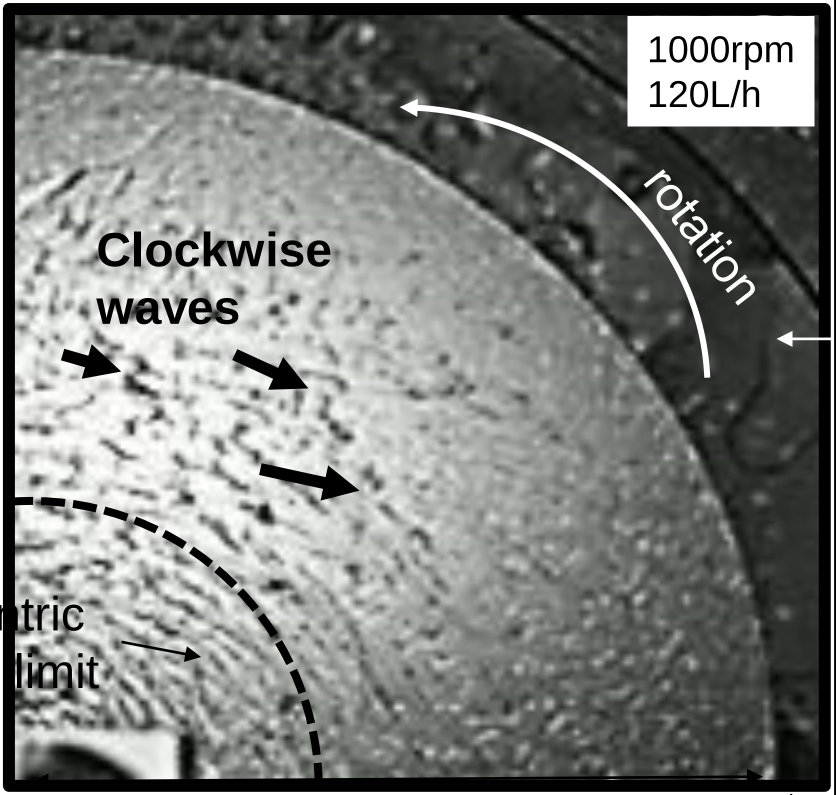


AIChE Journal. 2020;66:e16894.

1 Li&al, "Three-dimensional large eddy simulation of wave characteristics of liquid film flow in a spinning disk reactor",2019

Experimental observations:

300mm

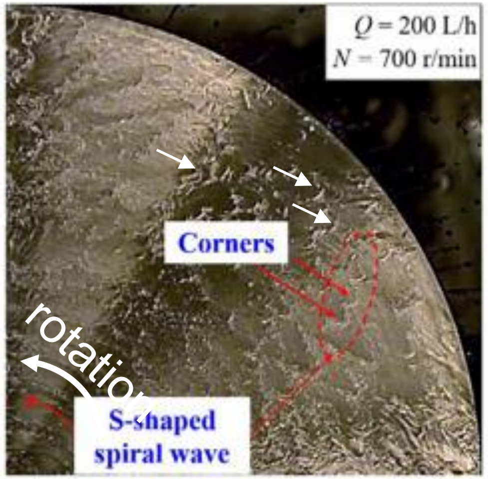


Concentric Waves limit

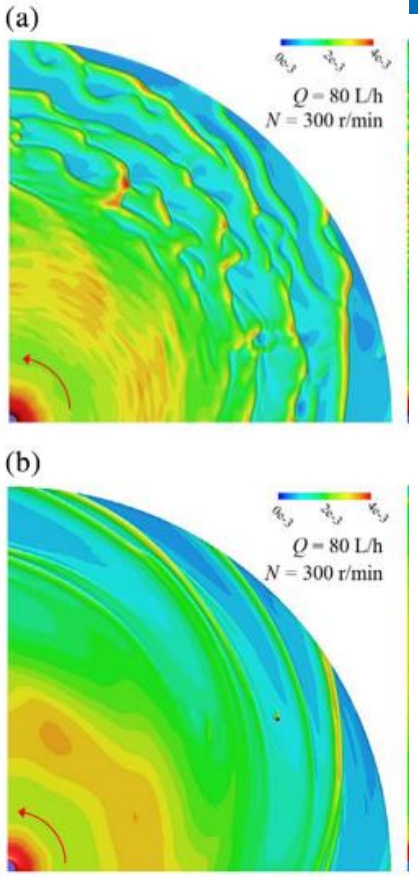
150mm

Our studied case

200mm



100mm



LES

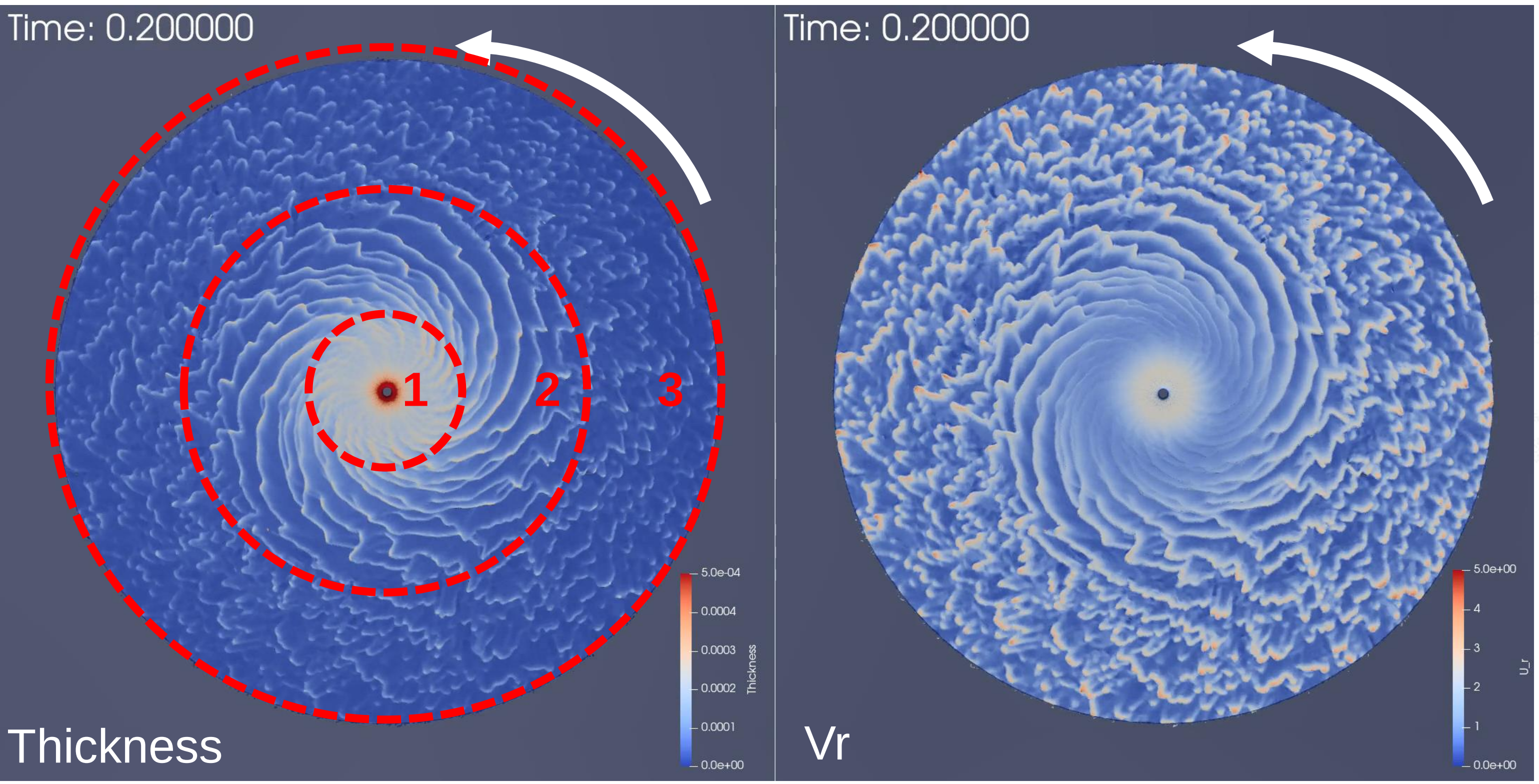
RANS SST-k-ω

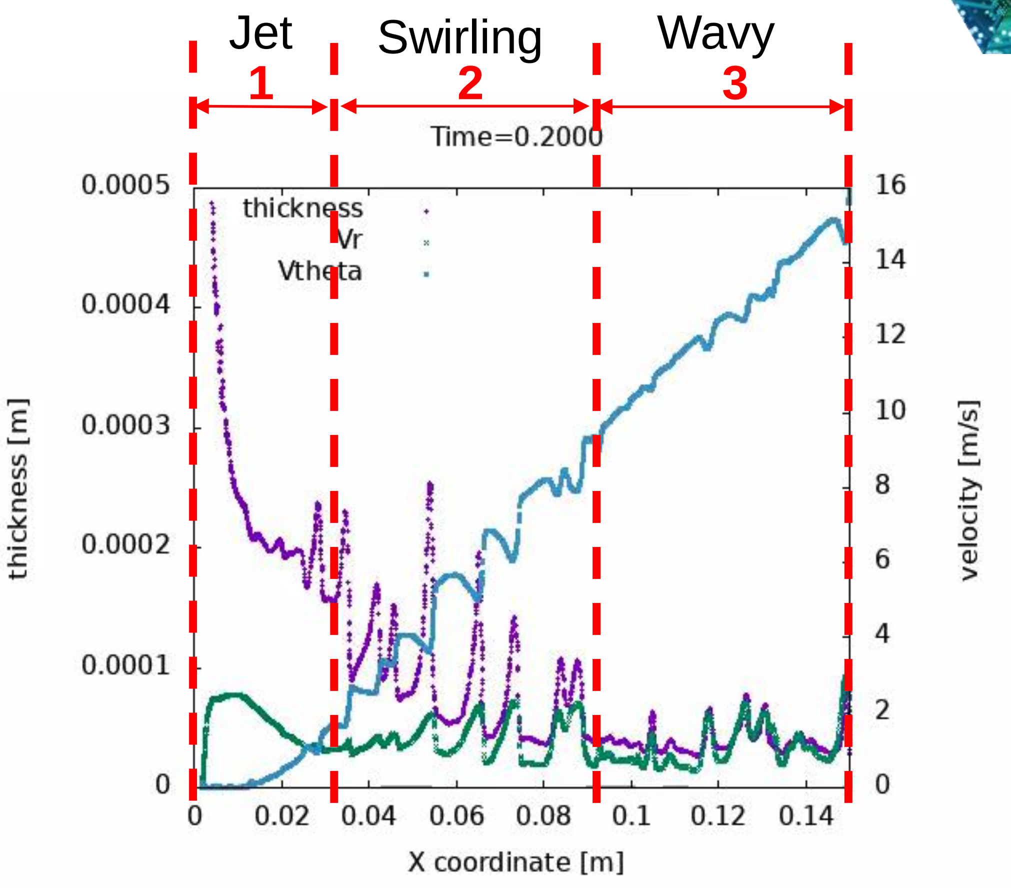
Reported case by Li&al on ANSYS & 90º pie[1]

RANS SST-k-ω and periodic BC in ANSYS, yielding oversimplified flow patterns,
At increased diameters, the liquid surface exhibits intricate patterns that are challenging to compute,
➔LES closer to real-world observations for complex liquid surface textures

Simulation results

- ♦ **Until 0.2sec with new full wafer model**





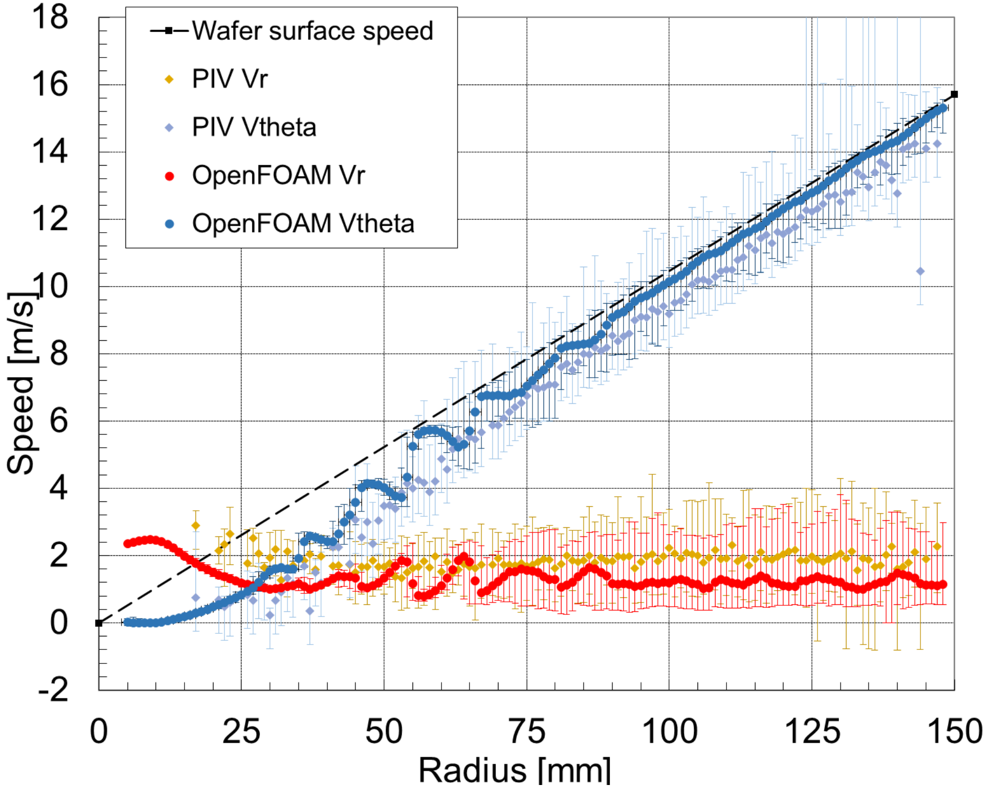
1- a laminar thick impinging inlet w/o waves,
2- a swirling wave area that follows the rotation direction,
3- a wavy turbulent area in shallow water where waves move in opposite direction of the rotation

Simulation confirmation:

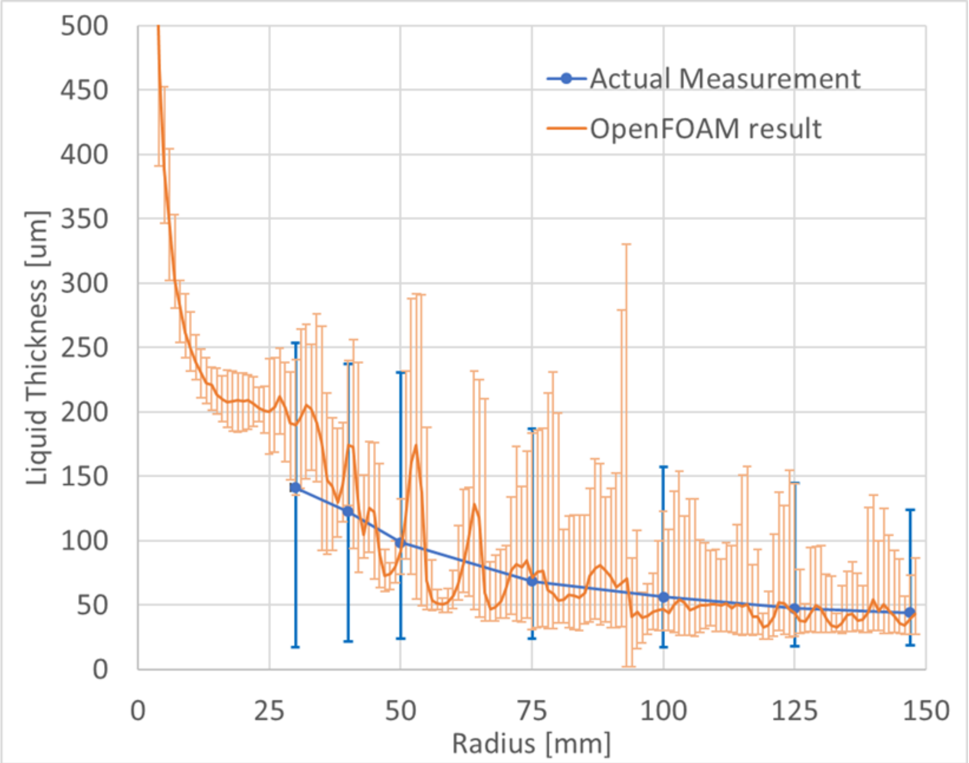
♦ Data analysis condition

– Obtained by Particles Imaging velocity (PIV) and Interferometry.

Angular and radial speed ($m.s^{-1}$)



Thickness (µm)



Excellent agreement between simulation & measured data of angular/radial velocity and thickness

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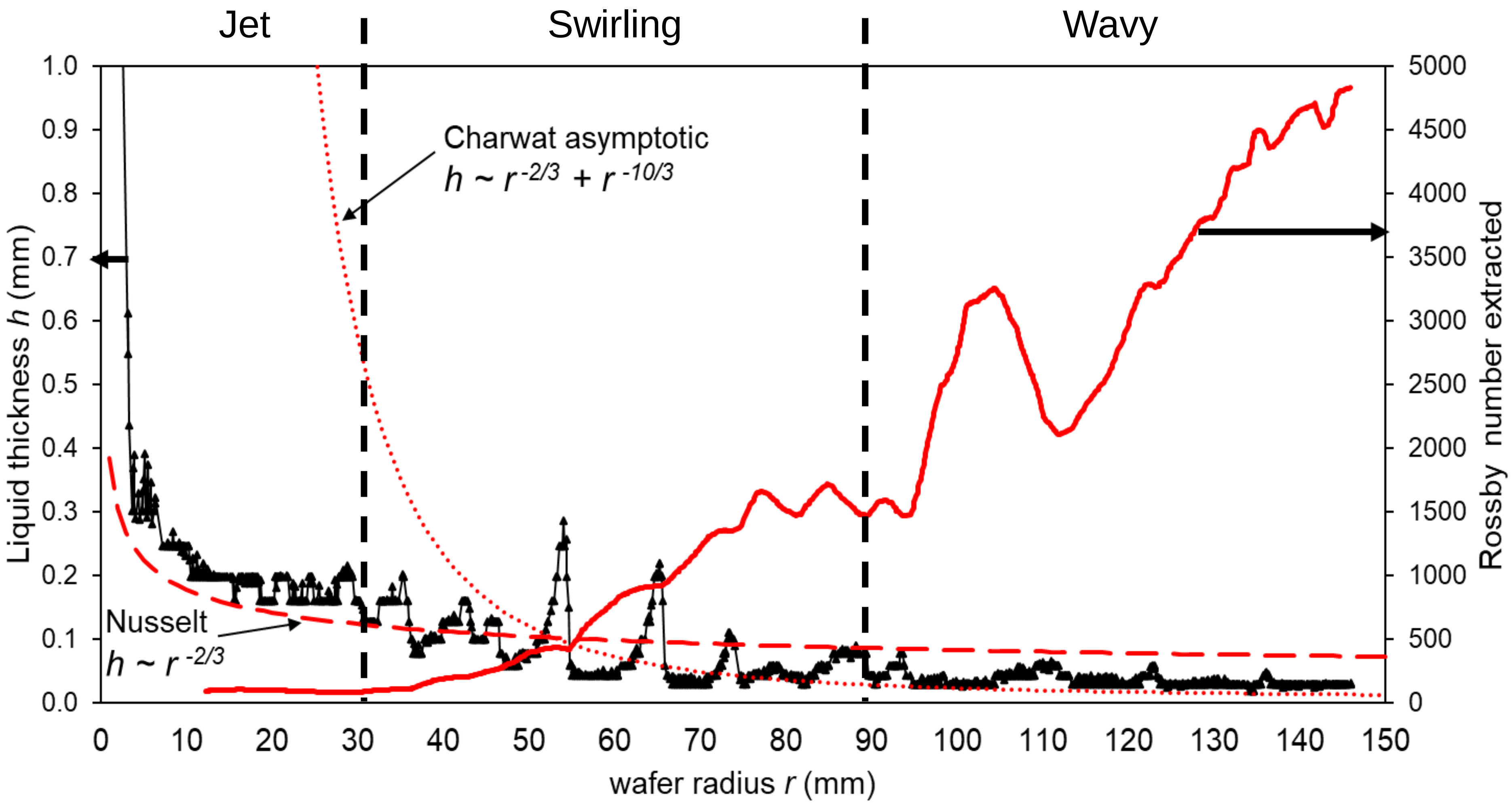
Scaling hydrodynamics numbers:

- **Dimensionless numbers like Reynolds, Rossby, and Ekman numbers play major roles in characterizing our studied flow regimes and the balance of involved forces.**

Hydrodynamics number	Ratio	Expression	Range	Interpretation
Reynolds Re	Inertial/viscous	$\bar{U}h/\nu$	200-2000	Laminar flow
Rossby Ro	Inertial/Coriolis	$\bar{U}/\omega h$	10-7000	Inertia dominates
Ekman Ek	Viscous/Coriolis	$\nu/\omega h^2$	0.01-30	Viscous dominates

The dominance hierarchy of forces in a rotating fluid :
Inertia > Viscous forces > Coriolis with low impact of gravity or capillary forces.

Thickness evolution at full coverage:



Ekman length for water at 1000rpm:

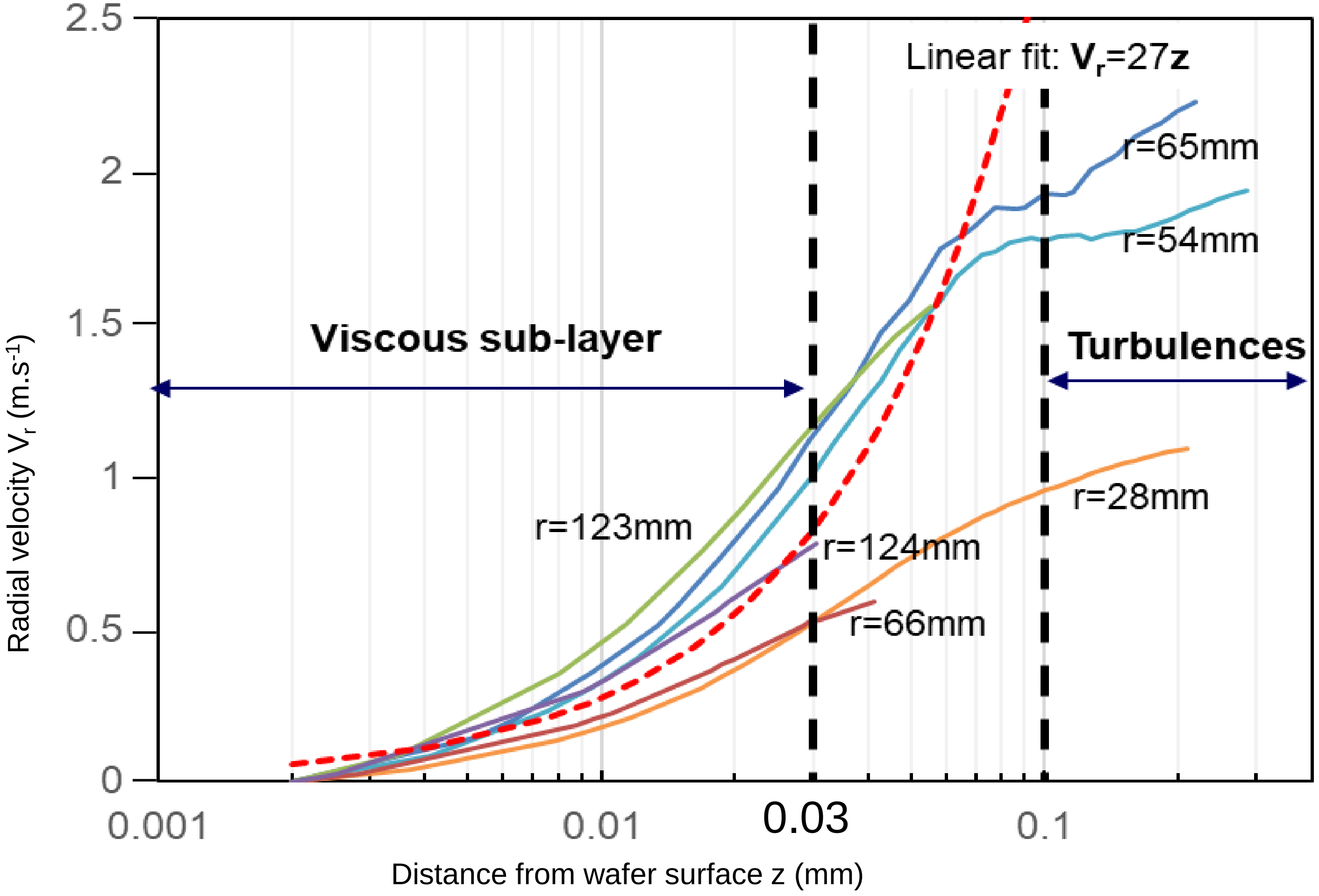
$$\delta = \sqrt{\frac{\nu}{\omega}} \sim 100\mu m$$

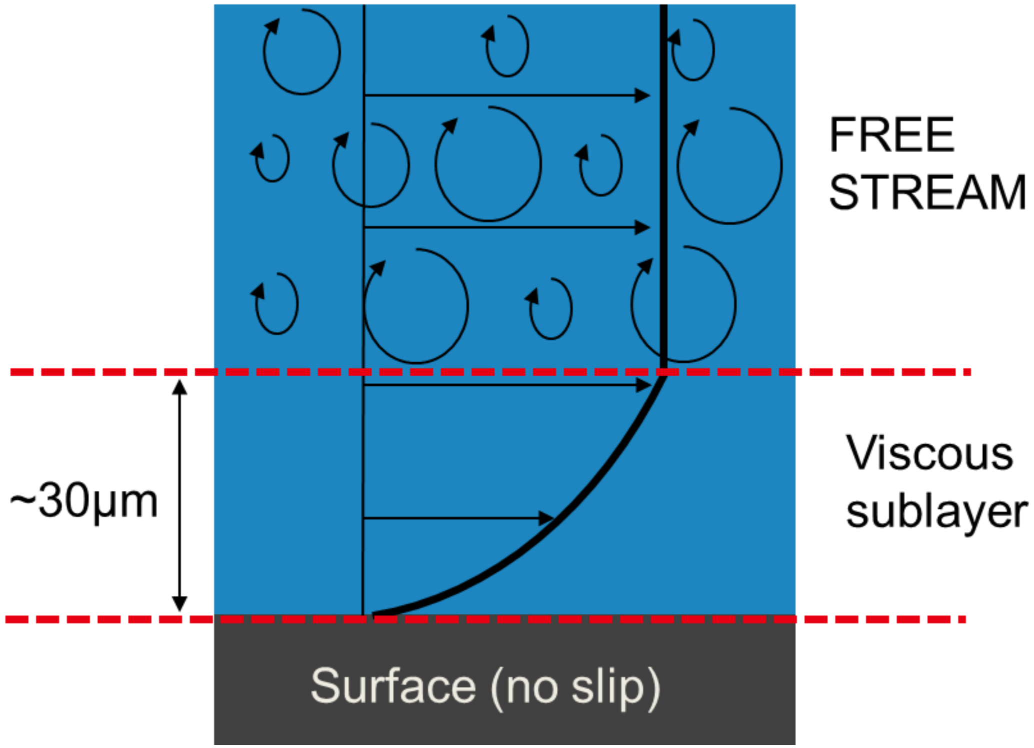
Viscous length scale for water at 2.5m/s:

$$\delta = \frac{\nu}{U} \sim 1\mu m$$

Ekman length = the depth over which surface frictional effects are significant in a rotating fluid.
In the viscous sublayer, viscous forces compete with Coriolis forces

Viscous sublayer thickness:





With a 30µm layer, contaminants < 30um might be shielded from the rinsing action.
To improve rinsing, the boundary layer should be minimized as much as possible.

Summary:

- **Importance of CFD LES:**
  - Higher computational cost but essential for capturing unsteady structures.
  - Crucial for understanding small-scale turbulent structures in our research.

- **Flow Dynamics Factors is governed by competition between:**
  - Coriolis forces (dependent on rotation speed and wafer radius).
  - Viscous frictional forces (relying on fluid and surface properties).
  - Identification of viscous sublayer is pivotal for wet cleaning and fundamental for precise models.

- **Optimization Strategies:**
  - Adjusting rinse fluid properties.
  - Modifying process parameters (flow rate, spin speed).

Acknowledgments

– This paper is based on results obtained from a project, JPNP20017, subsidized by the New Energy and Industrial Technology Development Organization (NEDO).

– This work was achieved through the use of SQUID at the Cybermedia Center, Osaka University.

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