Liquid coverage of rotating discs

A comparison of solvers and approaches

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  - Summary

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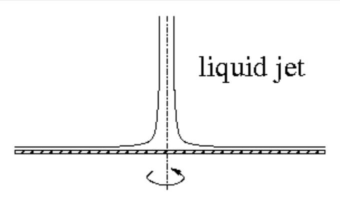
Wafer cleaning

- Important step during the production of semiconductor silicon-wafers
    - But the same happens during etching etc
- Two contradicting goals:
    - Wafer should be fully wetted
    - Minimum amount of liquid
- Goal of this project is to develop a simulation tool that helps with the planing of this process



Simulation features

- Liquid film
  - Thin (compared to the size of the geometry)
  - On a rotating surface
- Liquid jet impinges on the surface
  - Not necessarily on the center
  - Position and strength change during time
- Transport of reactants in the liquid
- All this should be achieved in a reasonable time-frame

Asymptotic solutions

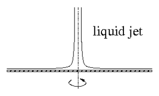
Nusselt solution

$$Ro^2 \ll 1,\ Ro^2 = \left(\frac{\bar{u}}{\omega r}\right)^2$$

$$\nu \frac{\partial^2 v_r}{\partial z^2} = -r\omega^2$$

Film thickness

$$\delta = \left(\frac{3}{2\pi}\frac{Q\nu}{\omega^2 r^2}\right)^{\frac{1}{3}}$$



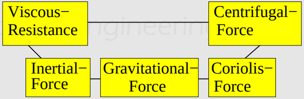
Asymptotic solution

Rauscher et al. (1973) [RKC73]:

$$\frac{\delta}{h_0} = r^{*-2/3} + \left(\frac{62}{315} - \frac{2}{9}F^{-1}\right) r^{*-10/3} + \mathcal{O}(r^{-4})$$

with $F^{-1} = \frac{2\pi g\nu}{3\omega^2 Q}$, $r^* = r/l$

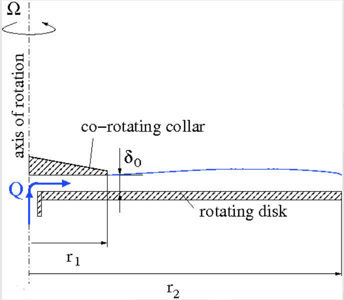
characteristic lengths: $l = \left(\frac{9Q^2}{4\pi^2\nu\omega}\right)^{\frac{1}{4}}$ and $h_0 = \left(\frac{\nu}{\omega}\right)^{\frac{1}{2}}$



leading order balance

higher order correction

Ozar et el



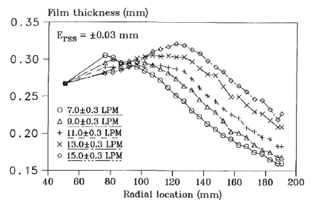
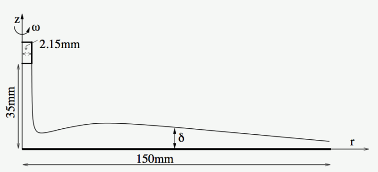


Fig. 8 Film thickness versus radial location for different flow rates

- Rotating disc
- Inlet at the center
  - Not by a jet, but through a collar
  - This allows a good control over the flow properties
- Lots of experimental data

Charwat et al

- Impinging jet on the center of the disc
  - Closer to the actual application
  - Still axi-symmetric
- Described in [CKG72]
- Analytical solution in [KK09]



The Volume of Fluid Method

- Multiphase solver for 2 liquids with a high density difference
- Volume fraction of one liquid is solved for
- Implemented in OpenFOAM™ in the `interFoam`-family of solvers
  - For details look elsewhere

Different implementations

- There are 3 schemes to calculate VoF in Fluent:

HRIC	High resolution interface capturing
QUICK	Quick Upwind Interpolation for Convective Kinematics
PLIC	Geometric reconstruction

- "only" one implementation in OpenFOAM$^{\text{TM}}$

γ-differencing scheme	Implementation in `interFoam` and others

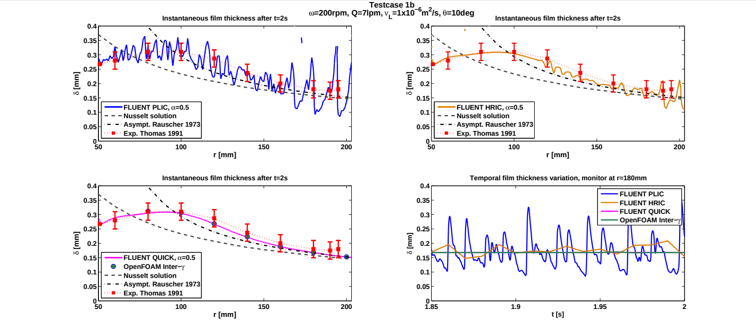
- If not otherwise noted the same grid was used in Fluent and OpenFOAM$^{\text{TM}}$ for all calculations

Motivation

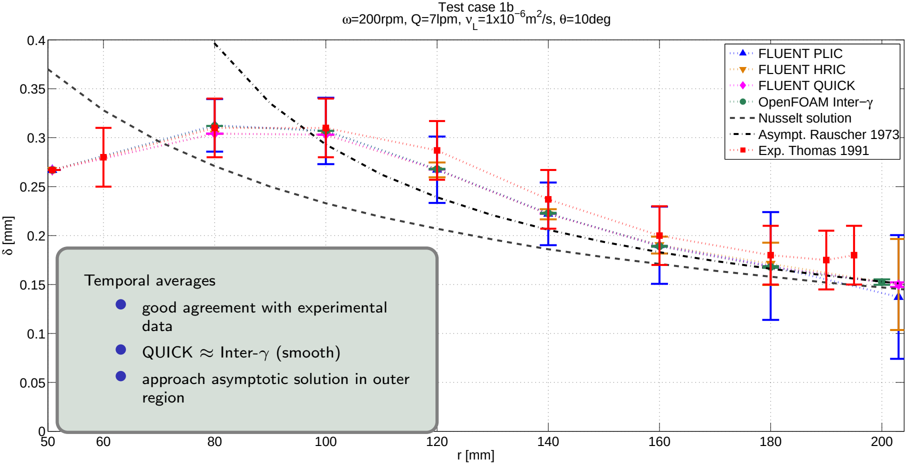
- Both sets of experiments were set up in an axially symmetric fashion
- Minimizes amount of computational time
    - More calculations possible
- Of course assumes that all the effects are symmetric
- Slightly different implementation:

OpenFOAM	Needs a modified mesh and special boundary conditions
Fluent	Modifies all the differential operators but uses a 2D-mesh

Comparing a case (200 rpm, 7 l/min)



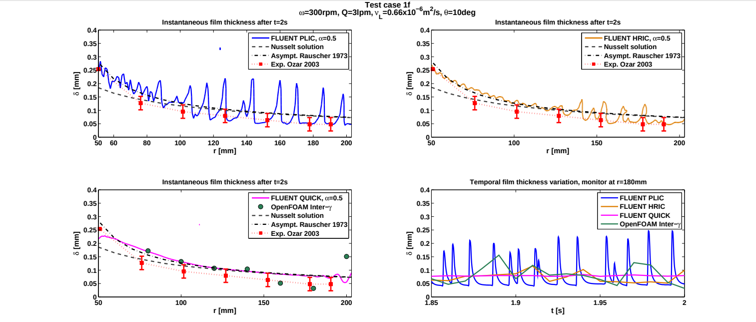
Comparing a case (200 rpm, 7 l/min) - time average



Temporal averages

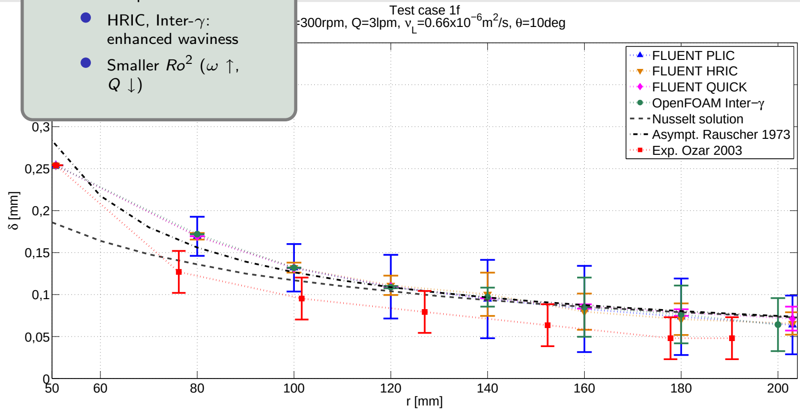
- good agreement with experimental data
- QUICK $\approx$ Inter-γ (smooth)
- approach asymptotic solution in outer region

Comparing another case (300 rpm, 3 l/min)

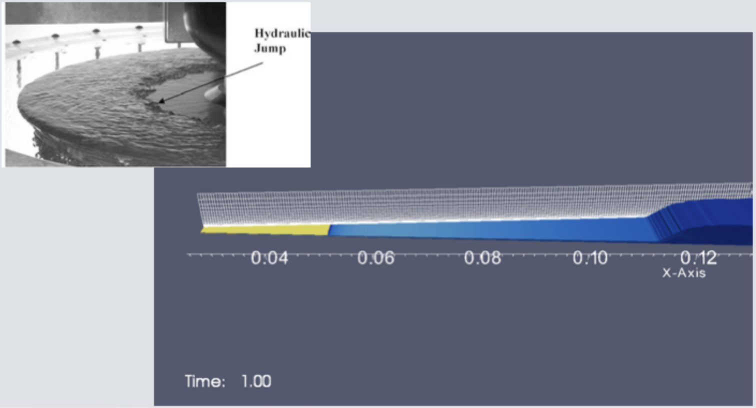


Comparing anothert case (300 rpm, 3 l/min) - time average

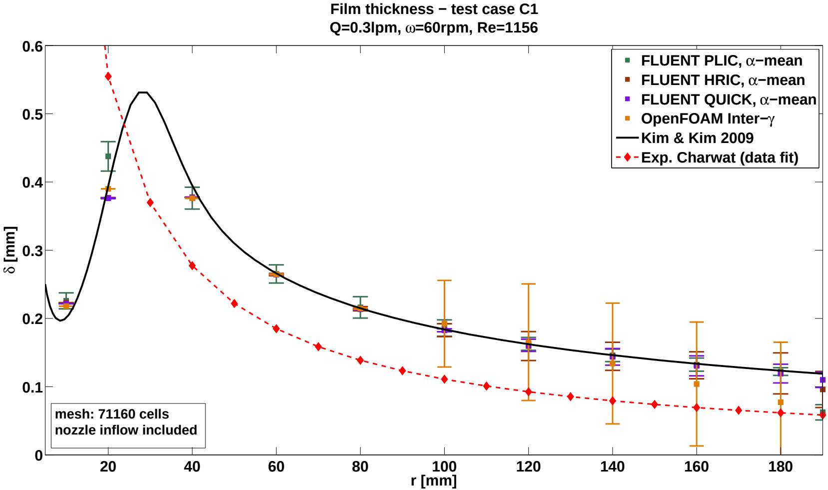
- Exp. data overpredicted
- HRIC, Inter-γ: enhanced waviness
- Smaller Ro^2 ($\omega \uparrow$, $Q \downarrow$)



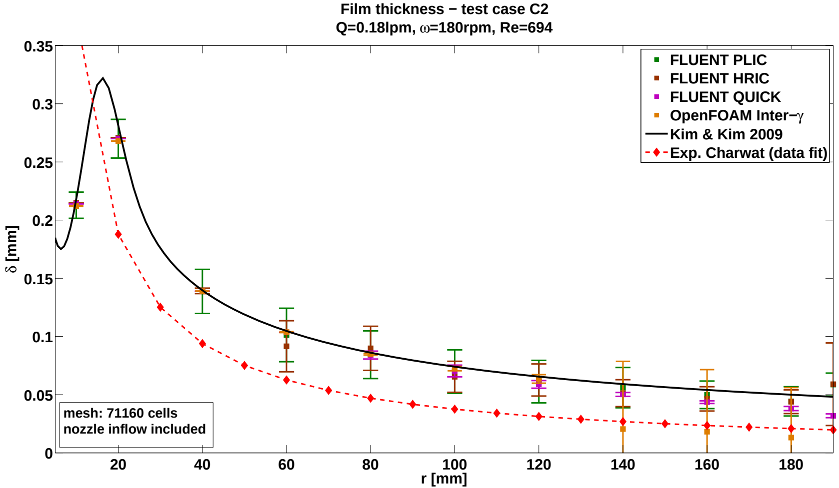
Hydraulic jump on stationary disc (7 l/min)



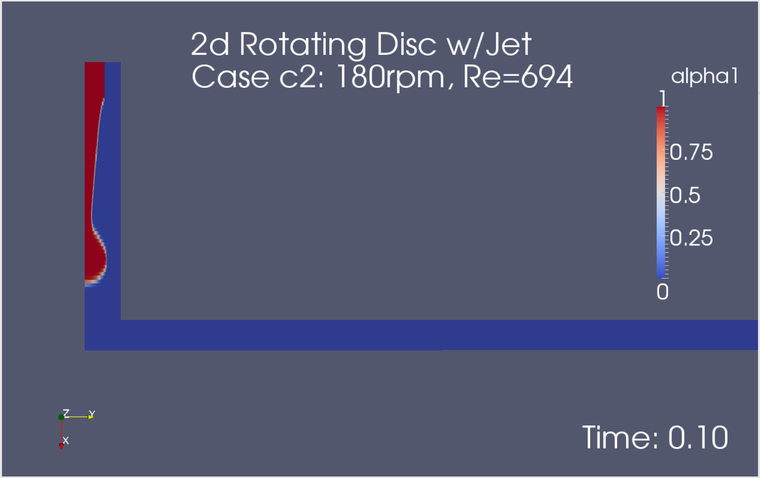
Comparison impinging jet (Charwat 1)



Comparison impinging jet (Charwat 2)



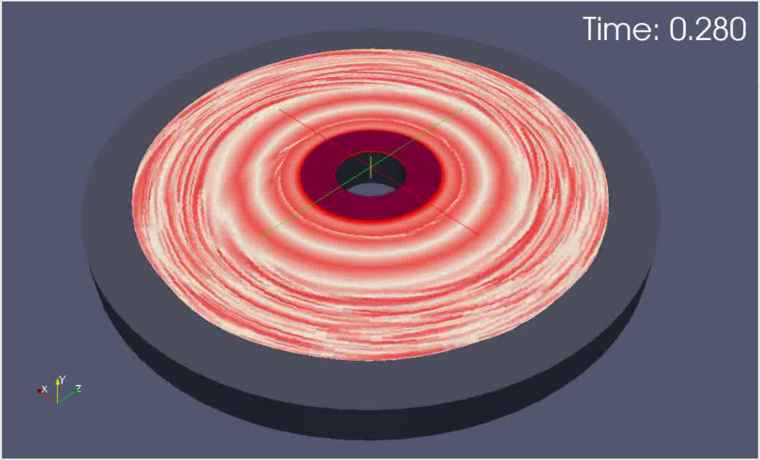
MOVIE: Impinging jet



Motivation and model setup

- Full 3D was considered
    - Large meshes due to different length-scales (wafer diameter vs. film thickness)
    - Grid near the wafer determines the resolution of the film
- The solution: `interDyMFoam`
    - Finer grid resolution at the surface of the liquid
- The Ozar case was calculated
    - Coarse `blockMesh`

MOVIE: Dynamically meshed case



Comparison of the VoF-approaches

- All approaches and solvers give similar time averaged results which are consistent with the experimental data
  - Results are mesh-independent, except for PLIC
  - Instantaneous values differ significantly
- Axial-symmetric solution fast, but limited in physical phenomena it can tackle
- 3D with mesh refinement takes a long time
  - Even then the surface film is only 3–5 computational cells "thick"

Motivation

- Disadvantages of the VOF-approach:

Axial-symmetric	Can not simulate a jet that does not impinge on the center of the disc
3D-dynamic	Takes too long for reasonable grid resolutions

- The simulation should be able to
  - Simulate arbitrary processes
  - Computational times of months for processes that last in the order of a minute are unacceptable

The FiniteAreaMethod

- Specialisation of the FVM to flows on surfaces
    - Possible applications: wall-films
- Implementation by H.Jasak and Z.Tukovic in OPENFOAM$^{\text{TM}}$
    - Not in the "official" version. Only in 1.5-dev
- Only a demo-solver that models the transport-equation on a prescribed velocity field available
- Equations are solved on a boundary-patch of the volume mesh
    - Solution of the volume (impinging jet) can be used as a source term

The simplified wafer model

- Based on the shallow-water equations
- The height of the fluid-film takes a dual role as “Density” of the fluid and Pressure
- Equations are solved using an adapted PISO-approach
- Implemented using the finiteArea-approach

The modified shallow water equations

- Liquid velocity:

$$\frac{\partial \vec{u}}{\partial t} + \vec{u}\nabla\vec{u} + g\nabla h - \frac{\sigma}{\rho}\nabla\nabla^2 h = \nu\nabla^2\vec{u} + \frac{\nu}{h^2}(\vec{u}_{\mathrm{wafer}} - \vec{u})$$

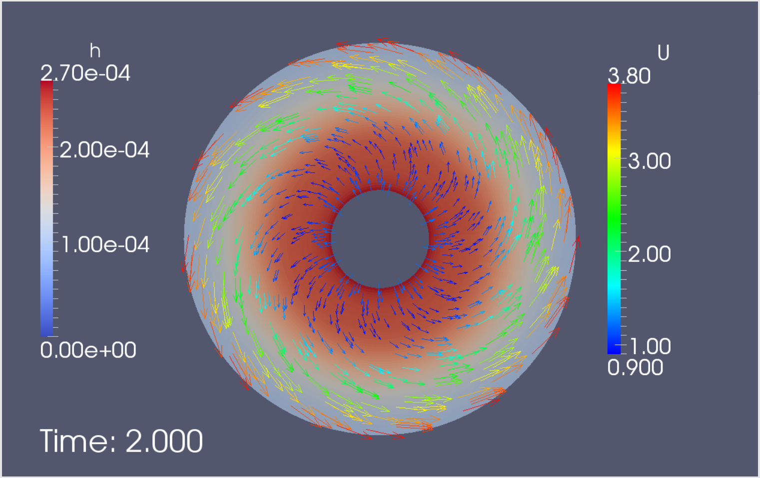
  - With added surface tension
  - and motion of the wafer
- Liquid height

$$\frac{\partial h}{\partial t} + h\nabla\vec{u} + \vec{u}\nabla h = 0$$

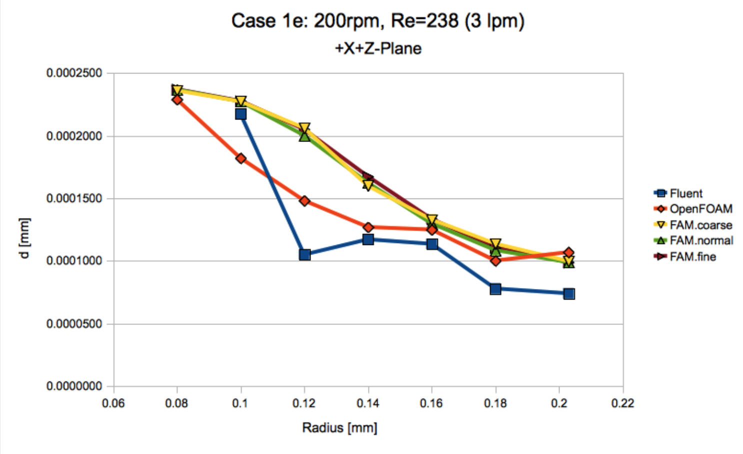
Replaying the Ozar case

- Need for validation of the solver:
  - Significantly differs from the VOF-approach
- Ozar case chosen for validation because:
  - It is easy to set up and well defined
    - Especially the inner boundary condition
    - For the Charwat case (and application) the impinging jet is modelled by a source term in the continuity equation
  - Experimental and computational data exists

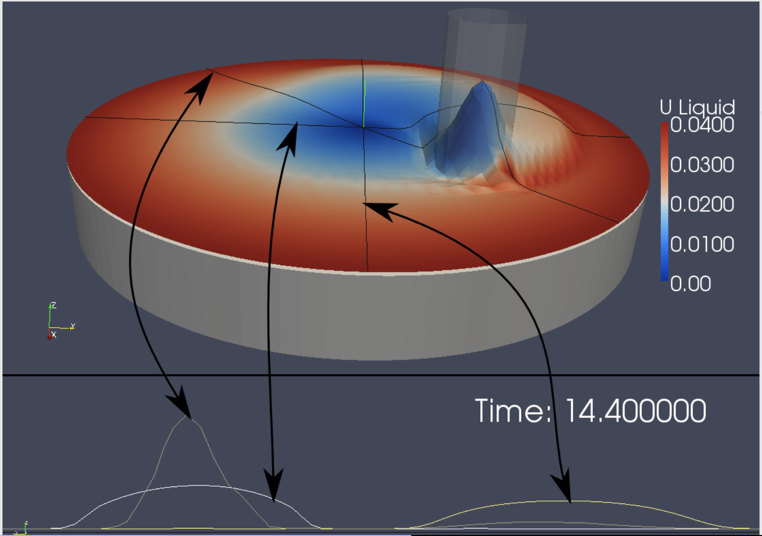
Film height and liquid velocity with FAM



Quantative comparison of the approaches



MOVIE: Transient covering of a wafer



Summary of the results

- Two different solvers were compared
- Two well-documented experimental cases were investigated
- A variety of different solutions to the cases were taken
  - Asymptotic solution
  - Axial-symmetric solution using VoF
  - Full 3D-solution of the VoF
  - A special solver using the FAM
- All approaches give similar results
- Potentially best results (not surprisingly) would be given by the full 3D-solution
- Usable for the actual application is the FAM-approach

Acknowledgements

- This work is part of the project RoWaFloSim which is funded by *Austrian Research Promotion Fund* within the ModSim-programme
- The industrial sponsor and user of this work is the Lam Research AG (`http://www.lamrc.com/`)
- This work would not have been possible without the people who brought us OpenFOAM^{TM}, especially Henry Weller and Hrvoje Jasak
- No dams were hurt during the making of this study

The End

Thanks for listening!

Questions?

Previous work

[CKG72] A F Charwat, R E Kelly, and C Gazley. The flow and stability of thin liquid films on a rotating disk. *Journal of Fluid Mechanics*, 53:2:227–255, 1972.

[KK09] Tae-Sung Kim and Moon-Uhn Kim. The flow and hydrodynamic stability of a liquid film on a rotating disc. *Fluid Dynamics Research*, 41(3):035504 (28pp), Juni 2009.

[OCF03] B. Ozar, B. Cetegen, and A. Faghri. Experiments on the flow of a thin liquid film over a horizontal stationary and rotating disk surface. *Experiments in Fluids*, 34:556–565, 2003.

[RKC73] J. Rauscher, R. Kelly, and J. Cole. An asymptotic solution for the laminar flow of thin films on a rotating disk. *Appl. Mechanics*, 40:45–47, 1973.

[TFH91] S. Thomas, A. Faghri, and W. Hankey. Experimental analysis and flow visualization of a thin liquid film on a stationary and rotating disk. *Journal of Fluids Engineering*, 113:73–80, 1991.