Liquid coverage of rotating discs
A comparison of solvers and approaches

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Outline

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   Overview
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Summary VoF
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 planning 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

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

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

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]:

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

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

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

leading order balance

higher order correction

Viscous–Resistance

Centrifugal–Force

Inertial–Force

Gravitational–Force

Coriolis–Force
Ozar et al.

- 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

**Problem description**

- 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™ γ-differencing scheme Implementation in interFoam and others
- If not otherwise noted the same grid was used in Fluent and OpenFOAM™ 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

Test case 1b
\(\omega=200\text{rpm}, Q=7\text{lpm}, \nu_L=1\times10^{-6}\text{m}^2/\text{s}, \theta=10\text{deg}\)

- FLUENT PLIC
- FLUENT HRIC
- FLUENT QUICK
- OpenFOAM Inter-\(\gamma\)
- Nusselt solution
- Asympt. Rauscher 1973
- Exp. Thomas 1991

Temporal averages:
- good agreement with experimental data
- QUICK \(\approx\) Inter-\(\gamma\) (smooth)
- approach asymptotic solution in outer region
Comparing another case (300 rpm, 3 l/min)

Test case 1:
ω = 300 rpm, Q = 3 l/min, ν = 0.66 x 10^{-6} m^2/s, θ = 10 deg

![Graphs showing instantaneous film thickness after t=2s](image1.png)

![Graphs showing temporal film thickness variation, monitor at r=180mm](image2.png)
Comparing another case (300 rpm, 3 l/min) - time average

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

Test case 1f
$\omega = 300$ rpm, $Q = 3$ l/min, $\nu_L = 0.66 \times 10^{-6}$ m$^2$/s, $\theta = 10$ deg

FLUENT PLIC  
FLUENT HRIC  
FLUENT QUICK  
OpenFOAM Inter-γ  
Nusselt solution  
Asympt. Rauscher 1973  
Exp. Ozar 2003
Hydraulic jump on stationary disc (7 l/min)
Comparison impinging jet (Charwat 1)

Film thickness – test case C1
Q=0.3 lpm, \( \omega = 60 \text{rpm} \), Re=1156

<table>
<thead>
<tr>
<th>FLUENT PLIC, ( \alpha )-mean</th>
<th>FLUENT HRIC, ( \alpha )-mean</th>
<th>FLUENT QUICK, ( \alpha )-mean</th>
<th>OpenFOAM Inter-( \gamma )</th>
<th>Kim &amp; Kim 2009</th>
<th>Exp. Charwat (data fit)</th>
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<tbody>
<tr>
<td>mesh: 71160 cells</td>
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<td>nozzle inflow included</td>
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\( \delta \) [mm]

\( r \) [mm]
Comparison impinging jet (Charwat 2)

Film thickness – test case C2
Q=0.18lpm, ω=180rpm, Re=694

FLUENT PLIC
FLUENT HRIC
FLUENT QUICK
OpenFOAM Inter−γ
Kim & Kim 2009
Exp. Charwat (data fit)

mesh: 71160 cells
nozzle inflow included
MOVIE: Impinging jet

2d Rotating Disc w/ Jet
Case c2: 180rpm, Re=694

Time: 0.10
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 Finite Area Method

- Specialisation of the FVM to flows on surfaces
  - Possible applications: wall-films
- Implementation by H. Jasak and Z. Tukovic in OpenFOAM™
  - 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:
  \[
  \frac{\partial \vec{u}}{\partial t} + \vec{u} \nabla \vec{u} + g \nabla h - \frac{\sigma}{\rho} \nabla \nabla^2 h = \nu \nabla^2 \vec{u} + \frac{\nu}{h^2} (\vec{u}_{wafer} - \vec{u})
  \]
  - 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

Time: 2.000
Quantitative comparison of the approaches
MOVIE: Transient covering of a wafer

Time: 14.400000
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

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- This work would not have been possible without the people who brought us OpenFOAM™, especially Henry Weller and Hrvoje Jasak

- No dams were hurt during the making of this study
The End

Thanks for listening!

Questions?
Previous work


