Numerical investigation of liquid film flow on a rotating disk

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Outline

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Motivation

Spin Processor Technology
- Single wafer one-sided etching
- Liquid supplied from above
- Rotating chuck

Objective
- Film flow on rotating surface
- CFD solvers: FLUENT, OpenFOAM
Problem statement

- Impinging jet on rotating disk

- Film motion governed by highly complex dynamics

Inertial forces

Viscous forces

Capillary forces

Gravitational forces

Coriolis forces

Centrifugal forces
Asymptotic solution

Nusselt solution

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

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

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) [1]:

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

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

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
Numerical Simulation - VoF Method (Hirt, Nichols [3])

Volume fraction $\alpha$

$$\alpha(\vec{x}, t) = \begin{cases} 
1 & \text{liquid} \\
0 & \text{gas} \\
0 < \alpha < 1 & \text{2-phase zone}
\end{cases}$$

Advection equation ($\nabla \cdot \vec{u} = 0$)

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \vec{u}) = 0$$

Surface tracking

Interpolation of face values:
- boundedness criterion
- preserve sharp interface
- Higher Order Differencing (HRIC, Inter-$\gamma$, QUICK, ...)
- Reconstruction Schemes (PLIC, ...)

Figure adopted from [2]

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Test cases (Experiments: Thomas et al. 1991, Ozar et al. 2003)

Radially injected liquid sheet

Volumetric flowrate $Q$, rotational speed $\omega$ and $\delta_0$ prescribed.
Inner radius: $r_1=50.8\text{mm}$, outer radius: $r_2=203\text{mm}$.

- **Test case I:**
  $\omega = 200\text{rpm}$, $Q = 7\text{lpm}$

- **Test case II:**
  $\omega = 300\text{rpm}$, $Q = 3\text{lpm}$

Thomas et al., 1991 [4],
Ozar et al., 2003 [5]
Test case I - Instantaneous film thickness \((\omega = 200\, rpm, \, Q = 7\, lpm)\)

![Instantaneous film thickness after t=2s](image1)

![Instantaneous film thickness after t=2s](image2)

![Temporal film thickness variation, monitor at r=180mm](image3)

![Temporal film thickness variation, monitor at r=180mm](image4)
Test case II - Instantaneous film thickness \((\omega = 300 \text{ rpm}, Q = 3 \text{ lpm})\)

Instantaneous film thickness after \(t=2s\)

- **FLUENT PLIC**, \(\alpha=0.5\)
- Asympt. Rauscher et al.
- Exp. Ozar et al.

Temporal film thickness variation, monitor at \(r=180\text{mm}\)

- FLUENT PLIC
- Asympt. Rauscher et al.
- Exp. Ozar et al.
Test case I - Time averaged values

(ω = 200rpm, Q = 7lpm)

Test case I

ω=200rpm, Q=7lpm, ν_{L}=1 \times 10^{-6} \text{m}^2/\text{s}, \theta=10\text{deg}

Temporal averages

good agreement with experimental data

QUICK ≈ Inter-γ

approach asymptotic solution in outer region

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Test case I - Time averaged values

\( (\omega = 200 \text{rpm}, Q = 7 \text{lpm}) \)

Test case I

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

Temporal averages
- good agreement with experimental data
- \( \text{QUICK} \approx \text{Inter-} \gamma \) (smooth)
- approach asymptotic solution in outer region
Test case II - Time averaged values $(\omega = 300\text{rpm}, Q = 3\text{lpm})$

\[
\omega=300\text{rpm}, Q=3\text{lpm}, \nu_L=0.66 \times 10^{-6} \text{m}^2/\text{s}, \theta=10\text{deg}
\]

Graph showing the behavior of $\delta$ vs $r$ for various methods and data sets.
Test case II - Time averaged values
($\omega = 300 \text{rpm}, Q = 3 \text{lpm}$)

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

Test case II
300rpm, Q=3lpm, $\nu_L=0.66 \times 10^{-6} \text{m}^2/\text{s}$, $\theta=10\text{deg}$

- FLUENT PLIC
- FLUENT HRIC
- FLUENT QUICK
- OpenFOAM Inter-$\gamma$
- Nusselt solution
- Asympt. Rauscher et al.
- Exp. Ozar et al.
Conclusions 1/2

Comparison: OpenFOAM - FLUENT

- Both CFD codes produce comparable time averaged values
- Significant differences in instantaneous values associated with surface tracking method
  - PLIC: interface highly distorted
  - HRIC, Inter-$\gamma$ and QUICK show smoother solutions with smaller waviness
- Sensitivity of instantaneous results to surface tracking schemes requires further investigations
Conclusions 2/2

Comparison against Experiments & Asymptotic solution

- Asymptotic solution:
  good agreement of time averaged values in both cases

- Experimental:
  - Good agreement for Test case I
    \( \omega = 200 \text{rpm}, \ Q = 7 \text{lpm} \)
  - Overpredictions for Test cases II
    \( \omega = 300 \text{rpm}, \ Q = 3 \text{lpm} \)
    → possibly enhanced 3d-effects?
    → influence of measurement technique?


