Numerical investigation of liquid film flow on a rotating disk

Doris Prieling[1], Helfried Steiner[1], Petr Vita[2]

[1]Institute of Fluid Mechanics and Heat Transfer
Graz University of Technology

[2]Petroleum Production and Processing
University of Leoben

Ercoftac ADA PC meeting
Vienna, 6.11.2009

Outline

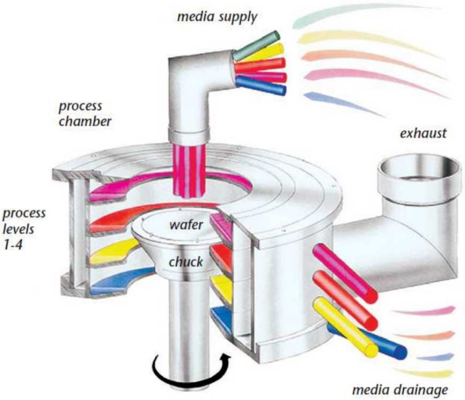
Motivation

Spin Processor Technology

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

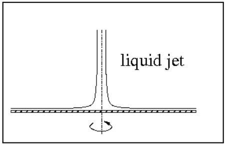
Objective

- Film flow *on* rotating surface
- CFD solvers: *FLUENT, OpenFOAM*

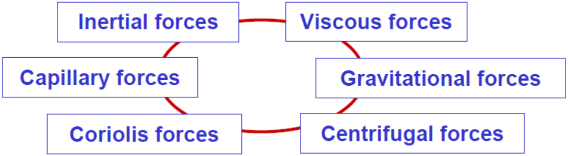


Problem statement

- Impinging jet on rotating disk



- Film motion governed by highly complex dynamics



Asymptotic solution

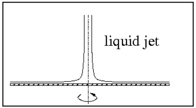
Nusselt solution

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

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

Film thickness

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



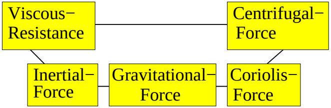
Asymptotic solution

Rauscher et al. (1973) [1]:

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

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

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

Volume fraction α

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

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

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

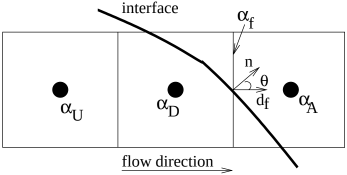
Surface tracking

Interpolation of face values:

- boundedness criterion
- preserve sharp interface

Surface tracking methods

- **Higher Order Differencing** (HRIC, Inter-γ, QUICK, ...)
- **Reconstruction Schemes** (PLIC, ...)



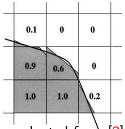


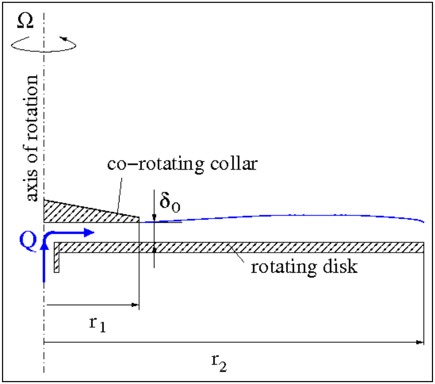
Figure adopted from [2]

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

Radially injected liquid sheet

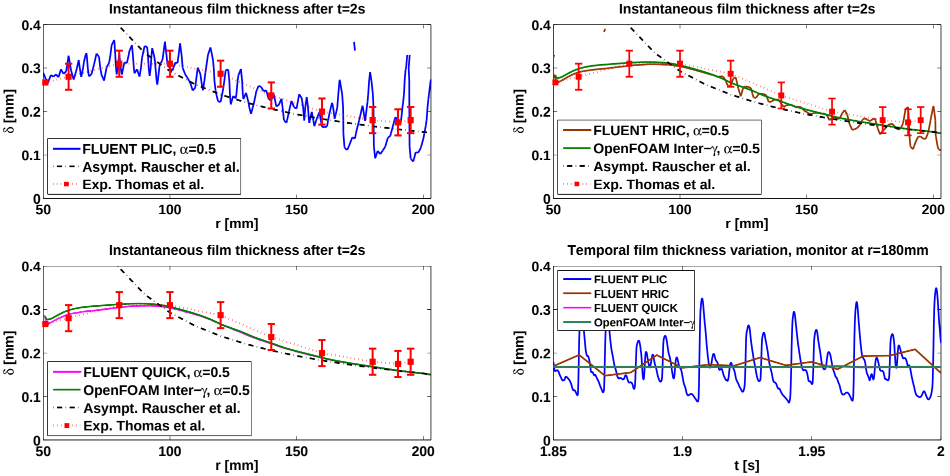
Volumetric flowrate Q, rotational speed ω and δ_0 prescribed.
Inner radius: r_1=50.8mm, outer radius: r_2=203mm.

- Test case I: $\omega = 200 rpm, Q = 7 lpm$
- Test case II: $\omega = 300 rpm, Q = 3 lpm$

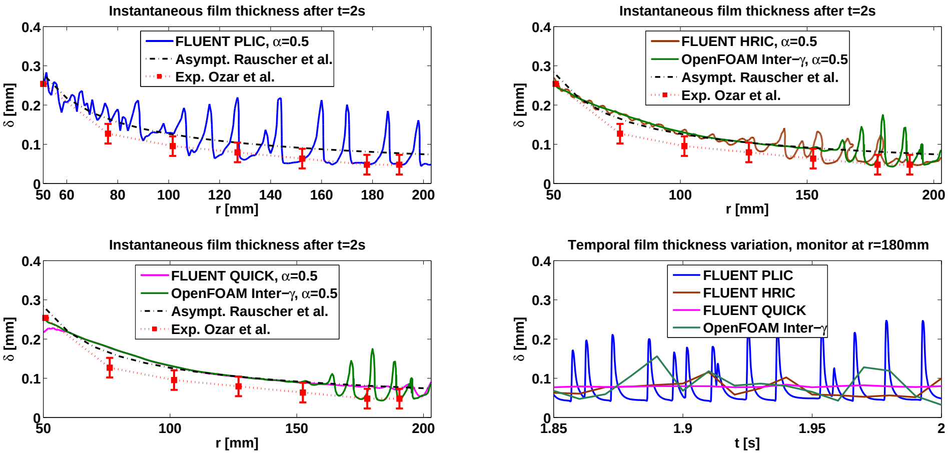


Thomas et al., 1991 [4], Ozar et al., 2003 [5]

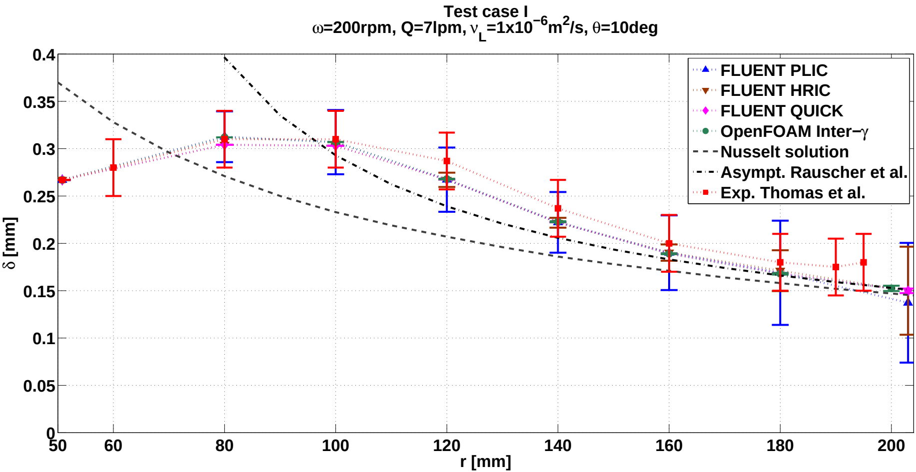
Test case I - Instantaneous film thickness ($\omega = 200 rpm$, $Q = 7 lpm$)



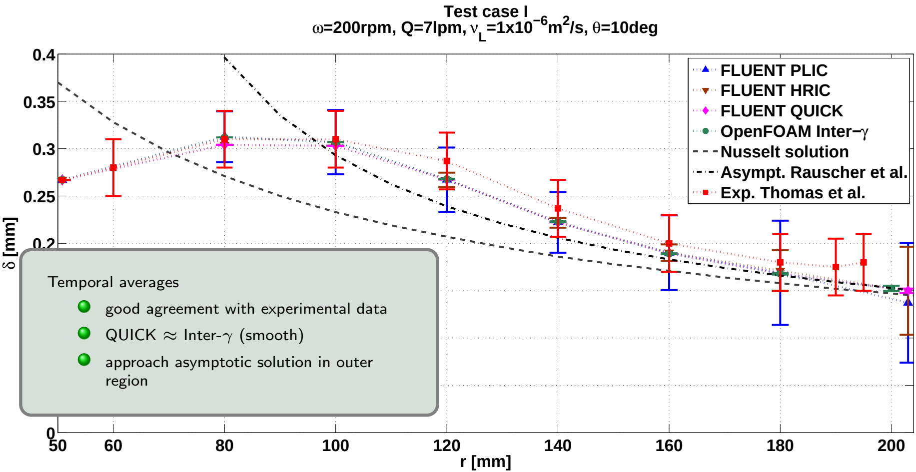
Test case II - Instantaneous film thickness ($\omega = 300rpm$, $Q = 3lpm$)



Test case I - Time averaged values ($\omega = 200rpm$, $Q = 7lpm$)



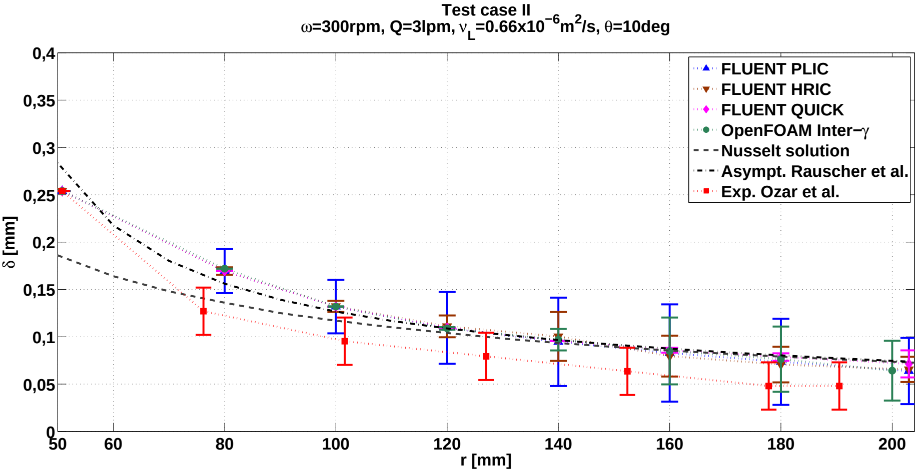
Test case I - Time averaged values $(\omega = 200 rpm,\ Q = 7 lpm)$



Temporal averages

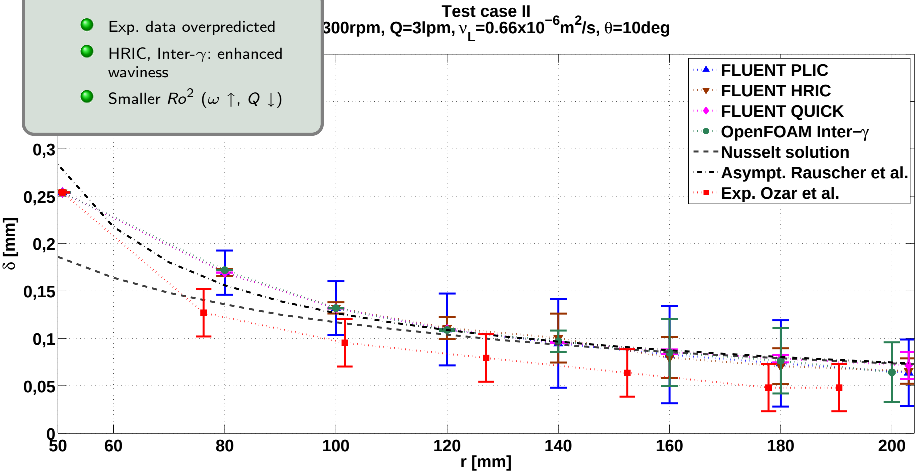
- good agreement with experimental data
- QUICK $\approx$ Inter-γ (smooth)
- approach asymptotic solution in outer region

Test case II - Time averaged values $(\omega = 300 rpm,\ Q = 3 lpm)$



Test case II - Time averaged values $(\omega = 300rpm,\ Q = 3lpm)$

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



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-γ and QUICK show smoother solutions with smaller waviness
- Sensitivity of instantaneous results to surface tracking schemes requires further investigations

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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
    ($\omega = 200 rpm,\ Q = 7 lpm$)
  - Overpredictions for Test cases II
    ($\omega = 300 rpm,\ Q = 3 lpm$)
    $\rightarrow$ possibly enhanced 3d-effects?
    $\rightarrow$ influence of measurement technique?

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