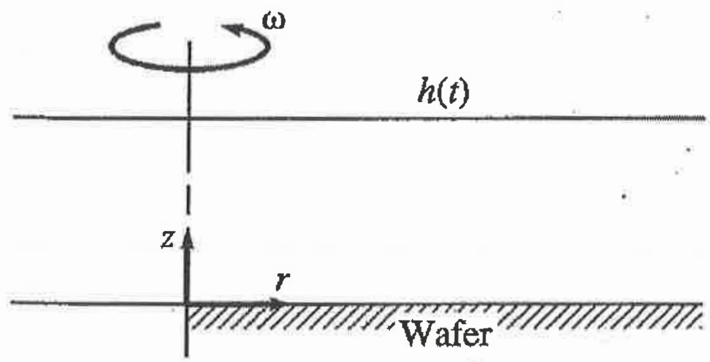
DRAFT v1 – SPIN COATING PROBLEM (ME 347 – FALL 2016)

Problem Statement:

In the microelectronics industry, very thin coatings of liquids are created on planar substrates by a process known as spin coating. The most common application of spin coating is to deposit photo-sensitive liquids, called photoresists, onto silicon wafers for pattern transfer. During the spin coating process, a liquid is first dispensed at the center of a substrate. The substrate is typically a flat circular surface. Following the dispense step, the substrate is rotated at a low speed (several hundred rpm) in order to spread the liquid uniformly across the surface. The film thickness at the end of this spread cycle is h_0. Finally, the substrate is rotated at high speed (typically several thousand rpm) for a desired period of time to produce a thin film. During this spin cycle the film thickness is everywhere uniform; however, it is a function of time, i.e. $h(t)$ only. Your goal is to obtain an expression for the liquid film thickness h as a function of the spin speed ω, the spin time t, liquid viscosity μ, and liquid density ρ. Consider the problem to be one of axisymmetric laminar flow of a Newtonian fluid, where at any time during the spin cycle the liquid film is of uniform thickness everywhere on the substrate. Also consider that the substrate is uniformly covered with a thick layer of liquid prior to the spin, i.e., $h_0(t=0) \gg h(t)$. You may also assume that the viscosity of the liquid is such that viscous effects dominate over inertial effects. Note that although in practice the substrate has a finite diameter D, your solution will not depend on the extent of the substrate.



FIND
$h(\omega, t, \mu, \rho)$

ASSUME
AXISYMMETRIC
NEWTONIAN FLUID
LAMINAR FLOW
UNIFORM THICKNESS EVERYWHERE
* $h_0(t=0) \gg h(t)$
VISCOUS EFFECTS DOMINATE INERTIAL $\Rightarrow$ Re is small

STANDARD ATMOSPHERE
INCOMPRESSIBLE
UNIFORM DENSITY
CONSTANT VISCOSITY
$g = g\hat{e}_z$

FIND

$h(t, w, \mu, \rho)$ or $h(t, w, \nu)$

ASSUME

AXISYMMETRIC
NEWTONIAN FLUID
LAMINAR FLOW
UNIFORM THICKNESS
$h_0(t=0) \gg h(t)$
VISCOUS EFFECTS DOMINATE INERTIAL ⇒ Re is small

STANDARD ATMOSPHERE
INCOMPRESSIBLE
UNIFORM DENSITY
CONSTANT VISCOSITY
$g = g\hat{e}_z$

IGNORE EVAPORATION

EQUATION OF MOTION: CYLINDRICAL NAVIER STOKES

- ONLY r-DIRECTION IS SIGNIFICANT

$$\rho\left(\frac{\partial v_r}{\partial t}^{\nearrow 0} + \left[v_r\frac{\partial v_r}{\partial r}\right]^{? 0} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta}^{\nearrow 0} - \frac{v_\theta^2}{r} + \left[v_z\frac{\partial v_r}{\partial z}\right]^{\text{small}}\right)$$

small change; small continuity?; axisymmetric; possibly small

$$= -\frac{\partial p}{\partial r}^{\nearrow 0} + \rho g_r^{\nearrow 0} + \mu\left[\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right)\right]^{? 0} - \left[\frac{v_r}{r^2}\right]^{? 0} + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2}^{\nearrow 0} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta}^{\nearrow 0} + \frac{\partial^2 v_r}{\partial z^2}\right]$$

insignificant zero; not in r direction; negligible?

$$-\rho\frac{v_\theta^2}{r} = \mu\frac{\partial^2 v_r}{\partial z^2}$$

$$v_\theta = wr$$

$$-\rho\frac{(wr)^2}{r} = \mu\frac{\partial^2 v_r}{\partial z^2}$$

$$-\rho w^2 r = \mu\frac{\partial^2 v_r}{\partial z^2}$$

→

SECOND ORDER ORDINARY DIFFERENTIAL EQUATION WITH CONSTANT COEFFICIENTS

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

SEPARATE INTEGRATE

$$\partial\left(\frac{\partial v_r}{\partial z}\right) = -\frac{\rho}{\mu}\omega^2 r \int \partial z$$

$$\frac{\partial v_r}{\partial z} = -\frac{\rho}{\mu}\omega^2 r \left[z + C_1 \right]$$

ASIDE: BOUNDARY CONDITIONS

① $\frac{\partial v_r}{\partial z}(z=h) = 0$
free surface
no stress

② $v(z=0) = 0$
surface
no slip

APPLY BC ①

$$\frac{\partial v_r}{\partial z}(z=h) = -\frac{\rho}{\mu}\omega^2 r (h + C_1) = 0$$

$$\Rightarrow C_1 = -h$$

$$\frac{\partial v_r}{\partial z} = -\frac{\rho}{\mu}\omega^2 r (z - h)$$

SEPARATE INTEGRATE

$$\partial(v_r) = -\frac{\rho}{\mu}\omega^2 r \int (z-h)\partial z$$

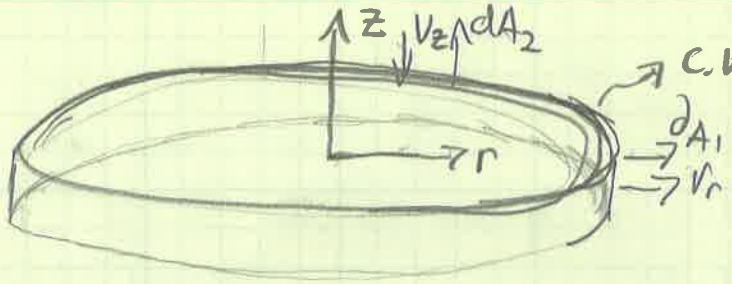
$$v_r = -\frac{\rho\omega^2 r}{\mu}\left(\frac{z^2}{2} - hz + C_2\right)$$

APPLY BC ②

$$v(z=0) = -\frac{\rho\omega^2 r}{\mu}(0 - 0 + C_2)$$

$$\Rightarrow C_2 = 0$$

$$\boxed{v_r(z) = -\frac{\rho\omega^2 r}{\mu}\left(\frac{z^2}{2} - hz\right)}$$



R.T.T OF MASS

$$\frac{\partial m}{\partial t}\Big)_{sys} = \frac{\partial}{\partial t}\int_{CV} \rho \, dV + \int_{A1} \rho v_r \, dA_1 - \int_{A2} \rho v_z \, dA_2$$

$$\rho \int v_r \, dA_1 = \rho \int v_z \, dA_2$$

$$2\pi R^2 v_z = 2\pi R \int_0^h \frac{\rho \omega^2}{\mu} R \left(hz - \frac{z^2}{2}\right) dz$$

$$\pi R^2 v_z = 2\pi \frac{\rho \omega^2 R^2}{\mu} \int_0^h \left(hz - \frac{z^2}{2}\right) dz$$

$$= 2\pi \frac{\rho \omega^2 R^2}{\mu} \left[\frac{hz^2}{2} - \frac{z^3}{6} \right]_0^h$$

$$= 2\pi \frac{\rho \omega^2 R^2}{\mu} \left(\frac{h^3}{2} - \frac{h^3}{6} \right)$$

$$\pi R^2 v_z = \frac{2\pi \rho \omega^2 R^2 h^3}{3\mu}$$

$$\boxed{v_z = \frac{2 \rho \omega^2 h^3}{3\mu}}$$

$$V_z = -\frac{\partial h}{\partial t}$$

SUBSTITUTE

$$-\frac{1}{h^3}\,\partial h = \frac{2}{3}\frac{\rho w^2}{\mu}\,dt$$

$$\int_{h_0}^{h} -\frac{1}{h^3}\,dh = \int_0^t \frac{2}{3}\frac{\rho w^2}{\mu}\,\partial t$$

$$\frac{1}{h^2}\Big|_{h_0}^{h} = \frac{2}{3}\frac{\rho w^2}{\mu}\int \partial t$$

$$\frac{1}{2h^2} - \frac{1}{2h_0^2} = \frac{2\rho w^2 t}{3\mu}$$

* ASSUME $h_0(t=0) >> h(t)$

$$h(t) = \sqrt{\frac{3\mu}{4\rho w^2 t}}$$

$$\boxed{h(t) = \sqrt{\frac{3\mu}{4\rho w^2 t}}}$$

7/24/16 SPIN COATING ME-347 - RESEARCH SAMUEL LEE 1

LAB PLAN

RESTRICTIONS

ω - 0 - 6000 rpm

t 0 - 1000 sec

Scale resolution 0.001 grams

Wafer diameter 2" - 6.5"

STEPS:

1. CUT WAFERS
2. MEASURE MASS OF WAFER
3. PLACE FLUID
4. SPIN
5. REMEASURE FINAL MASS
6. CALCULATE PERCENT ERROR

EQUATIONS NAVIER STOKES
CONTINUITY EQUATION

(2)

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial(\rho r v_r)}{\partial r} + \frac{1}{r}\frac{\partial(\rho v_\theta)}{\partial \theta} + \frac{\partial(\rho v_z)}{\partial z} = 0$$

EQUATION OF MOTION

r-direction ☆ z

(3)

$$\rho\left(\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z\frac{\partial v_r}{\partial z}\right)$$

$$= -\frac{\partial p}{\partial r} + \rho g_r + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) - \frac{v_r}{r^2} + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2}\right]$$

θ-direction

$$\rho\left(\frac{\partial v_\theta}{\partial t} + v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z\frac{\partial v_\theta}{\partial z}\right)$$

$$= -\frac{1}{r}\frac{\partial p}{\partial \theta} + \rho g_\theta + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_\theta}{\partial r}\right) - \frac{v_\theta}{r^2} + \frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2}\right]$$

z-direction

(1)

$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}\right)$$

$$= -\frac{\partial p}{\partial z} + \rho g_z + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right]$$

BOUNDARY CONDITIONS

(1) $v(z=0)=0$ surface, no slip

(2) $\frac{\partial v}{\partial z}(z=h)=0$ free surface, atmosphere

Neglect gravity? neglect pressure gradient?
so thin

THOUGHT CHECK

- STEPS
  1. ASSUMPTIONS ⇒ NAVIER STOKES
  2. BOUNDARY CONDITIONS
  3. CONTINUITY? MASS IS CONSERVED

$$\frac{\partial V}{\partial t} \quad \frac{\partial \rho}{\partial t} \; ?$$

WHAT CAN BE NEGLECTED?

1. GRAVITY? g_z

   REASON: THE ω (RPM) HAS A MUCH GREATER EFFECT

2. $\frac{\partial P}{\partial z}$

   REASON: THIN, PRESSURE CHANGE IS MINIMAL ≈ 0

ASSUMPTIONS IN MORE DETAIL

① AXISYMMETRIC

WHY:

SIG:

② NEWTONIAN

WHY:

SIG:

③ LAMINAR

WHY:

SIG:

④ UNIFORM THICKNESS

WHY:

SIG:

⑤ $h_0(t=0) \gg h(t)$

WHY:

SIG:

⑥ VISCOUS EFFECTS DOMINATE INERTIAL

WHY

SIG:

ASSUMPTIONS CONTINUED

⑦ STD. ATM

WHY:

SIG:

⑧ INCOMPRESSIBLE

WHY:

SIG:

⑨ UNIFORM DENSITY

WHY:

SIG:

⑩ CONSTANT VISCOSITY

WHY:

SIG:

⑪ $g = g\,\hat{e}_z$

WHY:

SIG:

$\frac{\partial p}{\partial t}$ does not change with time

$\frac{\partial v_\theta}{\partial \theta}$ constant

$\frac{\partial v_r}{\partial t}$ constant

$\frac{\partial v_r}{\partial \theta}$ v_r does not change with theta

$\frac{\partial v_r}{\partial z}$ does not change with z, negligible

$\frac{\partial p}{\partial r}$ does not change with r

$\rho g_r \quad g_z = g_z$

r-directions ?

$$\rho\left(v_r \frac{\partial v_r}{\partial r} - \frac{v_\theta^2}{r}\right) = \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) - \frac{v_r}{r^2} + \frac{\partial^2 v_r}{\partial z^2}\right]$$

$$-\rho\frac{v_\theta^2}{r}$$

θ-direction

$$\rho v_r \frac{v_\theta}{r} = \mu\left[-\frac{v_\theta}{r^2}\right] \quad \rho v_r = \frac{\mu}{r}$$

$\frac{\partial v_z}{\partial r}$ not a

z-direction

$$\rho v_z \frac{\partial v_z}{\partial z} = \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right)\right] \Rightarrow \frac{\partial v_z}{\partial z} = 0 \text{ ?} \quad (1)$$

Continuity

$$\frac{1}{r}\frac{\partial(r v_r)}{\partial r} + \frac{\partial v_z}{\partial z} = 0$$

$$\frac{1}{r}\frac{\partial(r v_r)}{\partial r} = 0 \quad (2)$$

$$v_r \frac{\partial r}{\partial r}$$

$$\frac{1}{r} r \frac{\partial v_r}{\partial r} + \frac{v_r}{r}\frac{\partial r}{\partial r} = 0$$

$$\frac{\partial v_r}{\partial r} + \frac{v_r}{r}\frac{\partial r}{\partial r} = 0$$

z direction

$$\rho\frac{\partial v_z}{\partial t} + \rho v_z \frac{\partial v_z}{\partial z} =$$

$$\frac{\partial v_z}{\partial t} = -v_z\frac{\partial v_z}{\partial z} \Rightarrow \frac{\partial v_z}{\partial z} = \frac{-\partial v_z}{v_z\,\partial t}$$

$$-\rho \frac{v_\theta^2}{r} = \mu \frac{\partial^2 v_r}{\partial z^2} \qquad v_\theta = \omega r$$

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

separate and integrate

$$-\frac{1}{\mu}\rho\omega^2 r \int \partial z = \partial\left(\frac{\partial v_r}{\partial z}\right)$$

$$\frac{\partial v_r}{\partial z} = -\frac{1}{\mu}\rho\omega^2 r(z + c_1)$$

BC ② $\frac{\partial v_r}{\partial z}(z = h) = 0$

$$0 = -h\rho\omega^2 r + c_1 \Rightarrow$$

$$c_1 = h$$

$$\frac{\partial v_r}{\partial z} = -\frac{1}{\mu}\rho\omega^2 r(z + h)$$

$$v_r = -\frac{1}{\mu}\rho\omega^2 r\left(\frac{z^2}{2} + hz + c_2\right)$$

BC ① $v_r(0) = 0$

$$0 = \left(\frac{z^2}{2} + hz + c_2\right) \qquad c_2 = 0$$

$$v_r = -\frac{1}{\mu}\rho\omega^2 r\left(\frac{z^2}{2} + hz\right)$$

$$\boxed{v_r = -\frac{\rho}{\mu}\omega^2 r\left(\frac{z^2}{2} + hz\right)}$$

CONTINUITY

$$\frac{1}{r}\frac{\partial(r v_r)}{\partial r} + \frac{\partial v_z}{\partial z} = 0$$

$$\boxed{r\frac{\partial h}{\partial t}}\ ??$$

$$V = \pi r^2 h$$

$$\frac{\partial V}{\partial t} = \pi \frac{\partial r^2 h}{\partial t} = \pi r^2 \frac{\partial h}{\partial t} + 2\pi h r \frac{\partial r}{\partial t}$$

$$\boxed{\frac{\partial V}{\partial t} = \pi r^2 \frac{\partial h}{\partial t} + 2\pi r \frac{\partial r}{\partial t}}$$

CONTINUITY

$$0 = \frac{1}{r}\frac{\partial(r v_r)}{\partial r} + \frac{\partial v_z}{\partial z} \approx \frac{1}{r}\frac{\partial(r v_r)}{\partial r}$$

$$\rho\left(v_r\frac{\partial v_r}{\partial r} - \frac{v_\theta^2}{r}\right) = \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) - \frac{v_r}{r^2} + \frac{\partial^2 v_r}{\partial z^2}\right]$$

≈ 0

* 0? * 0? ? *

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

$$Q = 2\pi r\int_0^h u_r \, \partial z = -\pi R^2\frac{dh}{dt}$$

$$= 2\pi r\int_0^h -\frac{\rho}{\mu}\omega^2 r\left(\frac{z^2}{2} + hz\right)\partial z$$

$$= -\frac{2\pi\rho\omega^2 r^2}{\mu}\left(\frac{z^3}{6} + \frac{hz^2}{2}\right) = -\pi R^2\frac{dh}{dt}$$

$$= -2\frac{\rho\omega^2}{\mu}\left(\frac{h^3}{6} + \frac{h^3}{2}\right) = -\frac{dh}{dt}$$

$$\left(\frac{1h^3}{6} + \frac{3}{6}h^3\right)$$

$$\frac{4}{6}$$

$$= \frac{4}{3}\frac{\rho\omega^2}{\mu}h^3 = \frac{\partial h}{\partial t}$$

$$\frac{dh}{dt} = \frac{4}{3}\frac{\rho\omega^2 h^3}{\mu}$$

$$\frac{1}{h^3}\,\partial h = \frac{4}{3}\frac{\rho\omega^2}{\mu}\,{}^{3}\,dt$$

$$h^{-3} \quad \frac{h^{-2}}{-2}\Big|_{h_0}^{h}$$

$$h^{-2}$$

ENGINEERING DATA SHEET
Excel Spreadsheet
Sheet: Spin Coating Data
File : ME 347 - Spin Coating Project.xlsm

Mechanical Engineering CAL POLY

Sheet No. X - 1 Date
Prepared by: HCM 08/01/16
Checked by: XXX XX/XX/XX
Approved by: XXX XX/XX/XX

Data from spin coating experiments (H. Mayer & S. Lee)

Liquid:	Karo Syrup (DARK)		Sub. Dia.:	100	[mm]
Viscosity:	3300	[mPa-s]	Time:	50	[sec]
Density:	1370	[kg/m^3]			

Data No. [-]	Speed [rpm]	Bare Mass [gm]	Spun Mass [gm]	Liq. Mass [gm]	Thickness [um]	Unc.± [um]
1.1	3000	14.019	14.270	0.251	23.3	1.26
1.2	3000	13.602	13.850	0.248	23.0	1.24
1.3	3000	14.071	14.316	0.245	22.8	1.23
1.4	3000	13.977	14.224	0.247	23.0	1.24
1.5	3000	13.955	14.205	0.250	23.2	1.25
1.6	3000	13.883	14.133	0.250	23.2	1.25
1.7	3000	13.354	13.603	0.249	23.1	1.25
1.8	3000	13.853	14.103	0.250	23.2	1.25
2.1	6000	13.962	14.100	0.138	12.8	0.69
2.2	5000	14.041	14.178	0.137	12.7	0.69
2.3	4000	13.360	13.543	0.183	17.0	0.92
2.4	3000	13.984	14.217	0.233	21.7	1.17
2.5	2000	13.870	14.198	0.328	30.5	1.64
2.6	1000	13.888	14.544	0.656	61.0	3.28
3.1	6000	13.612	13.733	0.121	11.2	0.61

Notes:
1. Static charge from glove-substrate-paper towel contact can have a dramatic effect on the accuracy of measurements.
Exampel, data point 2.1 is highly suspect and should be replaced with data point 3.1.

Data from spin coating experiments (H. Mayer & S. Lee)

Liquid:	Canola Oil		Sub. Dia.:	100	[mm]
Viscosity:	70	[mPa-s]	Time:	50	[sec]
Density:	920	[kg/m^3]			

Data No. [-]	Speed [rpm]	Bare Mass [gm]	Spun Mass [gm]	Liq. Mass [gm]	Thickness [um]	Unc.± [um]
1.1	1000	13.609	13.689	0.080	11.1	0.60
1.2	5000	14.075	14.089	0.014	1.9	0.13
2.1	6000	13.797	13.810	0.013	1.8	0.12
2.2	5000	13.607	13.622	0.015	2.1	0.13
2.3	4000	14.076	14.099	0.023	3.2	0.18
2.4	3000	13.357	13.383	0.026	3.6	0.21
2.5	2000	13.968	13.998	0.030	4.2	0.23
2.6	1000	13.858	13.936	0.078	10.8	0.59
2.7	2000	13.886	13.924	0.038	5.3	0.29
2.8	1500	13.984	14.037	0.053	7.3	0.40

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Mechanical Engineering CAL POLY

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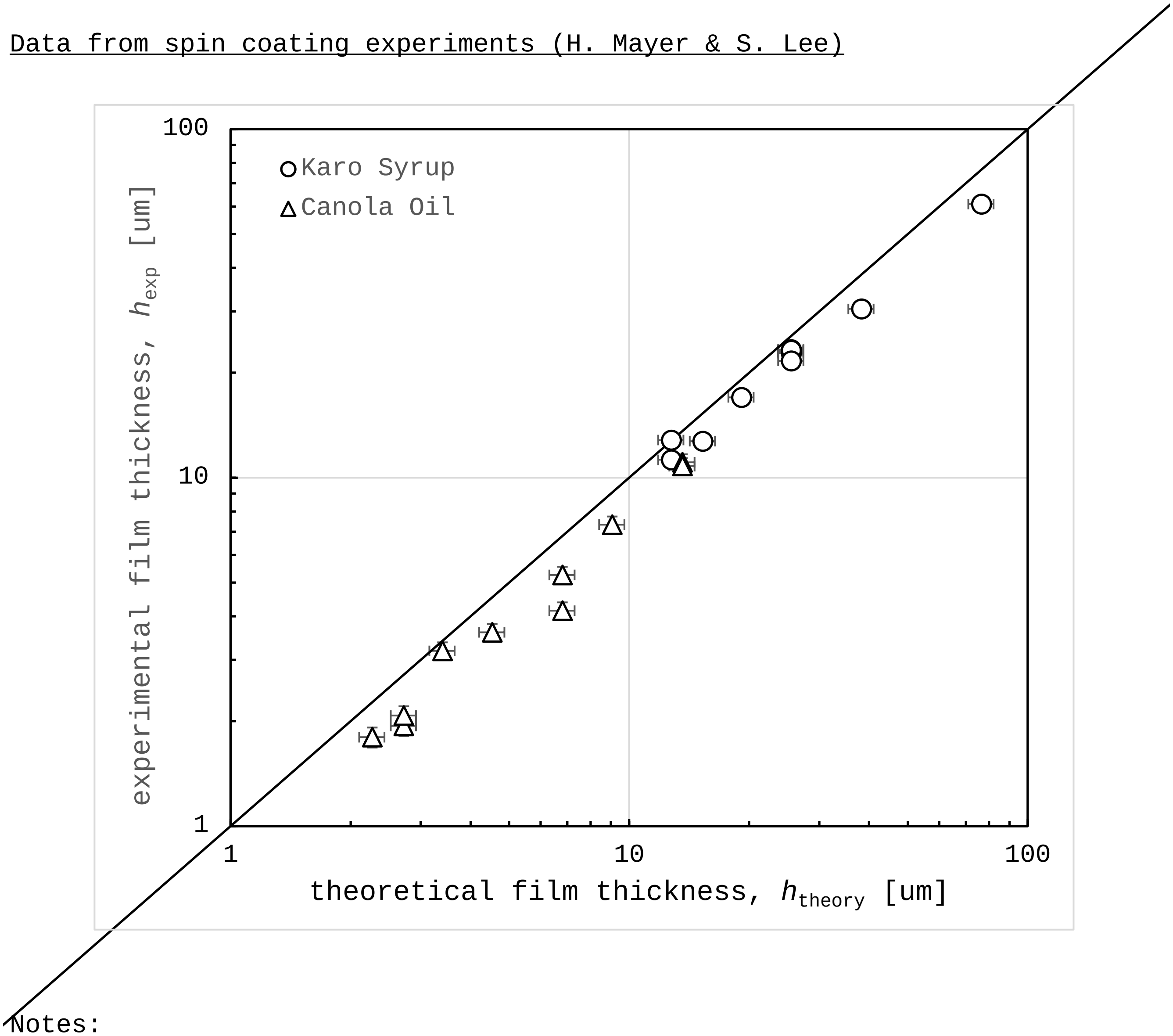
Checked by: XXX	XX/XX/XX
Approved by: XXX	XX/XX/XX

Data from spin coating experiments (H. Mayer & S. Lee)



Notes:

1. Plot 1:1 line 0.1 0.1
1000 1000

HYPOTHETICAL thicknesses for future EXPERIMENTS

Liquid:	Molassas		Sub. Dia.:	100	[mm]
Viscosity:	10800	[mPa-s]	Time:	50	[sec]
Density:	1400	[kg/m^3]			

Data No. [-]	Speed [rpm]	Bare Mass [gm]	Spun Mass [gm]	Liq. Mass [gm]	Thickness [um]	Unc.± [um]
1.1	1000	14.000	15.506	1.506	137.0	7.38
1.2	5000	14.000	14.753	0.753	68.5	3.69
1.3	6000	14.000	14.502	0.502	45.7	2.46
1.4	5000	14.000	14.376	0.376	34.2	1.84
1.5	4000	14.000	14.301	0.301	27.4	1.48
1.6	3000	14.000	14.251	0.251	22.8	1.23

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Mechanical Engineering CAL POLY

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Checked by: XXX	XX/XX/XX
Approved by: XXX	XX/XX/XX

HYPOTHETICAL thicknesses for future EXPERIMENTS

Liquid:	Mineral Oil		Sub. Dia.:	100	[mm]
Viscosity:	15	[mPa-s]	Time:	50	[sec]
Density:	920	[kg/m^3]			

Data No. [-]	Speed [rpm]	Bare Mass [gm]	Spun Mass [gm]	Liq. Mass [gm]	Thickness [um]	Unc.± [um]
1.1	1000	14.000	14.045	0.045	6.3	0.35
1.2	5000	14.000	14.023	0.023	3.1	0.18
1.3	6000	14.000	14.015	0.015	2.1	0.13
1.4	5000	14.000	14.011	0.011	1.6	0.11
1.5	4000	14.000	14.009	0.009	1.3	0.10
1.6	3000	14.000	14.008	0.008	1.0	0.09

THEORETICAL film thicknesses calculated for experimental conditions

Liquid:	Karo Syrup (DARK)		Sub. Dia.:	100	[mm]
Viscosity:	3300	[mPa-s]	Time:	50	[sec]
Density:	1370	[kg/m^3]			

Data No. [-]	Speed [rpm]	Thickness [um]	Unc.± [um]	% Diff [%]
1.1	3000	25.5	1.86	-8.561
1.2	3000	25.5	1.86	-9.654
1.3	3000	25.5	1.86	-10.747
1.4	3000	25.5	1.86	-10.018
1.5	3000	25.5	1.86	-8.925
1.6	3000	25.5	1.86	-8.925
1.7	3000	25.5	1.86	-9.289
1.8	3000	25.5	1.86	-8.925
2.1	6000	12.8	0.93	0.547
2.2	5000	15.3	1.11	-16.818
2.3	4000	19.1	1.39	-11.111
2.4	3000	25.5	1.86	-15.118
2.5	2000	38.3	2.79	-20.340
2.6	1000	76.5	5.57	-20.340
3.1	6000	12.8	0.93	-11.840

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THEORETICAL film thicknesses calculated for experimental conditions

Liquid:	Karo Syrup (DARK)		Sub. Dia.:	100	[mm]
Viscosity:	70	[mPa-s]	Time:	50	[sec]
Density:	920	[kg/m^3]			

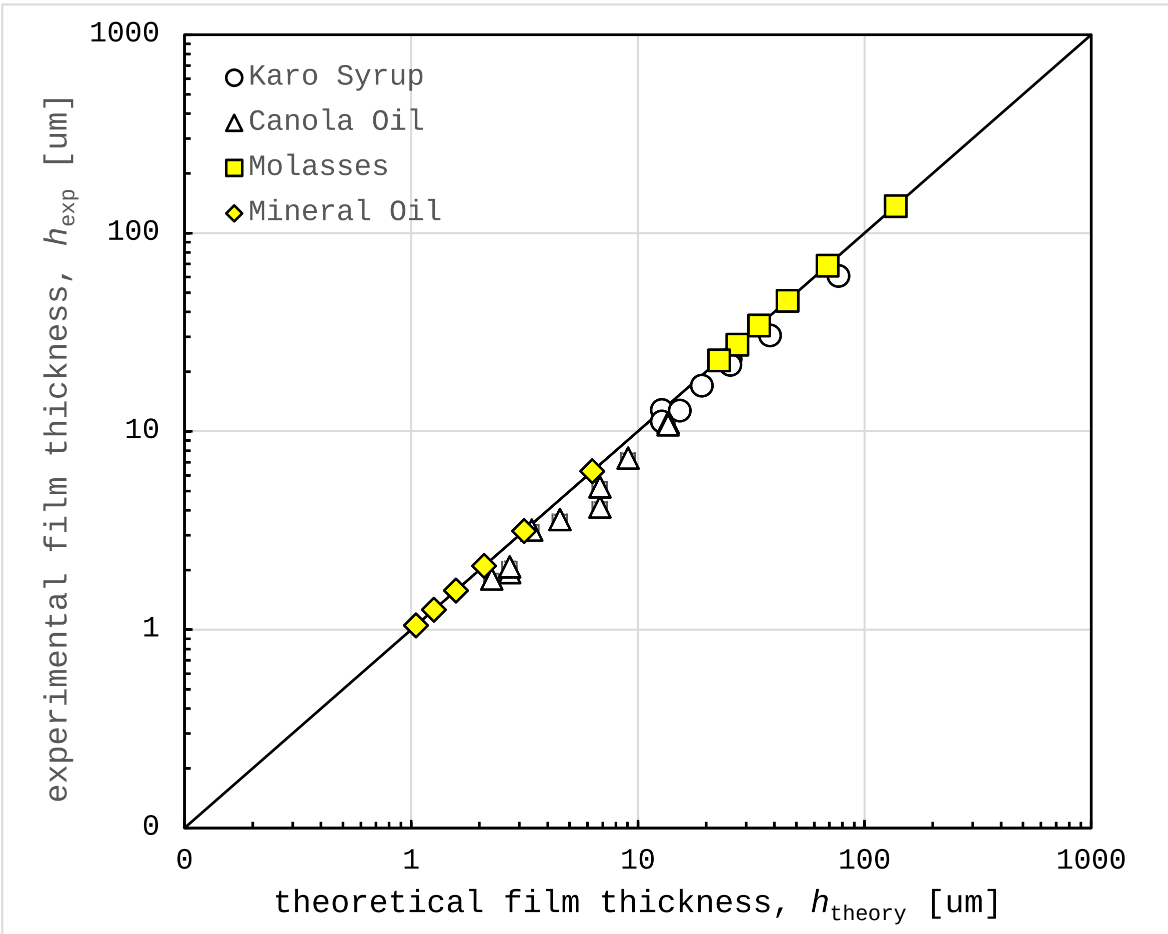
Data No. [-]	Speed [rpm]	Thickness [um]	Unc.± [um]	% Diff [%]
1.1	1000	13.6	0.99	-18.604
1.2	5000	2.7	0.20	-28.779
2.1	6000	2.3	0.17	-20.639
2.2	5000	2.7	0.20	-23.692
2.3	4000	3.4	0.25	-6.395
2.4	3000	4.5	0.33	-20.639
2.5	2000	6.8	0.50	-38.953
2.6	1000	13.6	0.99	-20.639
2.7	2000	6.8	0.50	-22.674
2.8	1500	9.1	0.66	-19.113

ENGINEERING DATA SHEET
Excel Spreadsheet
Sheet: Spin Coating Data
File : ME 347 - Spin Coating Project.xlsm

Mechanical Engineering CAL POLY

Sheet No. X - 8 | Date
Prepared by: HCM 08/01/16
Checked by: XXX XX/XX/XX
Approved by: XXX XX/XX/XX

PLOT WITH EXPERIMENTAL DATA AND HYPOTHETICAL DATA



HYPOTHETICAL thicknesses (THEORETICAL)

Liquid:	Molasses		Sub. Dia.:	100	[mm]
Viscosity:	10800	[mPa-s]	Time:	50	[sec]
Density:	1400	[kg/m^3]			

Data No. [-]	Speed [rpm]	Thickness [um]	Unc.± [um]	% Diff [%]
1.1	1000	137.0	9.97	0.000
1.2	2000	68.5	4.99	0.000
1.3	3000	45.7	3.32	0.000
1.4	4000	34.2	2.49	0.000
1.5	5000	27.4	1.99	0.000
1.6	6000	22.8	1.66	0.000

HYPOTHETICAL thicknesses (THEORETICAL)

Liquid:	Mineral Oil		Sub. Dia.:	100	[mm]
Viscosity:	15	[mPa-s]	Time:	50	[sec]
Density:	920	[kg/m^3]			

Data No. [-]	Speed [rpm]	Thickness [um]	Unc.± [um]	% Diff [%]
1.1	1000	6.3	0.46	0.000
1.2	2000	3.1	0.23	0.000
1.3	3000	2.1	0.15	0.000
1.4	4000	1.6	0.11	0.000
1.5	5000	1.3	0.09	0.000
1.6	6000	1.0	0.08	0.000