"A best film thickness model in using interferometry in finding the pressure-viscosity coefficient alpha of a fluid"

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Shell Global Solutions

A best film thickness model in using interferometry

in finding the pressure-viscosity coefficient α of a fluid

TU/e technische universiteit eindhoven

Hamburg, June 19, 2009
5th Arnold Tross Colloquium
Harry van Leeuwen

Presentation Outline

1. Introduction and aim
2. Analysis and methods
3. Results and Discussion
4. More homework ….
5. Results and Discussion (continued)
6. Conclusions

1. Introduction and aim (1)

Why?

- In many lubricated tribosystems the pressure-viscosity coefficient (α) is important but not known
- This is especially true for hard EHL contacts (having high moduli of elasticity and very high contact pressures) $\Rightarrow$ a guess easily leads to gross errors in the film thickness
- In addition, the pressure dependency of fluids is becoming more and more important. Think of common rail injection of diesel fuel, soon at 3,000 bars (0.3 GPa)

1. Introduction and aim (3)

Pressure viscosity coefficients for high pressures are determined at a few institutes only, e.g.

- at the Center for High Pressure Rheology of Georgia Tech, Atlanta (Scott Bair), or
- at Luleå University (Eric Höglund),
- at the RWTH Aachen (Peter Gold) or
- at the TU Clausthal (Hubert Schwarze)

To calculate EHL films the value of α has to be known.

Central question:

How can α be determined, having film thickness measurement equipment and some tribological knowledge?

1. Introduction and aim (2)

We want to find the (generalized) pressure-viscosity coefficient:

$$\alpha^* = \left(\int_0^\infty \frac{\eta_0}{\eta(p)}\, dp \right)^{-1} \qquad (Blok)$$

where

η the dynamic viscosity	(Pa.s)
η_0 the dynamic viscosity at p = 0	(Pa.s)
α* the reciprocal asymptotic isoviscous pressure,	(Pa^{-1})

…. a proven good estimate of α

For the simple Barus relationship:

$$\eta = \eta_0\, e^{\alpha p} \quad \Rightarrow \quad \alpha = \frac{1}{\eta}\frac{\partial \eta}{\partial p} \quad (Barus)$$

$$for\ \ a\ Barus\ relationship: \quad \alpha^* = \alpha$$

Overview

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2. Analysis and methods

The idea, already coined at the occasion of the IIIrd Arnold Tross Colloquium on June 8th, 2007:

Determine α through film thickness:

- perform film thickness measurements (all conditions known, except α)
- calculate these film thickness values by employing methods from numerical analysis, or approximation formulas
- assume a value for α which minimizes the error between measurement and calculation for all measurements

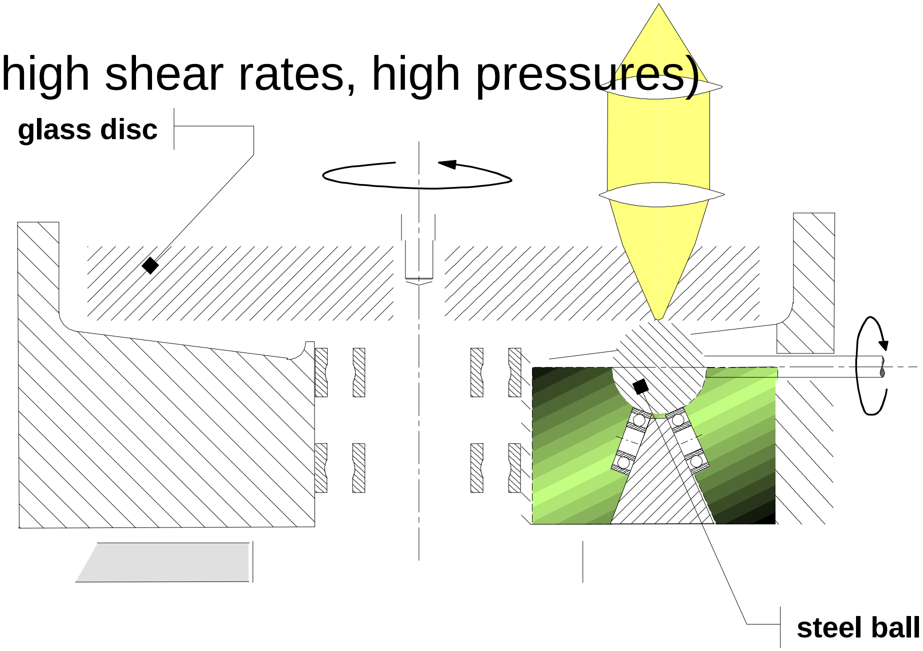
Now needed:

- an accurate film thickness measurement method
- an accurate film thickness problem solver or formula

2. Analysis and methods (2)

Advantages:

- Shell got such an accurate film thickness measuring device (a PCS Instruments Ultra Thin Film Measurement System, at Shell Westhollow, in Houston, TX)
- in general, film thickness rigs are more widely spread over the world than high pressure viscometers
- conditions are much like in practice (high shear rates, high pressures)



Figures: PCS Instruments EHL Ultra Thin Film Measurement System

2. Analysis and methods (3)

Abbe´s limit:

$h > \frac{1}{4}\lambda \approx 100\ \text{nm} = 0.1\ \mu\text{m}$

But: the inaccuracy of the measurement is less than 1 nm.

Now a trick is exploited:

spacer layer of 500 nm = 0.5 μm

allows 1 < h < 100 nm

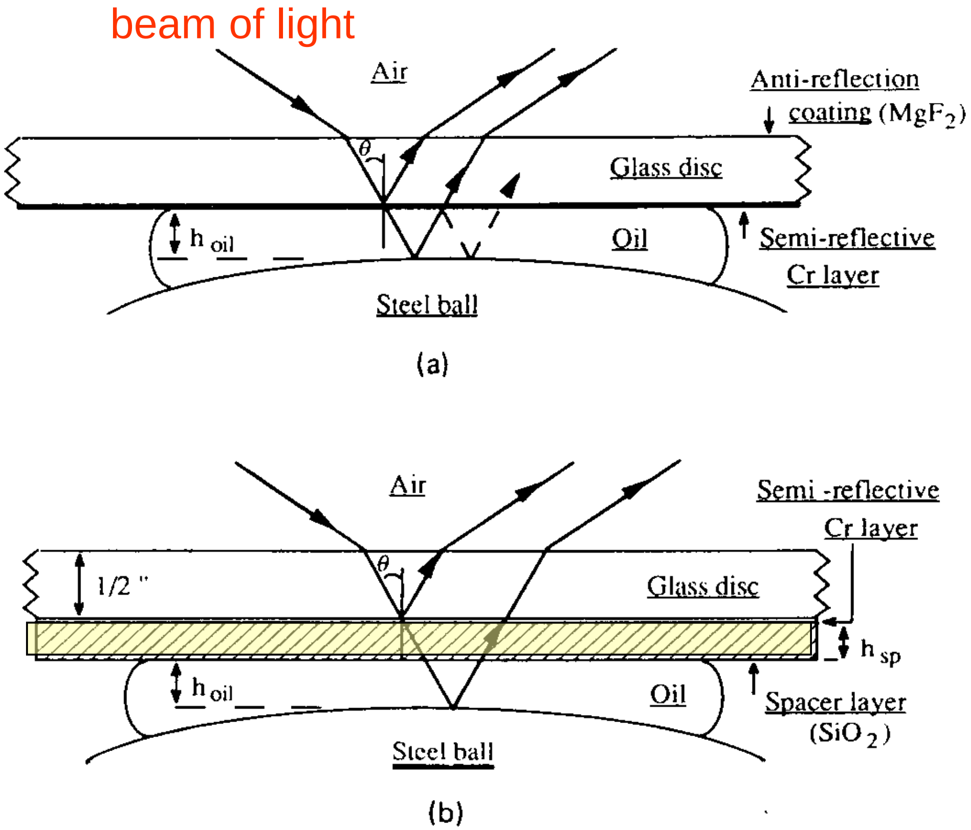


Fig. 1—(a) Basic interferometric method (two beam).
(b) Spacer layer method.

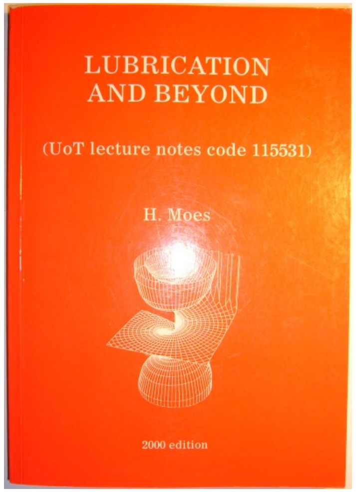
Source: Johnston et al., 1991

2. Analysis and methods (4)

The measurements part.

- a PCS Instruments EHL Ultra Thin Film Measurement System.
- This allows measurement of the central film thickness with an inaccuracy down to 1 nm.

The calculation part.
Back in 2007, is from a Textbook by Moes (2000), which provides an estimate of the central film thickness in nonconformal contacts, with claimed small inaccuracy (better than 10% everywhere)


LUBRICATION
AND BEYOND

(UoT lecture notes code 115531)

H. Moes

2000 edition

2. Analysis and methods (5)

Using the nondimensional groups now so common in EHL work, originally from Blok (1960) and Moes (1965), adapted for elliptical contacts, yields:

$$\textit{film thickness group } \hat{H} = \left(\frac{h}{R_e}\right)\left(\frac{E_r R_e}{2\eta_0 \bar{u}}\right)^{\frac{1}{2}}$$

$$\textit{load group } M = \left(\frac{F}{E_r {R_e}^2}\right)\left(\frac{E_r R_e}{2\eta_0 \bar{u}}\right)^{\frac{3}{4}}$$

$$\textit{lubricant group } L = (\alpha E_r)\left(\frac{2\eta_0 \bar{u}}{E_r R_e}\right)^{\frac{1}{4}}$$

$$\textit{ellipticity group } \omega = \left(\frac{R_t}{R_e}\right) \qquad \Rightarrow \textit{here } \omega = 1$$

Moes (2000) finds ⇒

$$\hat{H}_c = \left[\left\{{\hat{H}_{IR}}^{\frac{3}{2}} + \left({\hat{H}_{IE}}^{-4} + 0.1\omega^{-4}\right)^{-\frac{3}{8}}\right\}^{\frac{2}{3}\hat{s}} + \left({\hat{H}_{VR}}^{-8} + {\hat{H}_{VE}}^{-8}\right)^{-\frac{1}{8}\hat{s}}\right]^{\frac{1}{\hat{s}}}$$

where

$$\hat{s} = \frac{3}{2}\left\{1 + \exp\left(-1.2\frac{\hat{H}_{IE}}{\hat{H}_{IR}}\right)\right\}$$

and $\hat{H}_c = \hat{H}_c(M, L, \omega)$

2. Analysis and methods (6)

Moes states that in a domain $5 \leq M \leq 1000$, $0 \leq L \leq 25$
for a circular contact the inaccuracy of his latest approximation formula is $e < 10\%$

The advantages:

- one formula fits all: an enormous range of conditions, even beyond practice
- looks attractive

For a circular contact ⇒

But why should we believe these claims?

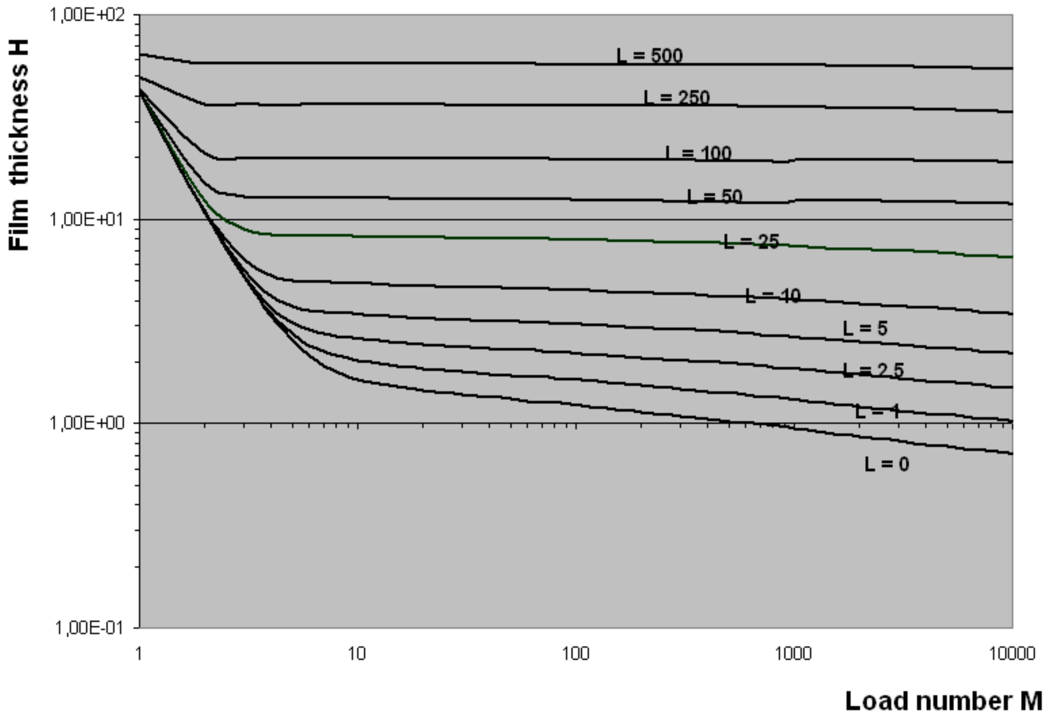


Figure: Nondimensional film thickness vs. Load Parameter M and Lube Parameter L

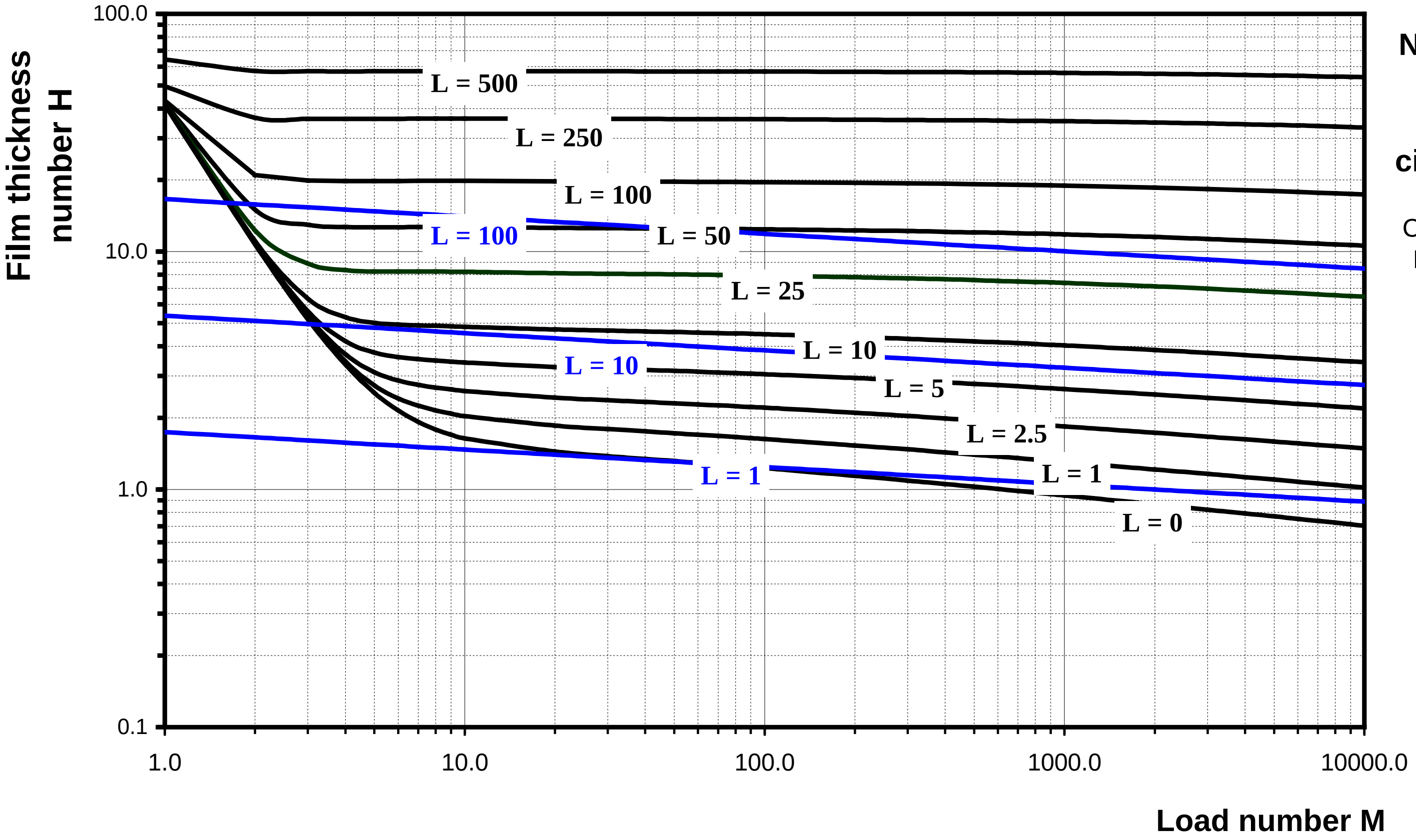
2. Analysis and methods (7)

Many more film thickness model equations exist:

- Archard and Cowking (1965) for circular hard contacts
- Hamrock and Dowson (1977, 1981) for circular and short elliptical contacts
- Hamrock et al. (2004) and Hamrock (1994) for circular and short elliptical contacts
- Chittenden et al. (1985) for circular and long elliptical contacts
- Hooke (1988)
- Sutcliffe (1989) for arbitrary elliptical contacts
- Greenwood (1988) for circular contacts
- Venner (1991), and Venner and Ten Napel (1992) for circular contacts
- Nijenbanning, Venner and Moes (1994) for circular and short elliptical contacts
- Venner and Lubrecht (2000) for circular contactsst
- Moes (2000) for arbitrary elliptical contacts

Is the Moes film model equation really the best one?

2. Analysis and methods (8)



Non-dimensional film thickness chart for circular contacts:

Comparison between Moes (2000) model

and

Chittenden et al. (1985) model

Contour map of H(M,L) showing lines of constant film thickness for Moes and Chittenden film models

2. Analysis and methods (9)

A comparison of some models for L = 10: large differences

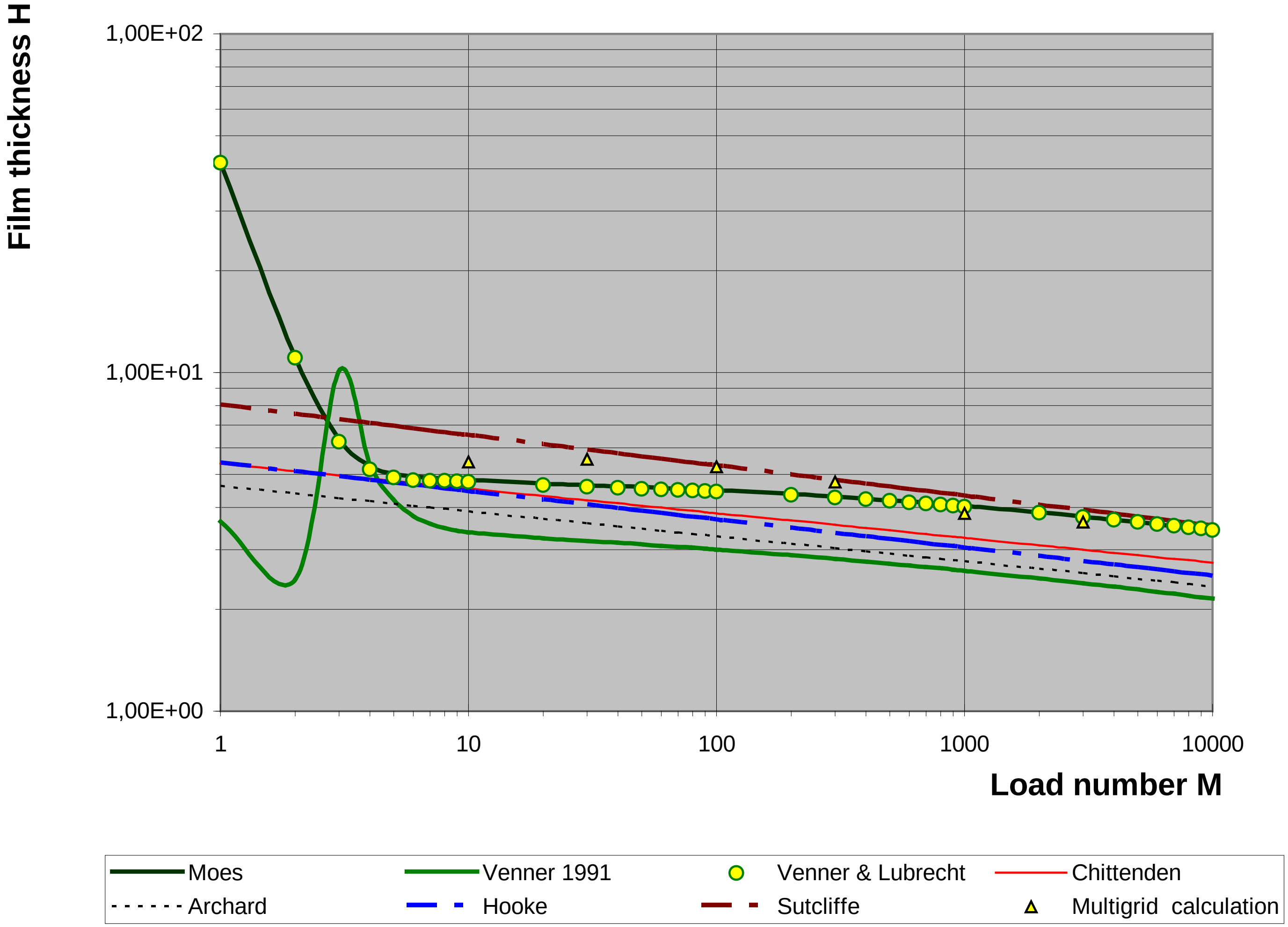


Figure: Nondimensional film thickness vs. M for L = 10

Overview

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5. Results and Discussion (continued)
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3. Results and Discussion

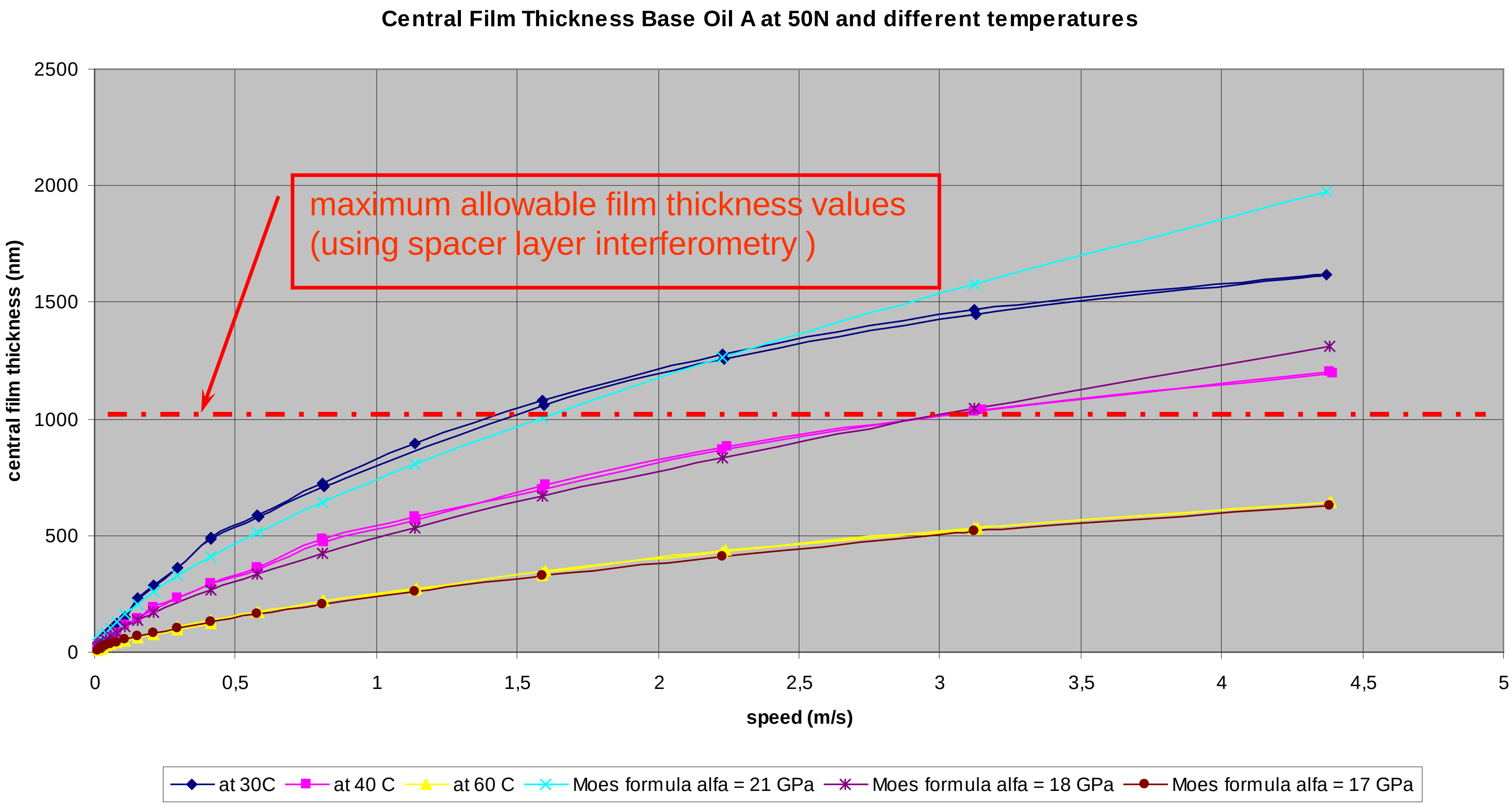
At the 3rd Arnold Tross Colloquium in 2007 we showed for the results for a base oil (a blend with unknown α value) the following results

- using the latest Moes (2000) formula,
- at 0.71 GPa and different temperatures

Base oil A @ 0.714 Gpa			
temperature ^{0}C	estimate for α (GPa^{-1})	stdrd dev in h_{centr}	correlation R^2
30	25.51	1.733E-08	0.99583
40	22.22	1.163E-08	0.99814
60	18.52	6.303E-09	0.99749

3. Results and Discussion (2)

For base oil A, we can now fit α for pressures and temperatures of interest, e.g.:



maximum allowable film thickness values
(using spacer layer interferometry)

Figure: Central film thickness with rolling speed for base oil A

3. Results and Discussion (3)

And that´s it.

Conclusions:

- the PCS system works in an enormous range of EHD conditions
- the Moes (2000) formula can be used in an enormous range of conditions
- measurement results can be fitted by the best choice of α, which allows the PCS system to be used as a versatile alternative to determine the pressure viscosity coefficient

Ready (in 2007).

Or …..?

It is unknown whether the estimated value of α equals the real value *or not*!

Overview

1. Introduction and aim
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5. Results and Discussion (continued)
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4. More homework ….

How can we be sure that the calculated α value is indeed the best one?

$\Rightarrow$ use a lubricant with known pressure-viscosity characteristics and run the same procedure

Let's use HVI60. This oil has $\alpha = 19.8$ GPa^{-1} at 40 ^{0}C

And, while doing this, why not run some other film thickness models?

Eleven (11) models will be tested on HVI60, almost all the literature has to offer:

1) Archard and Cowking (1965)
2) Hamrock and Dowson (1977, 1981)
3) Hamrock (1994) and Hamrock et al. (2004)
4) Chittenden et al. (1985)
5) Hooke (1988)
6) 'implied' Greenwood (1988)
7) Sutcliffe (1989)
8) Venner (1991), and Venner and Ten Napel (1992)
9) Nijenbanning, Venner and Moes (1994)
10) Venner and Lubrecht (2000)
11) Moes (2000)

4. More homework (2)

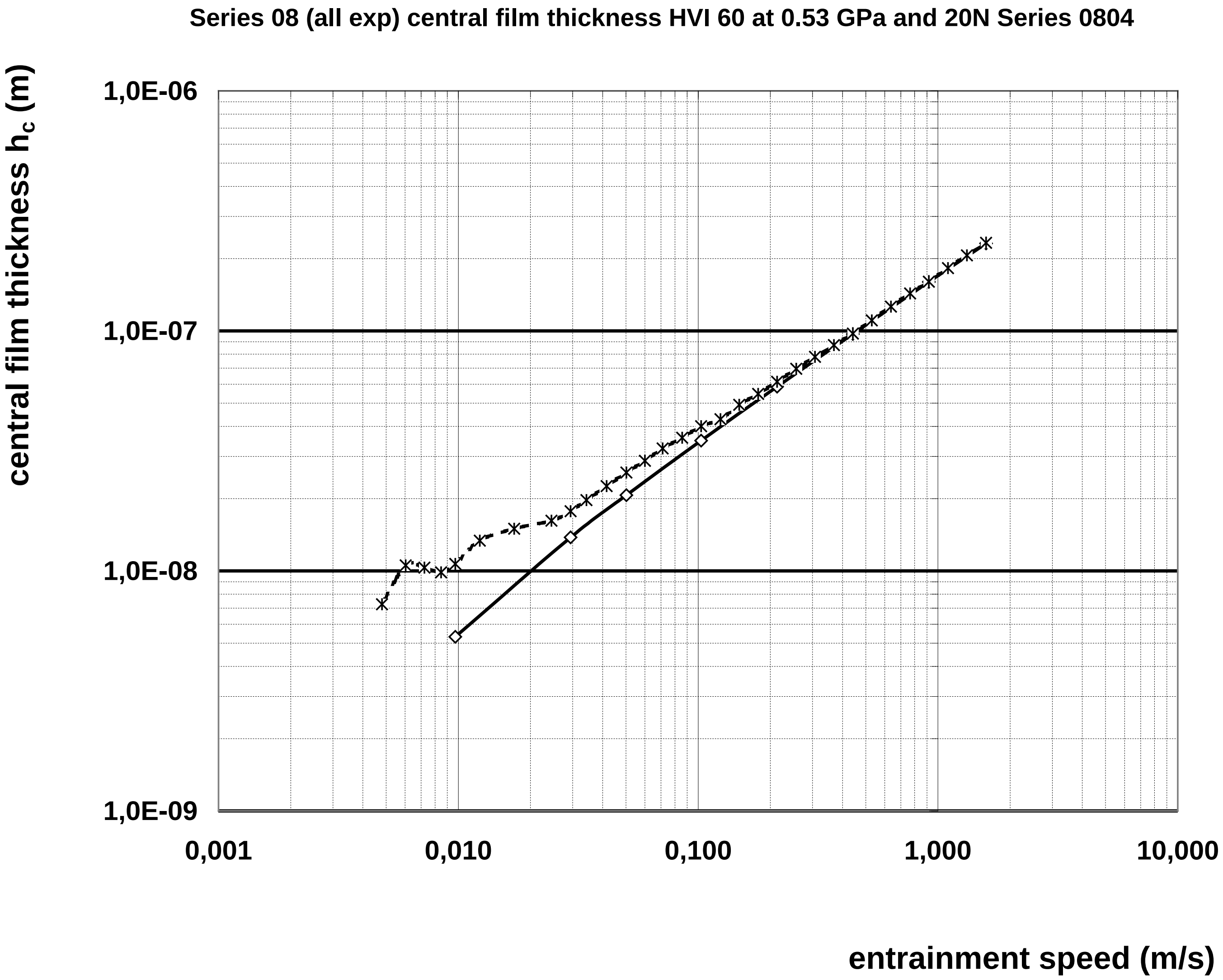

Figure: Data to be used. Central film thickness from experiments (x-x-x) and full multigrid calculations (①-①-①) vs. speed (series 2008)

Overview

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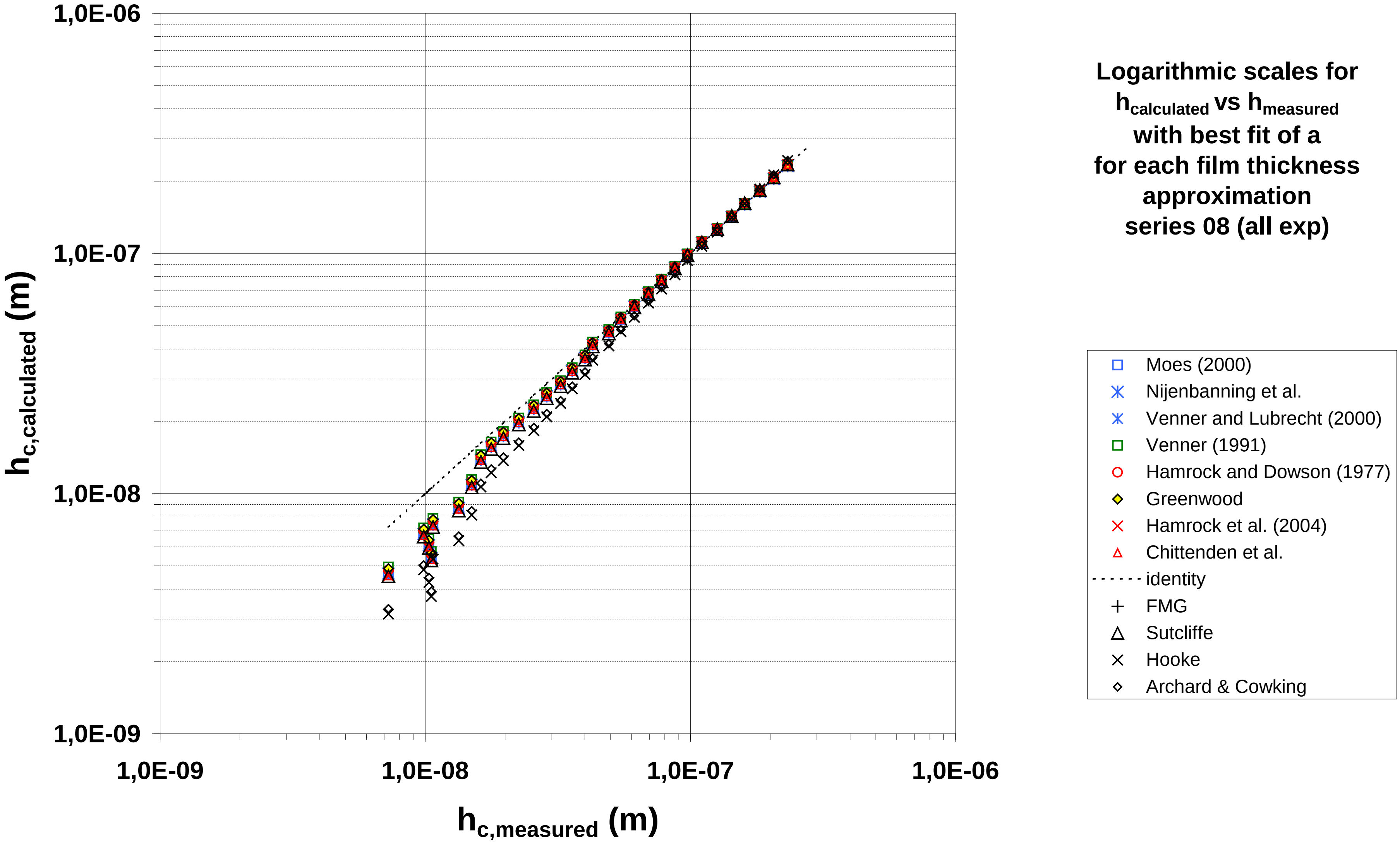
5. Results and Discussion (continued)

For a film thickness measurement series of HVI60 oil at 40 ^{0}C:

	For linear film thickness values **model**	estimate for α^* (Pa^{-1})	stdrd dev in lin h_{centr}	correlation R^2	deviation 1,98E-08
1	*Archard and Cowking*	2,92E-08	6,05E-09	0,9920	47,4%
2	*Hamrock & Dowson*	1,83E-08	2,34E-09	0,9987	-7,7%
3	*Hamrock et al.*	1,83E-08	2,76E-09	0,9982	-7,5%
4	*Chittenden et al.*	1,96E-08	2,76E-09	0,9982	-1,0%
5	*Hooke*	2,50E-08	6,59E-09	0,9905	26,3%
6	*Sutcliffe*	1,42E-08	2,95E-09	0,9979	-28,0%
7	*Greenwood*	1,82E-08	2,22E-09	0,9988	-7,9%
8	*Venner*	1,57E-08	2,17E-09	0,9989	-20,6%
9	*Nijenbanning et al.*	1,50E-08	2,72E-09	0,9982	-24,2%
10	*Venner & Lubrecht*	1,59E-08	2,54E-09	0,9985	-19,6%
11	*Moes*	1,50E-08	2,72E-09	0,9982	-24,1%

5. Results and Discussion (continued 2)



Logarithmic scales for
$h_{calculated}$ vs $h_{measured}$
with best fit of a
for each film thickness
approximation
series 08 (all exp)

Figure: The central film thickness from formulas and full multigrid calculations vs. the measured value (series 2008)

5. Results and Discussion (continued 3)

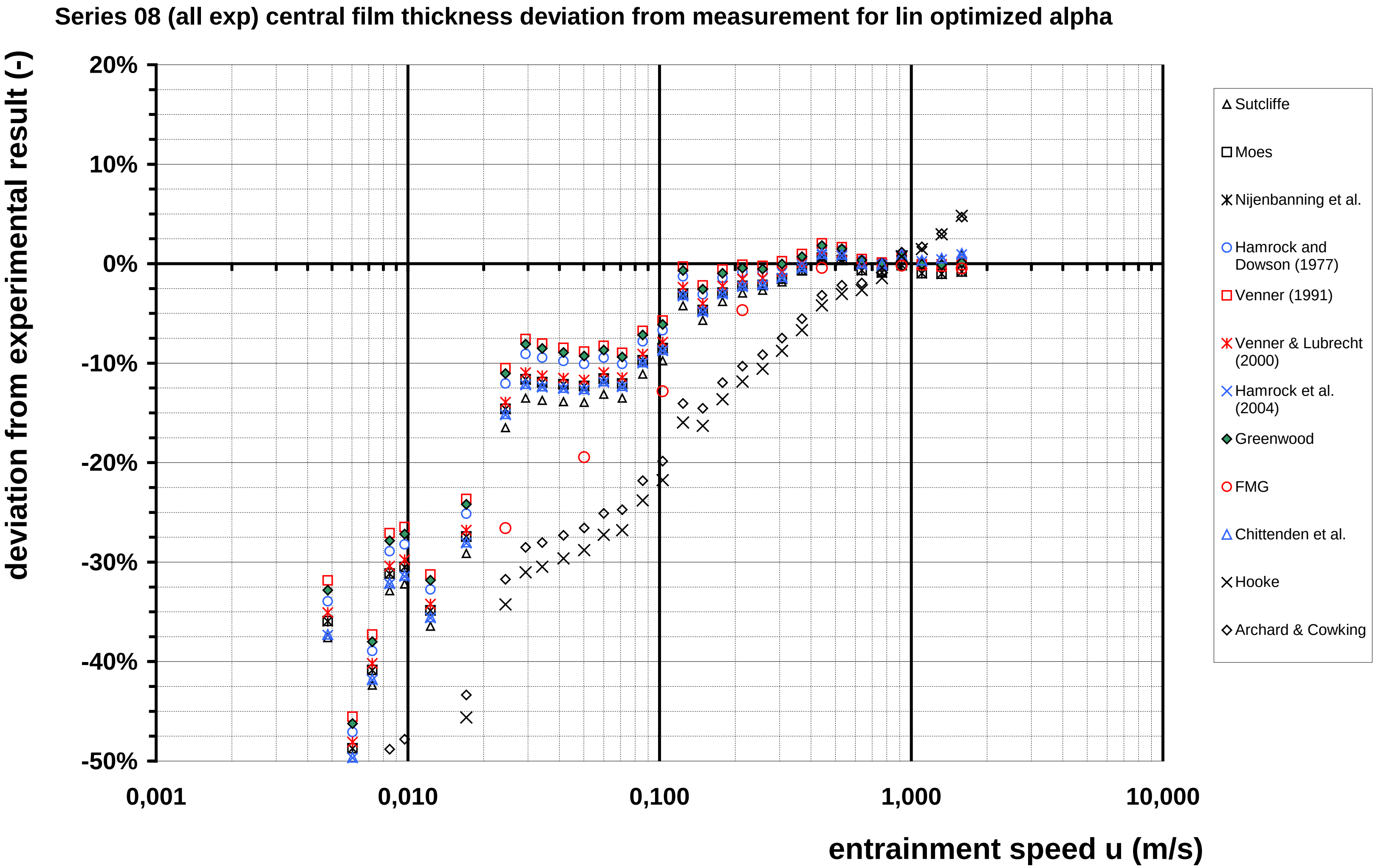


Figure: The deviations of calculated film thickness values based on best α from the measured values (series 2008)

5. Results and Discussion (continued 4)

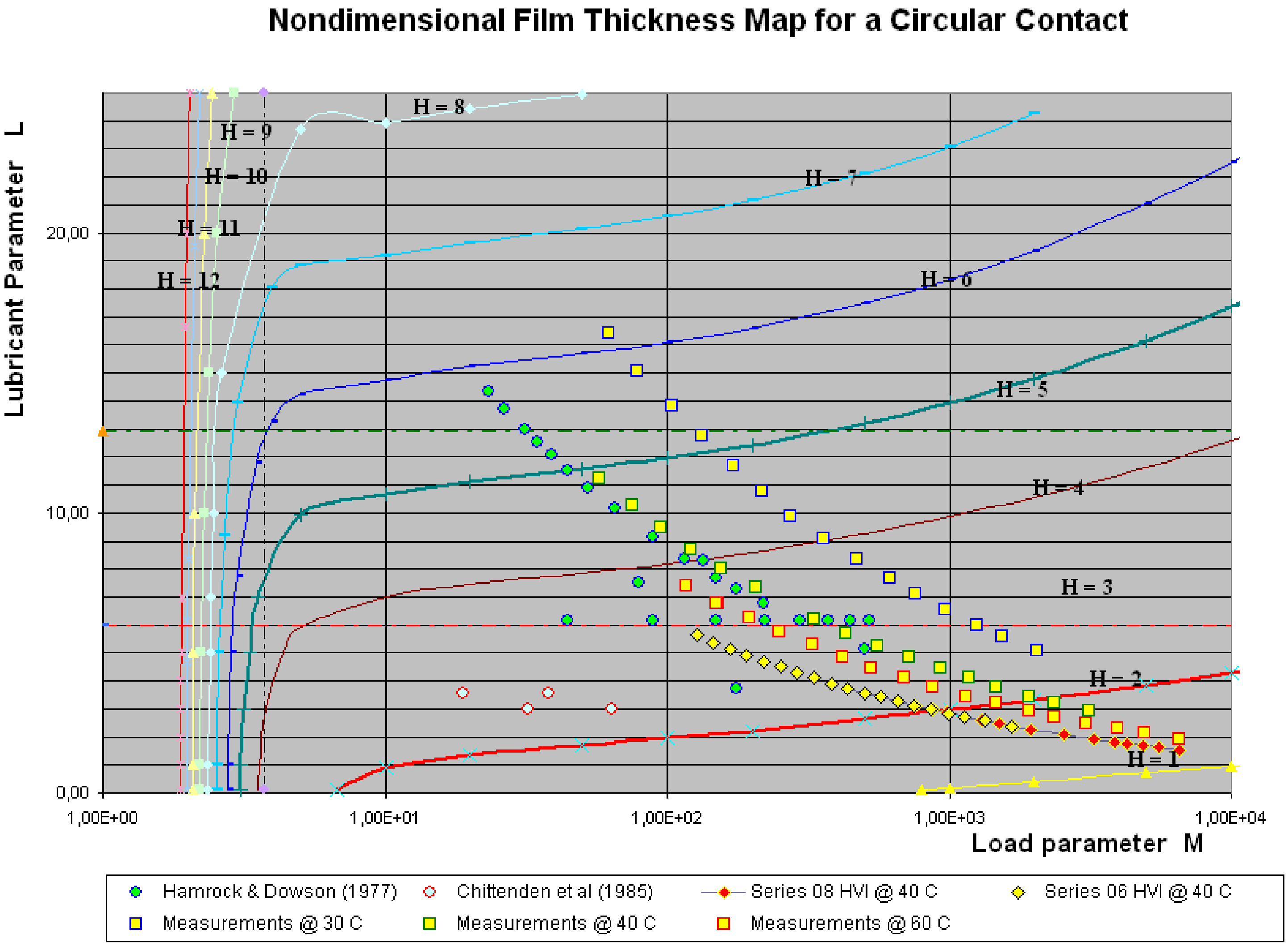
Many more figures, same pattern:

- At thin films the Moes formulas are closer to the measurement than at thick ones (< 30-40 nm ⇒ odd)
- The best overall performer is the Chittenden et al. (1985) formula, the Hamrock & Dowson (1977) is close.

Why?

Let us take a look at the (L,M) domain. The Chittenden work is based on their own calculations and Hamrock & Dowson’s, see the next Figure, which has been drawn using Moes (2000) equations

5. Results and Discussion (continued 5)



5. Results and Discussion (continued 6)

Hence

- a good approximation formula -seen from a statistical viewpoint-, is not a guarantee that it also is the best tribological tool. Beyond statistical arguments, the accuracy of the result is the most decisive factor,
- the Chittenden et al. (1985) approximation performed best out of 11 models tested in a domain $2 < L < 7$, $20 < M < 7000$. The regime $L > 7$ has not been explored yet for a fluid with a priori known alpha value

5. Results and Discussion (continued 7)

Now, what about that base oil A?

α through lin film thickness		Base oil A @ 0.7 GPa and 30 ^{0}C			Base oil A @ 0.7 GPa and 40 ^{0}C			Base oil A @ 0.7 GPa and 60 ^{0}C		
	model	estimate for α (GPa)	stdrd dev in lin h_{centr}	correlation R^2	estimate for α (GPa)	stdrd dev in lin h_{centr}	correlation R^2	estimate for α (GPa)	stdrd dev in lin h_{centr}	correlation R^2
1	*Archard and Cowking*	3.789E-08	2.102E-08	0.99431	3.350E-08	2.444E-08	0.99231	3.212E-08	6.936E-09	0.99719
2	*Hamrock & Dowson*	3.236E-08	1.939E-08	0.99466	2.550E-08	2.159E-08	0.99289	2.300E-08	7.122E-09	0.99678
3	*Hamrock et al.*	3.148E-08	1.826E-08	0.99536	2.497E-08	1.987E-08	0.99413	2.236E-08	6.546E-09	0.99728
4	*Chittenden et al.*	3.570E-08	1.827E-08	0.99535	2.993E-08	1.301E-08	0.99765	2.496E-08	6.414E-09	0.99742
5	*Hooke*	3.221E-08	2.250E-08	0.99356	2.845E-08	2.643E-08	0.99109	2.766E-08	7.625E-09	0.99664
6	*Sutcliffe*	2.310E-08	1.604E-08	0.99647	1.712E-08	3.633E-08	0.97890	1.731E-08	5.626E-09	0.99806
7	*Venner*	2.644E-08	1.764E-08	0.99565	2.318E-08	1.213E-08	0.99798	1.933E-08	6.656E-09	0.99718
8	*Nijenbanning et al.*	2.539E-08	1.735E-08	0.99580	2.220E-08	1.164E-08	0.99814	1.846E-08	6.356E-09	0.99744
9	*Venner & Lubrecht*	2.583E-08	1.736E-08	0.99580	2.262E-08	1.177E-08	0.99810	1.896E-08	6.301E-09	0.99749
10	*Moes*	2.551E-08	1.733E-08	0.99583	2.222E-08	1.163E-08	0.99814	1.852E-08	6.303E-09	0.99749

6. Conclusions & Recommendations

- Eleven approximation formulas for the central film thickness in EHL circular contacts have been compared. In the measurement range of this study the Chittenden et al. (1985) formula proved to be the best, and related formulas as from Hamrock and Dowson (1977) and Hamrock et al. (2004) are close.
- The Chittenden et al. formula for central film thickness can be used for estimating the value of the pressure-viscosity coefficient of a lubricant through an interferometric device with proper accuracy.
- The validity of the Chittenden et al. formula transcends the area where it was originally designed for.
- Experiments with a lubricant having a known α value, at high L and medium M values, are needed to find out which model is best in the upper part of the (L,M) domain
- The Moes formulas are the most versatile and general ones available, but in the range of the measurements they lack the accuracy of the Chittenden approximation.
- More and better numerical data in a wide area in the (L,M) domain, available at present, provide a basis for a better approximation formula, which yields an increased accuracy in the determination of α.

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