

Interpreting oscillatory-shear measurements of viscosity in unbounded flows to understand shear-thinning behavior of lubricants in lubricated contacts

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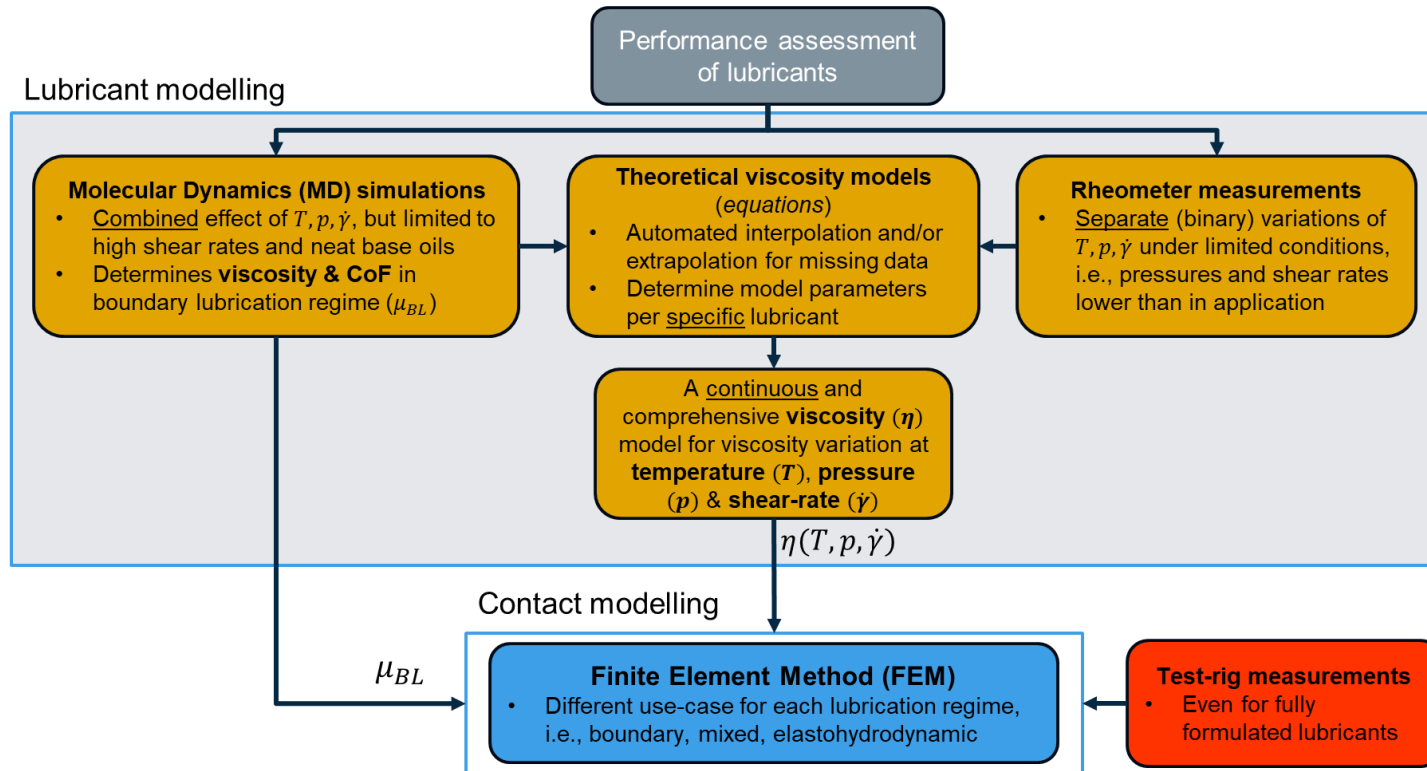
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Excellence Centre of Tribology

AC2T research GmbH

***Focussed on
friction, wear &
lubrication research***

Motivation Outline



Rheology Data

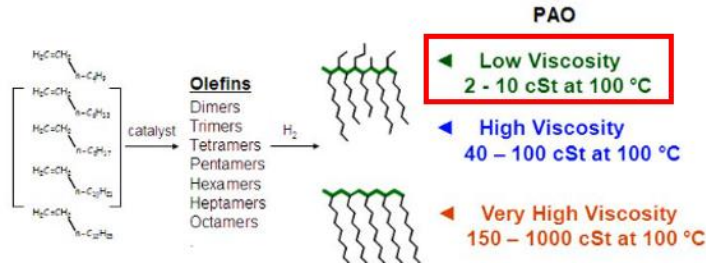
Measurement techniques

Measurement name	Principle	Temperature range (°C)	Pressure range (MPa)	Shear-rate range (1/s)
Flucon GmbH, Germany	Quartz crystal + capillary (Oscillatory shear driven)	20 – 120 (standard)	0 – 1000 (at 3.5e5 1/s)	1e1 – 1e7 (depends on the lubricant)
PCS – USV (Ultra-Shear Viscometer)	Flow between two concentric cylinders (steady shear driven Taylor-Couette flow)	40 – 150	atmospheric	0.5e6 – 1e7
Anton-Paar Rheometer	Flow between cone & disc (steady or oscillatory shear driven Couette flow)	-20 – 200	atmospheric	Steady: 0 – 5e4 (1/s) (Oscillatory: 0 – 650 (rad/s) at atmospheric pressure)
Non-Equilibrium Molecular Dynamics (NEMD)	SLLOD (steady shear driven Couette flow)	Reliable at higher temperatures	Reliable at lower pressures	Very high shear-rate 1e7 and above

Rheological characterization

Fluids tested

- PAOs → 4, 6, 8 and 10



- Squalane → plant-based ultra-pure
- Commercial Gearbox Oil
- PIB in S6

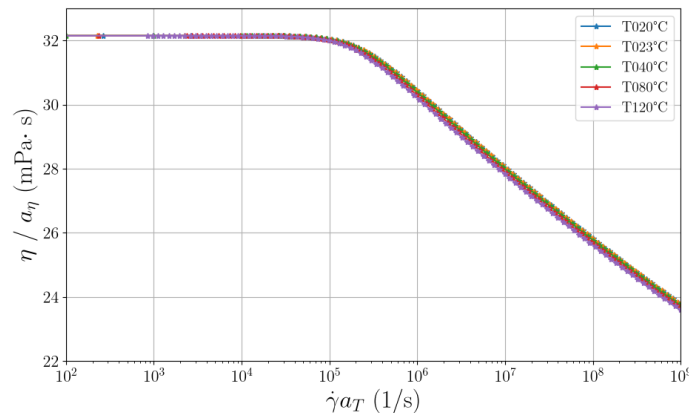
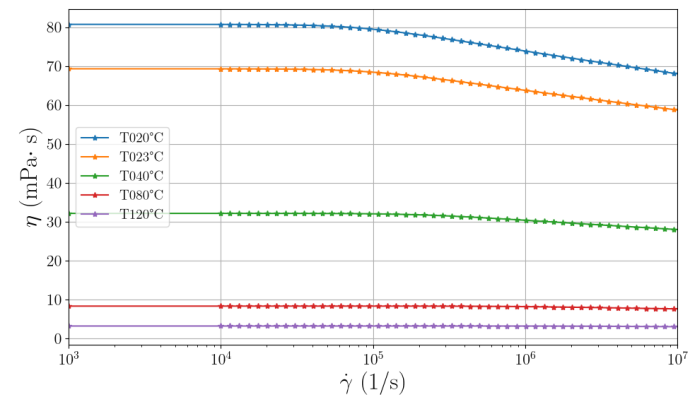
Material	Supplier	Key specification	Role
S6 viscosity standard	Van Waters & Rogers	7.442 mPa s at 25 °C	Base fluid/reference
Polyisobutylene	Sigma-Aldrich	$M_v = 1200 \text{ kg mol}^{-1}$	Viscosity modifier

Time-Temperature Scaling (TTS)

- Shear rate dependence at various temperatures is of similar shape
- Using a reference state, all curves can be transformed to collapse onto a mastercurve

$$a_\eta = \frac{\eta_0(T, \rho)}{\eta_r}, \quad a_T = a_\eta \frac{T_r \rho_r}{T \rho}$$

- Allows extraction of viscosity at any given temperature
- Focused on temperature in this work but also works for pressure

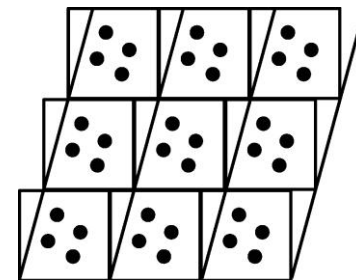
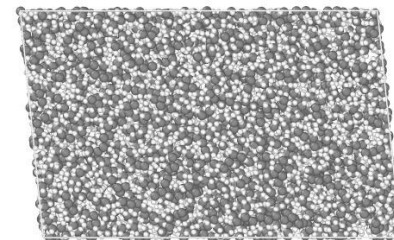


Bair, S., McCabe, C., Cummings, P. T. (2002) *Phy. Rev. Letts.* **88**, 5

- Homogeneous shear flow induced through equations of motion
- Lees-Edwards boundary conditions allow for simulations of shear flow without physical walls
- Viscosity η from shear stress $P_{\alpha\beta}$ (deviatoric component corresponding to the flow direction) and velocity gradient $\dot{\gamma}$

$$\eta = \frac{P_{\alpha\beta}}{\dot{\gamma}}$$

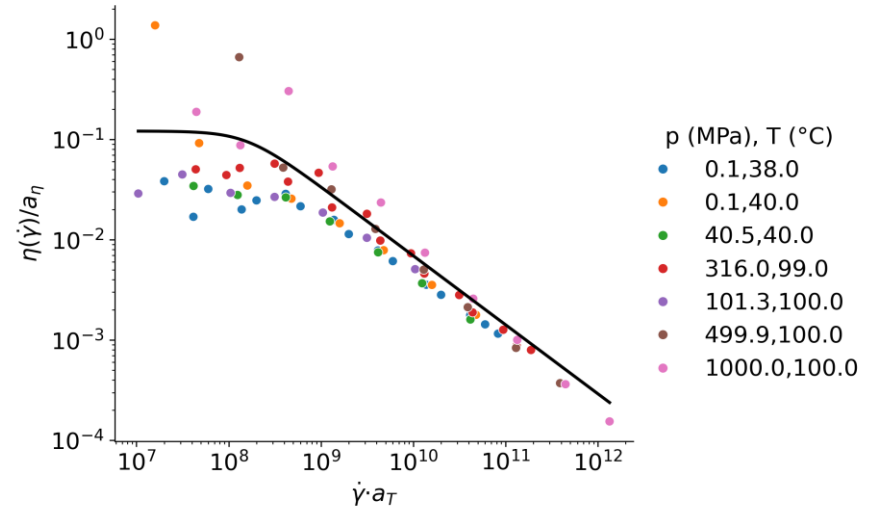
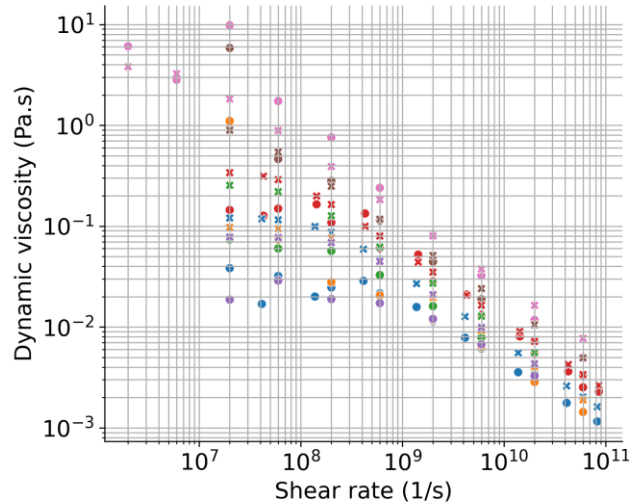
- This gives shear dependent viscosity estimation



Denis J Evans and GP Morriss. Nonlinear-response theory for steady planar Couette flow. Physical Review A, 30(3):1528, 1984.

Squalane

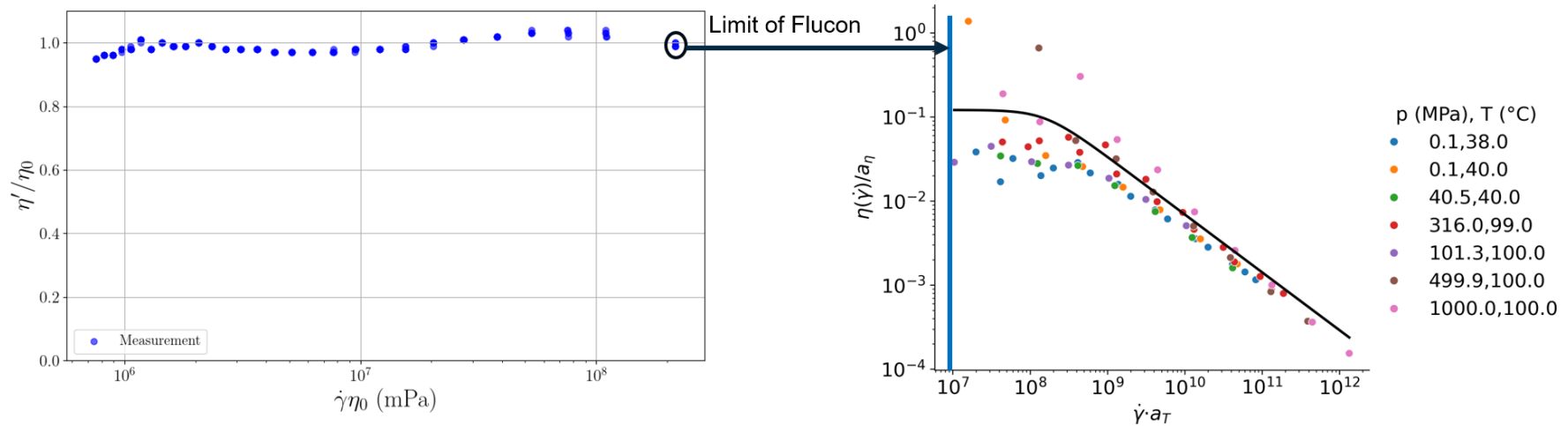
Transformation



Results

Shear limit of Flucon technique

- Shear dependence measurements of viscosity show shear thinning in the commercial oil but not in PAOs or squalane
- Applying the Time-Temperature Scaling on the Flucon data shows it is outside the shear-thinning range



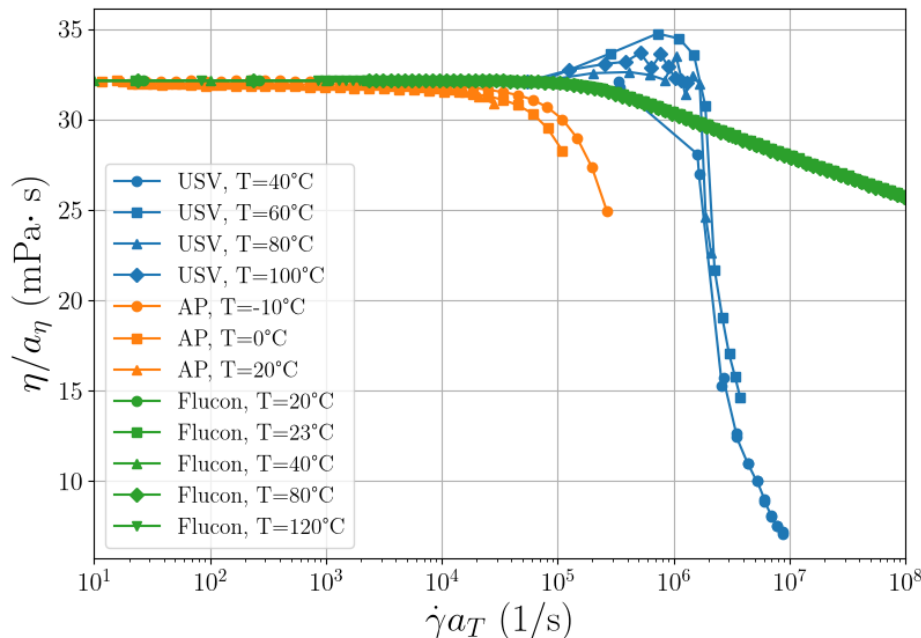
Squalane

Steady shear

- AP and USV both exhibit TTS
- The onset of shear thinning in USV is obscured by unexplained increase in viscosity
- Shear thinning regimes observed in the two techniques are different

Oscillatory shear

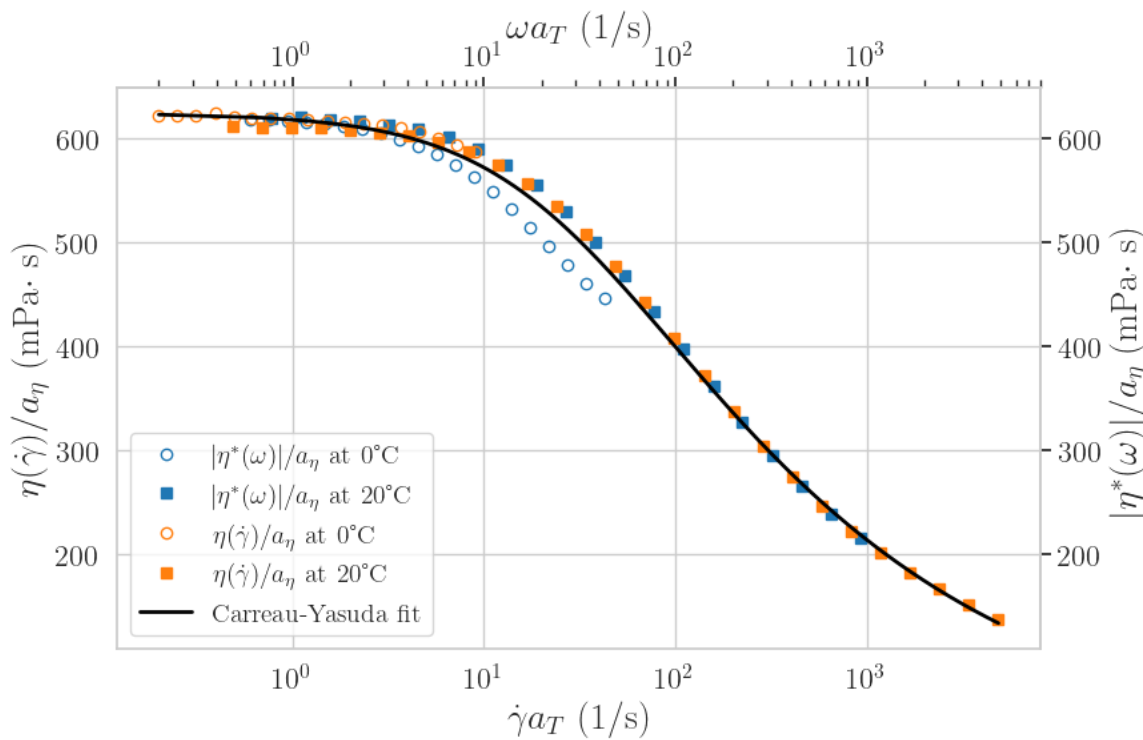
- The Flucon measurement show yet another behavior. Possible reasons ...
 - ▲ Oscillatory shear
 - ▲ Form of shear stress
 - ▲ Shear scanning technique



Commercial gear-box oil

- Oscillatory and steady shear data collapse onto one mastercurve

➔ Suggests that experimental method makes the difference, not the way shear is applied



2% PIB in S6

- Experimental techniques cover complementary regions of rheological parameter space
- SLLOD-MD extends this range into the high-shear regime and reproduces the TTS behaviour observed experimentally
- Combining data from different techniques is not straightforward: discrepancies remain even when individual datasets show good TTS scaling
- In particular, the conversion between oscillatory and steady-shear measurements requires further validation
- The resulting challenge is to combine experimental and simulation data into a consistent viscosity description for lubricant contacts

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