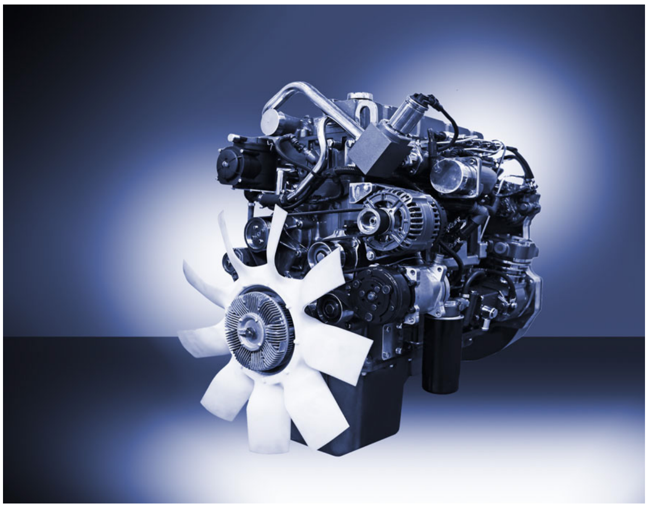
Influence of Rotational Mode on Rheometry of Low-Viscosity Fluids

Relevant for: MCR 702 TwinDrive, particle image velocimetry, turbulent flow, Taylor vortices, Couette mode, Searle mode, counter rotation mode

When working with low-viscosity fluids at high shear rates using a concentric cylinder system with a rotating bob and a fixed cup (Searle mode), inertial forces may cause secondary flow effects, which are known as Taylor vortices. These vortices are the result of centrifugal forces that push the low-viscosity sample from the inner cylinder towards the outer one. These pairwise counter-rotating Taylor vortices show patterns perpendicular to the direction of the main flow with a vortex height which is roughly equal to the gap between the inner and outer cylinders.



1 Introduction

When working with low-viscosity fluids at high shear rates using a concentric cylinder system with a rotating bob and a fixed cup (Searle mode), inertial forces may cause secondary flow effects, which are known as Taylor vortices. These vortices are the result of centrifugal forces that push the low-viscosity sample from the inner cylinder towards the outer one. These pairwise counter-rotating Taylor vortices show patterns perpendicular to the direction of the main flow with a vortex height which is roughly equal to the gap between the inner and outer cylinders (Figure 1).

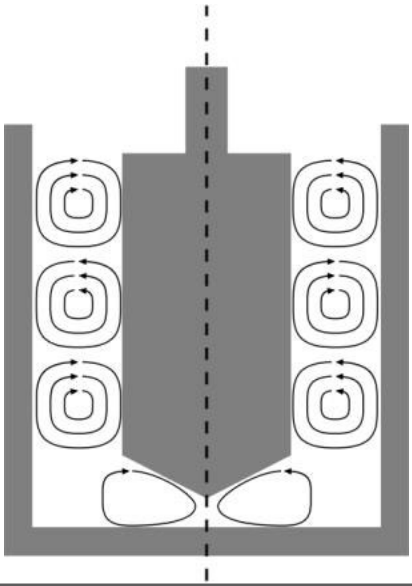


Figure 1: Schematic view of possible secondary flow in a concentric cylinder measuring system. Adapted from [1]

Above a certain critical value in angular velocity, or shear rate, the superposition of the laminar flow by the Taylor vortices increases the energy dissipation, causing an erroneous increase of the measured torque and the calculated viscosity of the sample [2][3].

Contrary to the Searle mode, there is no formation of Taylor vortices in the case of the Couette mode with a fixed inner cylinder (bob) and a rotating outer cylinder (cup)[4]. Nevertheless, along with Taylor vortices, further types of secondary flow appear at higher shear rates (e.g. vortices below the bottom of the inner cylinder), which may lead to inaccurate results in both Searle and Couette modes.

The aim of this application report was to compare the formations of secondary flow depending on the rotational mode of the geometry used (Searle, Couette or counter-rotation mode).

Furthermore, the impact of the rotational mode on the measuring performance at low torques and shear rates was investigated.

To eliminate the influences of geometry factors and surface properties of the measuring geometry, the measurements were carried out with the same geometry while the TwinDrive option of an MCR was used to enable investigations in Searle, Couette or counter-rotation mode.

2 Experimental Setup

2.1 MCR 702 TwinDrive

The MCR 702 combines a traditional stress- and strain- controlled rheometer within a single instrument. Equipped with just the upper motor running in the so-called combined motor transducer (CMT) mode, the MCR 702 enables the use of concentric-cylinder measuring systems in the Searle mode, in which the inner cylinder of a concentric-cylinder measuring system rotates while the outer geometry stands still (Figure 2).

When a second motor is mounted in the bottom of the MCR 702, which is feasible in just a few minutes, the rheometer can be used in the separate motor transducer (SMT) mode. In SMT mode, the upper motor runs in transducer mode, rebalancing the torque, while the lower motor performs the rotational or oscillatory movement. This allows the measuring system to be used in the Couette mode, in which the inner cylinder of a concentric cylinder measuring system stands still while the outer geometry rotates.

In addition, the two motors can rotate in counter-rotation (CR) mode, where one motor moves in the opposite direction to the other. This mode is entirely new for commercial rheometers and opens up new possibilities for rheo-microscopy and extensional rheology.

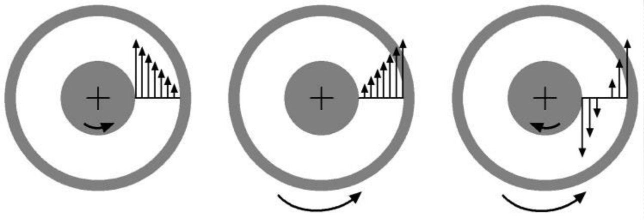


Figure 2: Schematic view of a concentric-cylinder measuring system working in Searle mode (left), Couette mode (middle) or counter-rotation mode (right).

2.2 Working with a Transparent Mooney–Ewart Cylinder System

A pigment/acetone dispersion was characterized using a transparent Mooney–Ewart cylinder system (ME-CC), which enables the measurement of velocity and related properties in fluids by optical methods (particle image velocimetry). With the ME-CC, it is possible to visualize probable secondary flow effects at high shear rates. The different types of configuration were generated by using an MCR 702 TwinDrive working in CMT (Searle), SMT (Couette) or CR mode.

2.2.1 Preset

The rotational speed was increased logarithmically from 10 to 1000 rpm, resulting in an increasing shear rate of $\dot{\gamma}$ from 23 to 2300 s^{-1}. Data generation consisted of 10 measuring points/decade with a measuring duration of 3 s/point.

2.3 Working with a CC20

The measurements were carried out with water and two types of mineral oil, by using a CC20 geometry to characterize the impact of Searle, Couette or CR mode on the measuring performance of a concentric-cylinder system.

2.3.1 Preset

The rotational speed was logarithmically increased from 0.006 to 3000 rpm for measurements in SMT and CMT modes. Data generation consisted of 10 measuring points/decade with a measuring duration of 10 s/point. Because one motor rotates in the opposite direction to the other in the CR mode, the upper rotational speed limit was set to 6000 rpm.

3 Results and Discussion

Figure 3 depicts the flow profile of a pigment/acetone dispersion at $\dot{\gamma}$ = 100 s^{-1} and 270 s^{-1} in the ME-CC as a function of the rotational mode of the measuring system. Working in the Searle mode (CMT) results in the formation of eddies with spiral structures whose axes are perpendicular to the direction of the main flow. Because of their structure, these eddies can be related to Taylor vortices.

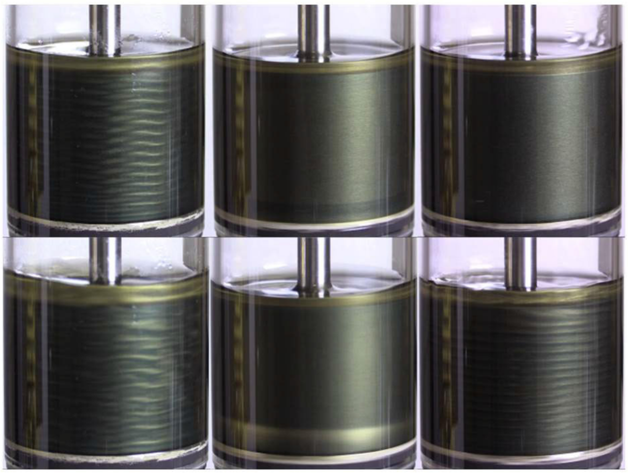


Figure 3: Pigment/acetone dispersion characterized in a ME-CC working in the Searle mode (CMT; left), Couette mode (SMT; middle) or in CR mode (right) at $\dot{\gamma}$ = 100 s^{-1} (top) and $\dot{\gamma}$ = 270 s^{-1}(bottom).

In contrast, no eddies of such structures are detectable when using the measuring system in the Couette mode (SMT). The sample is homogeneous in the region of the lateral area of the inner cylinder. Nevertheless, at the bottom of the measuring system, inhomogeneities are visible, which become more and more pronounced with increasing shear rate, and which might be related to the secondary flow different from Taylor vortices.

When working with the ME-CC in CR mode, no Taylor vortices are detectable at $\dot{\gamma}$ = 100 s^{-1}. However, with increasing shear rate, spiral structures become evident, which indicates that, in CR mode, Taylor vortices are delayed but not prevented (Figure 3).

In order to estimate the impact of the Searle, Couette or CR mode on the measuring performance of a concentric cylinder system, investigations with water were conducted using a CC20 geometry. As can be seen in Figure 4, the shear-rate region in which the characterization of water is possible depends strongly on the rotational mode of the measuring system.

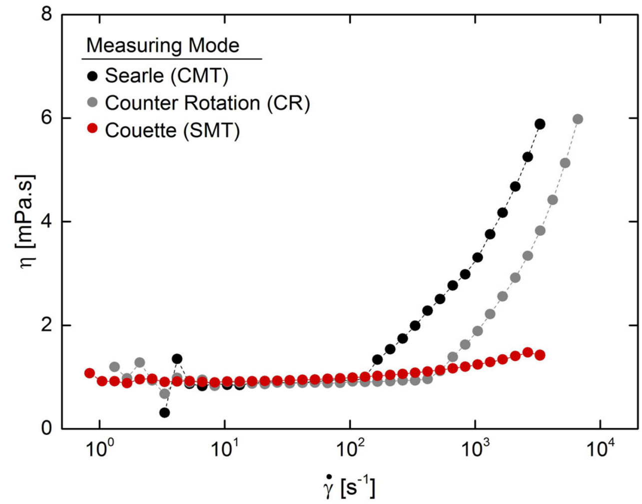


Figure 4: Viscosity function of water measured by using an MCR 702 TwinDrive with a CC20 in Searle, Couette or CR mode.

When CC20 is used in the CMT mode (Searle), the viscosity increases to $\dot{\gamma} \geq 130$ s^{-1}. Under the assumption of small measuring gaps ($R_o/R_i = \delta_{CC} \leq 1.04$), the critical Taylor number can be estimated as Ta ≥ 41.2. Hence, the critical angular velocity ω_C at which Taylor vortices theoretically appear can be calculated from the following equation:

$$\omega = \frac{\eta Ta}{\rho \cdot R_i^2 \cdot (\delta_{cc} - 1)^{3/2}}$$

in which η is the fluid's viscosity, ρ is the fluid's density and R_i is the radius of the inner cylinder [4]. Using the geometrical parameters of the CC20 results in a theoretical $\dot{\gamma}_C$ = 123 s^{-1} for water at 25 °C. Above this value, Taylor vortices influence the flow, which increases the viscosity. The calculated $\dot{\gamma}_C$ complies with the empirically determined $\dot{\gamma}$, above which an increase in η is detectable. Hence, the distinct increase in η of water determined with a CC20 in the Searle mode can be correlated with Taylor vortices.

Using CC20 in CR mode also results in an increase in ηdue to secondary flow effects. But the critical shear rate above which an increase of η is evident is shifted to a higher $\dot{\gamma}$ of about 420 s^{-1} in comparison to the Searle mode.

Contrary to the CMT and CR modes, there is no distinct increase in η detectable when using the CC20 in SMT mode (Couette). Nevertheless, even in the SMT mode, a continuous increase in η is evident for $\dot{\gamma} \geq 100$ s^{-1}. Because the formation of Taylor vortices is not expected in the SMT mode, the increase in η is attributed to other specific secondary flow effects. Hence, the use of the SMT mode offers only a slight advantage over the CMT mode at higher shear rates.

On the other hand, at lower shear rates, the deviation in η detectable in the SMT mode is lower than in the CMT or CR modes. With the SMT mode, the upper motor acts as a transducer. As this motor stays in a fixed position, the torque range could even be enhanced by a factor of two relative to the CMT or CR modes, and therefore enables the characterization of low-viscosity fluids also at lower shear rates.

Investigation of two different mineral oils confirms the results determined with water. It can be seen in Figure 5 that the deviations at low shear rates vary with rotational mode. Taking the η value at $\dot{\gamma}$· = 100 s^{-1} as reference, at low shear rates, only results within ±5 % deviation of this reference are shown. These measurements indicate a more precise rheological characterization at low torques or shear rates when using SMT mode.

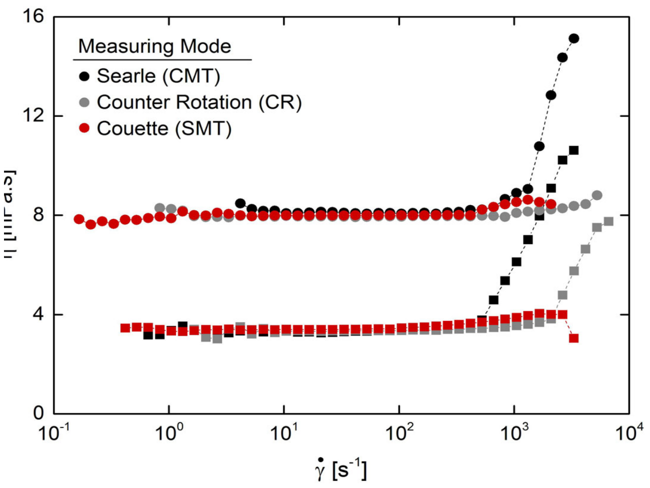


Figure 5: Viscosity function of two mineral oils measured by using an MCR 702 TwinDrive with a CC20 in Searle, Couette or CR mode.

At higher shear rates, a distinct increase in η is detectable when measuring in the CMT mode. The calculated critical shear rates for the investigated oils are $\dot{\gamma}_{C,Oil\,I}$ = 530 $s^{-1}$and $\dot{\gamma}_{C,Oil\,II}$ = 1300 s^{-1}, above which Taylor vortices influence the flow behavior of the samples. These calculated values correlate with the empirically determined limits of Newtonian behavior at a critical shear rate of $\dot{\gamma}_{C,Oil\,I}$ = 560 s^{-1} or $\dot{\gamma}_{C,Oil\,II}$ = 1400 s^{-1}.

Similar to the situation with water, the impact of secondary flow effects on the measuring performance in SMT mode is also much lower for the two oils. Nevertheless, even in this mode, there are clear deviations from Newtonian behavior. At higher shear rates, the sample overflows out of the cup, which abruptly reduces the measured η values. Hence, when working in Couette mode, the increasing impact of secondary flow effects cannot be neglected.

Interestingly, using the CR mode results in the lowest deviations of the viscosity from Newtonian behavior at high shear rates until there is a distinct increase in η, similar to the CMT mode.

4 Summary

Investigations of a pigment/acetone dispersion, water and low-viscosity oils show that the measuring performance of a geometry is influenced by the type of rotational mode used. Working in the Searle mode (CMT) at high shear rates results in the formation of eddies with spiral structures whose axes are perpendicular to the direction of the main flow. Because of their structure, these eddies can be related to Taylor vortices, which distinctly increase viscosity.

In contrast, no such eddies re detectable when using the measuring system in the Couette mode (SMT). Nevertheless, with increasing shear rate, the impact of secondary flow is detectable, even in the Couette mode. While this viscosity increase is less pronounced than in the Searle mode, an overflow of the sample can be determined when working in Couette mode at high shear rates.

When working in CR mode, the critical shear rate, above which the viscosity increases, is higher than in the Searle mode. Because eddies with spiral structures also become evident at higher shear rates, it can be concluded that, in CR mode, Taylor vortices are delayed but not prevented. Interestingly, up to this critical shear rate, the lowest deviations of the viscosity from Newtonian behavior can be seen.

Further investigations at low shear rates show that measurements with an MCR 702 TwinDrive in the SMT mode allow the smallest deviation in viscosity to be determined. Hence, the SMT mode is the most sensitive configuration when working at low torques, and therefore offers advantages for characterizing low-viscosity fluids.

5 References

[1] Meichsner, G., Mezger, T.G., Schröder, J. (2003) Lackeigenschaften messen und steuern. Rheologie-Grenzflächen-Kolloide. Vincentz Network, Hannover

[2] Macosko, C. W. (1994). Rheology Principles, Measurements and Applications. Wiley-VCH, New York

[3] Malkin, A.Y., Isayev, A.I. (2006). Rheology: Concepts, Methods and Applications. ChemTec Publishing, Toronto

[4] Anonymous, (2008), DIN 53019-3:2008-09: Viscosimetry - Measurement of viscosities and flow curves by means of rotational viscometers – Part 3: Errors of measurements and corrections, DIN German Institute for Standardization, Berlin

Contact Anton Paar GmbH

Tel: +43 316 257-0

rheo-application@anton-paar.com

www.anton-paar.com