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APPLICATION OF CFD-BASED CORRECTION FACTORS TO INCREASE THE ACCURACY OF FLOW CURVE DETERMINATION IN A COUETTE RHEOMETER

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ABSTRACT:
The measurement and the investigation of the errors in a Couette rheometer have been a topic of considerable interest in many rheometric studies. In the present study, a more accurate predictor-corrector method based on CFD and the analytical solution of the problem is described. Comparing to the previous CFD-based method, in addition to considering the effect of the end parts, the presented correction factors also take into account the effect of the wide gap into a single coefficient. The correction factors are computed for both Newtonian and non-Newtonian fluids in wide and narrow gap rheometry. Results showed that the shear rate distribution across the gap is highly non-linear in non-Newtonian wide gap rheometry. Moreover, for very shear thinning fluid i.e. $n < 0.4$ in narrow gap rheometry, there is a need to apply correction factor to the calculated fluid properties. Comparing the presented CFD approach and the current approach, the correction factor can be enhanced up to 16 % depending on the fluid behavior and the gap distance.

KEY WORDS:
Couette rheometer, CFD, inverse problem, fluid properties, correction, power-law fluid.

1 INTRODUCTION

Maurice Couette [1] introduced concentric cylinders as a first practical rotational rheometer in 1890. The Couette rheometer is a simple device, which is widely used in research and industrial applications. It consists of two co-axial cylinders and the space between the cylinders contains the liquid. One of the cylinders can rotate by a constant torque or with a constant angular velocity giving rise to shearing of the fluid between the cylinders. There is a longstanding problem in Couette rheometry, which is often referred to as the "Couette Inverse Problem" [2]. This problem arises when extracting the flow curve from the primary data of rotational rate and torque obtained from the experiment. This creates two sources of errors the first one is coupled with the solution of the integral, which relates the shear rate to the rotational speed and the second one is due to the effects of the top and bottom surfaces of the cylinder on the measured torque, which is used in the fluid model calculation. Equation 1 is the integration which associates the measured rotational speed to the shear rate:

$$\Omega = \int_{R_i}^{R_o} \frac{\dot{\gamma}}{r} dr \tag{1}$$

In Equation 1, R_o and R_i are the outer and inner radius of the cup and the cylinder (bob), respectively, Ω is the rotational speed, and $\dot{\gamma}$ is the shear rate. Firstly, the shear rate along the gap is not uniformly distributed and there is still no exact method found to calculate it, unless the fluid model is known or assumed. Secondly, the integral in Equation 1 is an ill-posed integral, because the integral should be inverted to extract $\dot{\gamma}$. This integral inversion is an even greater problem in the wide gap rheometry, because numerical differentiation should be carried out on noisy experimental data, which requires selecting a suitable algorithm [3]. Evaluating the shear rate distribution on a bob was first

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Figure 11 depicts the CFD approach corrected rheometer value of viscosity for narrow and wide gap of CMC fluid. As a reference a viscosity curve using the narrow gap data form Table 4, i.e. $\eta = 55.38\,\dot{\gamma}^{-0.54}$ is also added. As can be seen, the flow curves for narrow and wide gap overlap very well, indicating that the correction works for narrow as well as wide gaps.

5 CONCLUSIONS

A series of experiments and numerical simulations were performed to find a more precise correction procedure for Couette rheometry measurements based on predictor-corrector method. By using CFD, the flow fields were mapped in narrow and wide gap for Newtonian and non-Newtonian fluids. As this study showed, the shear rate distribution along the gap for the non-Newtonian fluid are highly non-linear in the wide gap rheometry. Therefore, the assumption of the constant shear rate in the calculations is not correct especially for the wide gap.

Traditional Couette inverse procedures which are based on analytical solution of the problem simplifies the solution and usually fail to take into account the effects of the end parts on the inverse calculation of the flow properties. As this study have shown, the integration approach, which is widely used in rheometric measurements, overestimates the viscosity of the measured fluid. This over-estimation is larger for the wide gap and for non-Newtonian fluids. The standard correction used, for example the DIN standard, is accurate in correcting the viscosity of a Newtonian fluid in a narrow gap, but fails in the wide gap and the non-Newtonian cases. Moreover, the current correction method by [16] using CFD as in this study only takes into consideration the end effects and does account for the effect of the wide gap.

The torque contribution for different parts of the bob was estimated in both narrow and wide gaps. Narrow gap rheometry is widely accepted as a reference for the fluid properties while our CFD calculations showed that there can also be a significant error in non-Newtonian narrow gap rheometry due to the end effects. This is especially the case for very high shear thinning fluids i.e. $n < 0.4$ for the type of rheometer used in this study. Previous studies have shown that the end part torque contributions are largely increased for the non-Newtonian liquids, but it has not been shown earlier that the torque contribution by different power-law indices differs using gaps of varying width.

For the different shear thinning fluids, the torque contribution was calculated. A different correction factor C_{CFD} was calculated for some shear thinning and Newtonian liquids. The more shear thinning the fluids, the higher the values of the correction factor. This correction factor was then compared with the correction factor C_e which is the one commonly used. It was shown that this approach, neglects the effect of the wide gap on the measured torque and overestimates the viscosity or consistency index as well, but it follows the same trend as CFD correction factor. However, for very high shear thinning fluid, i.e. $n < 0.4$ the behavior is significantly different.

CFD has the potential to investigate the flow field details and to understand the physics of the problem. The integration approach combined with the CFD calculation was used to find the correction coefficients. The proposed method is independent from experimental measurement and is easy to apply to the measurement data. Many rheometers are manufactured based on DIN standard and the flow curve computation follows the methodology recommended by this standard. Comparing the DIN standard formulation with the CFD correction method – and according to the constantly used correction factor recommended by this standard – shows that there is a need to apply a better correction coefficient, especially for non-Newtonian fluids and in the wide gap rheometry, in order to enhance the accuracy of the flow curve calculation.

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