Guard Ring Induced Distortion of the Steady Velocity Profile in a Parallel Plate Rheometer

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Abstract:
The shape and fracture of the free surface frequently limits the measuring range and impedes the use of optical velocimetric techniques in parallel plate and cone plate setups. To prevent this, various kinds of edge guards are often employed. In the present study, we elucidate how an edge guard distorts the steady velocity profile in a parallel plate setup. To this end, we analyzed the velocity field of a strongly shear-thinning fluid, a Newtonian fluid and a set of suspensions via particle image velocimetry in a parallel plate device. Several guard ring sizes were studied. The distortion is described by a simple three parameter model. These parameters are mostly constant for different fluids and suspensions with particle volume fractions below 45 %. With increasing radius, the guard ring's influence approaches a limiting value that we attribute to the influence of the fluid surrounding the gap. Our results indicate a limiting ratio of the difference between plate radius and guard to gap size that should always be exceeded. In the presence of a guard ring, even Newtonian fluids do not exhibit a constant shear rate for most radial distances within the gap. This distortion of the velocity field challenges the simple superposition approach of unguarded device and guard influence that is prevalent in the literature.

Key words:
Parallel plate, guard ring, edge guard, suspension, edge fracture

1 INTRODUCTION

The parallel plate (PP) and the cone plate (CP) setup are among the most frequently used devices in rheology. A major disadvantage of these systems is that the upper limit of the accessible shear rate range is not determined by the rheometer's specifications but by the onset of edge fracture. A factor that is mostly determined by the sample's properties and that frequently evokes inaccurate rheometric results. Even if no edge fracture occurs, the shape of the meniscus can affect the signal recorded by the instrument [1–4] and complicate optical accessibility [5], which is a prerequisite for techniques such as particle image velocimetry (PIV).

Several approaches to avoid these problems have been proposed. Gleissle [6] fitted a circumferential guard to a CP system to extent the measuring range for normal stresses to higher shear rates. This resulted in an actually steady torque signal for higher shear rates that he could not obtain without the guard ring. In a subsequent study, Mall-Gleissle et al. [7] shifted the shear stress obtained with the same setup to the values that were obtained without the guard ring in a range that is accessible to both setups. Thus, they determined an offset factor that was used to correct their results for the ring's influence. Another approach is the cone portioned plate (CPP) device [8], where only the inner part of the plate rotates and the outer annulus is fixed to the rheometers frame. The guard ring is thus replaced with a stationary fluid and the free surface is removed from the sheared volume. Schweizer [9] compared the CPP setup to a conventional CP and found that the CPP geometry resulted in higher shear stresses and normal forces but concluded that these differences were negligible. Another study [10], specifically targeted at polymer solutions, came to a similar conclusion regarding the steady state.

To minimize optical distortion at the free surface, a common approach, used for example by Meeker et al. [11–12], is to wrap the edge with a transparent film. In their work, Meeker et al. only studied a single radial distance with a particle tracking technique. They reported that the film's influence was negligible for this position even though it resulted in an apparent shear stress rise

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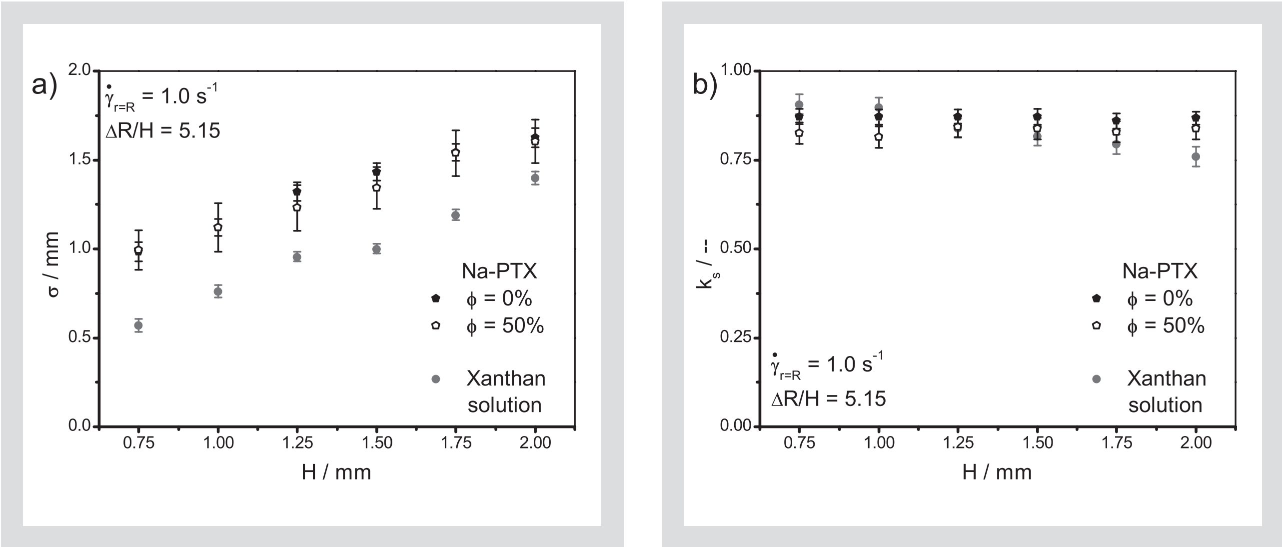

Figure 8: Model parameters as a function of the gap height for (a) edge and (b) slope parameter.

In contrast to the Newtonian fluid and the suspensions, the shear-thinning fluid's slope parameter actually approached k_s = 1 for increasing apparent shear rates, i.e. angular velocities. Thus, the results of a guarded PP setup actually improved for shear thinning fluids if the apparent shear rate is increased. While the other parameters were not affected, a changing shape of the velocity profile also means that the results obtained with different shear rates cannot be compared without accounting for this effect. To understand this effect, it is more convenient to argue based on the shear stress, rather than shear rate. Because the torque is distributed over a larger surface area at the lower than at the upper plate, the shear stress is also a function of the vertical coordinate and reaches its maximum at the upper plate. Higher local shear stresses result in higher local shear rates. This effect is small for Newtonian fluids, as displayed in Figure 3a. But for shear thinning fluids, the absolute viscosity difference for a given shear stress difference is lower for higher shear stresses than for lower levels. Thus, the absolute shear rate difference along the vertical coordinate is also lower for higher shear stresses and the curvature of the velocity profile decreases. The slope parameter, which represents the average deviation from unguarded PP systems, therefore also decreases.

By far the most important parameter for guarded systems of any kind is the gap height. While the edge parameter was insensitive to changes of the angular velocity, it scaled linearly with the gap height as shown in Figure 8a. Users of a guarded setup are thus well advised to keep the gap small. The relationship between edge parameter and gap was linear, but they were not proportional, i.e. even if the gap approached zero the velocity field would not conform to the ideal shape. The other two model parameters were generally not affected by the gap size. The only exception in this regard was the slope parameter of the shear-thinning fluid (Figure 8b). It decreased slightly with increasing gap size. Thus reducing the gap size of a guarded setup would be beneficial both regarding the velocity profile in the gap as well as its decay outside of it.

Supposedly, the main advantage of the CPP over other guarded systems is that it does not require an additional film or ring which is believed to affect the velocity field more than the additional fluid surrounding the sheared portion. In our own experiments, we found that the surrounding fluid created the majority of the distortion and the ring's influence was small. Figure 9 shows the edge parameter as a function of the relative radii difference $\Delta R/H$. This value increased if the distance between guard ring and rotating plate was larger. As is demonstrated by the graph, the shape of the velocity field outside of the gap was not affected by the ring for values of $\Delta R/H > 3$. Since the position parameter was generally lower for the shear-thinning fluid, it was still less influenced by the presence of the ring. Since the shape of the velocity field stabilizes for very small fluid reservoirs surrounding the sheared part, we conclude that it is entirely irrelevant if the surrounding fluid is contained by a film or tube.

4 CONCLUSION

The distortion of the steady velocity field in a parallel plate device was shown to be effectively characterized by a simple three parameter modification of the standard theoretical velocity function. These model parameters were largely independent of geometric factors. The exception to this was the rate of velocity decline outside of the gap. This parameter scaled linearly with the gap height. As the parameters were independent of the guards radius for a ratio of $\Delta R/H > 3$, we conclude that this limiting ratio should always be exceeded when experiments are designed that necessitate an edge guard. Regarding the different fluids, not even the Newtonian fluid exhibited a constant shear rate for outer radial positions within the sheared gap. However, this behavior was independent of the fluid for all the

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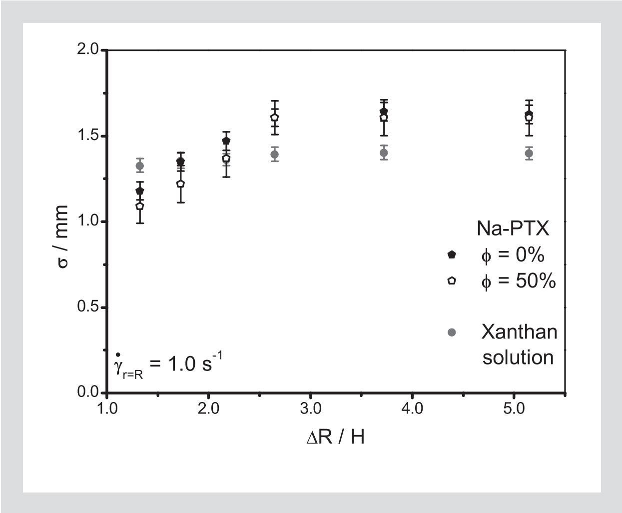

Figure 9: Edge parameter for varying ratio of radii difference to gap height.

homogeneous samples studied here and also for most of the suspensions. Only when the particle volume fraction approached 45 % stronger distortions of the velocity field occurred. The shear thinning fluid exhibited the strongest distortion in both vertical and horizontal sections of the gap. It was also distorted by factors, such as shear rate, that did not affect the Newtonian fluid or the suspensions.

While the model used in the present work can also predict the steady torque quite accurately, this presupposes that the parameters are well known for the respective fluid. Furthermore, it does not eliminate the problem that, in the presence of a guard ring, a representative shear rate is difficult to define. Since even Newtonian fluids exhibited a distorted velocity field, the previously prevalent approach, i.e. the superposition of unguarded device and guard influence, should be avoided if possible. An edge guard can still be useful to extent the measuring range that would otherwise not be accessible, if the distortions are properly accounted for. While the model parameters were only marginally influenced by experimental factors for the Newtonian fluid and the suspensions, caution is advised when using shear thinning fluids as these are more strongly distorted and even comparing measurements under identical conditions is problematic. While it should be good practice for any type of measurement, it is especially important for guarded setups to note the exact experimental conditions and geometric dimensions to prevent inappropriate conclusions.

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