Journal of Non-Newtonian Fluid Mechanics 223 (2015) 165–175

Contents lists available at ScienceDirect

Journal of Non-Newtonian Fluid Mechanics

journal homepage: http://www.elsevier.com/locate/jnnfm

Taylor–Couette flow of electrorheological fluids under electrical double layer phenomenon

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A R T I C L E   I N F O

Article history:
Received 22 July 2014
Received in revised form 20 May 2015
Accepted 1 July 2015
Available online 4 July 2015

Keywords:
Electrorheological fluids
Electrical double layer
Taylor–Couette flow
Extended Casson model

A B S T R A C T

We theoretically investigate the electrical double layer-driven alteration in the dynamics of Taylor–Couette flows in which the annular space between the two concentric cylinders is occupied by an electrorheological fluid. The physical phenomenon under consideration is perceived as a competing effect of the hydrodynamic shear and the spatially varying electrorheological effects as a consequence of the electrical field within the electrical double layer. Such considerations are further shown to dramatically alter the extent of existence of a shear free region within the annular space. We arrive at a mathematical model of the above phenomenon in order to predict the stress transfer mechanism. The consequent possibility of a relative augmentation in the torque transfer capacity as compared to that in Newtonian fluids finds emerging applications in several practical scenarios, such as in clutches and bearings.

1. Introduction

The advent of 'smart' materials has led to the development of various versatile devices which can spontaneously respond to external stimuli such as a mechanical stress, electric or magnetic field, photon radiation or chemical treatment. Electrorheological fluid (commonly abbreviated as ERFs) is one such class of 'smart' material which changes its rheological properties in presence of an electric field [1–8]. The so called Electrorheological (ER) effect is primarily manifested in the abrupt change of the apparent viscosity of the fluid [3,9–15] by orders of magnitude upon action by an electric field of high strength. Electrorheological fluids are generally characterised by a yield stress property which, depending on the magnitude of the electric field, essentially demarcates the solid or fluid like behaviour [1,2,16] through a yield plane. ER fluid flows, thus, generally exhibit a plug-like zone in the flow domain in presence of an electric field transverse to the flow [2,16–18] and are realised where the local yield stress of the ER fluid exceeds the local shear stress associated with the flow [5,10,19–21]. This dramatic rheological variation is, however, characterised by full reversibility on removal of the electric field and a rapid response, having a time scale in order of milliseconds [5,16,21]. This makes it suitable for a number of applications including stress transfer mechanisms [22], clutches and brakes [23,24], force feedback devices [25], vibration absorbers [26,27], etc. The physical mechanism of the ER effect is typically attributed to the difference in the effective dielectric permittivity between the two phases (particulate phase and solvent phase) and the detailed mechanism may be found elsewhere [3,5,16,17,21].

While exploiting ER effects for practical applications, most researchers have considered the application of an external electric field in an effort to alter the fluid rheology. Very recently, however, possible consequences of internally induced electrical field on ER effects have been discussed with particular emphasis on microfluidics and nanofluidics based applications [28]. The generation of an induced electric field, under these circumstances, has primarily been attributed to physicochemical interactions near the solid boundary, leading to the formation of an Electrical Double Layer (EDL). The presence of the charged substrate (solid boundary) attracts counterions from the solution towards itself, leading to the presence of a bulk mobile charge close to the wall [29–35]. This underlying interfacial phenomenon is central to the mechanisms of electroosmosis [36–39], streaming potential [40–43], electrophoresis [44–46] and sedimentation potential [47,48].

It is also important to mention in this context that an ERF can respond to two kinds of stimuli – one due to the presence of an electric field; and second, due to the nature of the imposed shearing. In the present work, we consider a scenario where an ERF is confined in between the annulus of concentric cylinders with relative rotational motion between them (which generates an intrinsic

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http://dx.doi.org/10.1016/j.jnnfm.2015.07.001
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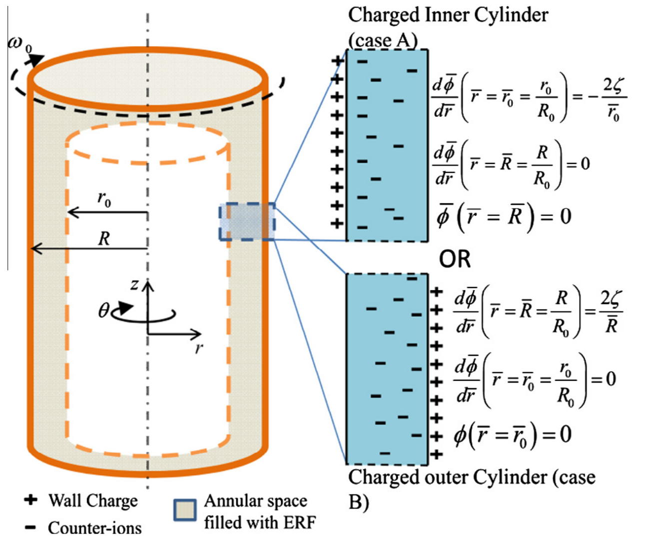

Fig. 1. Schematic of the cylindrical Couette flow of ERFs within the annular region of the concentric cylinders. An electrical double layer is set up with only counterions present in the dispersed medium.

hydrodynamic shear; see Fig. 1). Simultaneously, an EDL is established across this annular space which induces an internally varying radial electrical field, despite the absence of any externally applied electric field. The EDL is induced due to the presence of only counter-ions in the fluidic region (which is typical of such ER systems, since the solvent is typically non-polar or organic in nature). The electric field within the EDL, in turn, alters the rheological activity in the ER fluidic domain.

We consider the following two distinct cases; one where the EDL is generated on the inner cylinder (we refer this case as the charged inner cylinder), whereas in the other case it is generated on the outer cylinder (we refer this case as the charged outer cylinder; see Fig. 1). Accordingly, we bring out the influences of the induced ER effects, as driven by the EDL phenomenon, towards dictating the inception and extent of a shear free region within the annular space. We also investigate the torque transfer mechanism in the cylinder, in order to reveal the interplay of the shearing and electric field on the dynamics of the ERF in the narrow confinement, and demonstrate enhancement in the torque transfer between the inner cylinder to the rotating outer cylinder due to electrorheological and physicochemical interactions.

2. Mathematical formulation

We consider two concentric cylinders, having inner and outer radius r_0 and R, respectively, where the inner cylinder wall is held fixed and the outer cylinder is free to rotate about the central axis. An ERF is present in the concentric annular space while an EDL is established in the annular region in which only counterions, which are charges opposite to that at the wall, are present.

A surface can acquire a charge due to certain physico-chemical reactions resulting from a chemical potential gradient [30,49]. Usually, if a particular fluid-substrate pair is used in a geometry where the fluid is confined within a channel, the walls may acquire a net charge while the fluid domain will be oppositely charged with a total magnitude equal to the total surface charge [30,31]. Following certain charge transfer mechanism or transfer of certain surface active groups, the fluid acquires an opposite charge as compared to the wall substrate, where these transfer take place across the fluid-substrate interfacial layer [50]. There may be numerous other cases where absolutely no charge or EDL develops in particular fluid-substrate pairs. The scenario, as shown in the schematics, may be designed by keeping one cylinder neutral (grounded), differently patched or chemically treated while the other can induce a spontaneous EDL formation [51–53]. Besides this, there have also been a major variety of experimental and theoretical studies concerning the presence of only counterions in the fluid domain, whose distribution may be predicted from the Boltzmann equation [54–56]. Situations regarding the presence of only counterions in different non-polar fluid medium have also been investigated in which the presence of surface active groups in ionizable media or the orientation of permanent dipoles contribute to the so-called double layer formation [50]. Similar counterion-only cases may also be obtained in connections to organic electrolyte capacitors [35,57], ionic liquids [33], and liquid crystals (with external fields [58] or induced field [59] for model surface with sodium carboxylate salts). These fluids, as discussed above, also exhibit the ER effect as well [16,60,61]. ER fluids have been traditionally used in small scale devices including vibration-controllers, dampers and clutches, as mentioned above, where the mechanism of stress transfer holds a key role. This motivates the present study to investigate the stress transfer mechanism in light of the double layer-activated ER phenomena.

The present design as shown in the schematic may, thus, arise in various situations.

2.1. The electrical potential distribution

The ER effect occurs due to the non-uniform electric field across the annular space of the concentric cylinders. This induced field is, in turn, the manifestation of the distribution of the counterions across the annular space. Thus, first we shall look into the electrical potential distribution that is induced across the annular gap of the concentric cylinders. The distribution of the charge density of ions follows from the classical Boltzmann [56] picture, considering counterion-only scenario: $\rho_{el} = -nze\exp\left(-\frac{ze\phi}{kT}\right)$, manifesting an exponential decay from the boundary wall of the charged cylindrical channel. Here z represents the valency of the counterions, e denotes the fundamental protonic charge, n depicts the counterion number density, T denotes the absolute temperature, k denotes the Boltzmann constant and ϕ represents the local potential. For evaluating the potential, we invoke the Gauss' law, in conjunction with the Boltzmann distribution, to obtain the Poisson–Boltzmann equation which is given by [62,63]:

$$\frac{\varepsilon}{r}\frac{d}{dr}\left(r\frac{d\phi}{dr}\right) = -nze\exp\left(-\frac{ze\phi}{kT}\right) \quad (1)$$

The above governing equation can be expressed in a non-dimensional form using the parameters $\bar{\phi} = -(ze\phi/kT)$ and $\bar{r} = r/R_0$, so that

$$\frac{1}{\bar{r}}\frac{d}{d\bar{r}}\left(\bar{r}\frac{d\bar{\phi}}{d\bar{r}}\right) = \frac{nz^2e^2R_0^2}{\varepsilon kT}\exp(\bar{\phi}) \quad (2)$$

where R_0 is the reference radius which will be defined later. In this study, two general scenarios are studied; one where the inner cylinder is considered to be charged while the other one is, when the outer cylinder is considered to be charged. The typical surface charge density is in the order of 10^{-4} C/m^2 or higher [63] for cylinders with radius of the order of 1 mm. The corresponding linear charge density, λ (considering an infinitely long cylinder), has the form $\lambda = \sigma(2\pi r_i)$, where $r_i = r_0$ for inner charged cylinder and $r_i = R$ for outer charged cylinder. We introduce a dimensionless parameter ζ such that $\zeta = \bar{\lambda} l_B$ which denotes the dimensionless charge density which is equivalent to the number of charges along a Bjerrum length $\left(l_B = \frac{\kappa^2}{4\pi n R_0^2}\right)$ of the inner (or outer) cylinder where