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Comparative study of correction methods of wall slip effects for CMC solutions

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In this paper, an experimental analysis has been carried out in order to characterize the rheological properties of non-Newtonian CMC fluids (carboxymethylcellulose CMC solutions). Two solutions at low and medium concentrations, respectively 0.5 and 1.5%, have been tested. A comparative study of the three methods proposed by Mooney, Wiegreffe, and Geiger has been carried out. It was found that the two solutions follow the rheological power-law model of Ostwald/de Waele-type for the studied experimental range. The diameter of the flow channel influences the rheological behavior of the CMC solution and highlights the wall slip effects. For a 0.5% concentration, the methods of Mooney and Wiegreffe could not be used as they gave results that could not be explained physically. However, for a 1.5% concentration, the three of them gave satisfactory results.

1. Introduction

The flow of complex fluids often shows wall effects because of the interaction between the particles and the solid boundary lines. These effects lead to inhomogeneous distributions of particles in the less viscous (solvent) fluid, which plays a role as lubricant. The analyses of rheological measurements do not take into account these fluid–wall interactions and then lead to erroneous results [1]. The wall slip depends on three parameters: the test conditions (shear stress at the wall, pressure and temperature), the fluid–wall contact (physicochemical fluid–wall interactions, roughness of the wall), the fluid composition and its rheological properties (viscosity, molecular structure, additives). This complex phenomenon is still an open topic for both its interpretation and quantification [2].

To find the real rheological law of the fluid, we must use the correction of walls effect. Several correction methods exist in the literature for the wall slip effects and the aim of the present work is to make a comparative study of the three methods of Mooney, Wiegreffe and of that of Geiger for CMC solutions at low concentration (0.5%) and a medium one (1.5%).

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Nomenclature

Q	Total volumetric flow rate (m^3/s)
R	Pipe radius (m)
V	Velocity (m/s)
h	Thickness of the flat die (m)
d	Capillary diameter (m)
L	Capillary length (m)
ΔP	Pressure drop (Pa)

Greek letters

$\dot{\gamma}$	Shear rate (s^{-1})
τ	Shear stress (Pa)

Subscripts

app	apparent
s	slip
ws	without slip
w	wall

2. Theory

The phenomenon is frequently encountered in various types of fluids among polymer solutions for which the wall slip is often an apparent slip effect resulting from the formation of a thin fluid wall layer with low viscosity, due to a preferential orientation of molecules or particles.

The slip of a real fluid on a solid wall can be defined by the existence of a tangential fluid velocity V_s, different from zero at the wall. Various authors tried to interpret this phenomenon.

According to Joshi et al. [3] for charged polymers, the wall slip mechanism looks more like a real slip: when the surface energy of the wall material is low, the wall slip mechanism appears by breaking the connections that link the macromolecular chains to the wall under the shear effect.

On the other hand, when the surface energy is high, there is a cohesive break by mess between the chains that are adsorbed at the wall and the linked chains. For concentrated suspensions, the wall slip resembles an apparent slip. This results in the formation of a thin layer of lubricating fluid on the wall.

Uhland [4] studies the phenomenon in cylindrical channels; he stipulates that the wall slip would be due to a thin layer on the wall. This layer is due to the migration of a low-viscosity product towards zones with strong gradients. The layer on the wall being more fluid, the energy dissipated during its shear is less important.

Different methods of quantification of wall slip exist [5–8]; the first one was proposed by Mooney in 1931. It is based on the fact that the relationship between stress and shear rate at the wall is independent of the geometry. The literature abounds in examples of application of this method for diverse mixtures, as shown in the papers of Kanu and Shaw [9], Karam [10,11], Jepsen and Räbiger [12], Boube et al. [13], Vergnes et al. [14], Mezry [15], Lanteri [16]. It assumes that the slip velocity V_s depends only on the single shear stress at the wall τ_w, and expresses the flow rate as the sum of two terms, as shown in Eq. (1):

$$Q = Q_s + Q_{ws} \tag{1}$$

The apparent shear rate is then given by Eq. (2):

$$\dot{\gamma}_{app} = A(\tau_w) + \frac{4V_s}{R} \tag{2}$$

By plotting $\dot{\gamma}_{app}$ versus $(\frac{1}{R})$ for a given stress τ_w, a straight line is obtained. Its intercept is $\dot{\gamma}_{ws}$ (the apparent shear rate with no slipping) and the slope $4V_s$. By repeating this procedure for different values of τ_w, one obtains a series of straight lines with the corresponding values of V_s and $\dot{\gamma}_{ws}$. Hence, one can deduce both the slip velocity and the corrected flow behavior of the fluid.

Wiegreffe [7] has modified the Mooney method by linking the slip velocity to the geometry. Assuming that $V_s = V_s(\tau_w, R)$, this is inversely proportional to the radius and one admits that the total volume rate is the sum of two components: the first one is due to the slip and the second one to the shear flow. The apparent shear rate is then written as:

$$\dot{\gamma}_{app} = A(\tau_w) + \frac{4a(\tau_w)}{R^2} \tag{3}$$

The apparent shear rate is then plotted as a function of R^{-2} and not against R.

Geiger assumes that the slip velocity depends not only on the stress, but also on the radius and agrees with the idea of Wiegreffe. He assumes that the apparent shear and the slip rates (with no apparent shear) $g(\tau_w)$ are connected by the relation:

$$\dot{\gamma}_{app} = g(\tau_w) \cdot f(h, \tau_w) \tag{4}$$