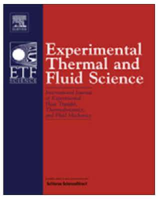
Experimental Thermal and Fluid Science 39 (2012) 167–175

Contents lists available at SciVerse ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs



Measurement of shear rate on the surface of a cylinder submerged in laminar flow of power-law fluids

N.-E. Sabiri [a],*, R.P. Chhabra [b], J. Comiti [a], A. Montillet [a]

[a] *Laboratoire de Génie des Procédés en Environnement et Agroalimentaire, GEPEA UMR CNRS 6144, Université de Nantes, CRTT, 37 Bd de l'Université, 44602 Saint-Nazaire, France*
[b] *Department of Chemical Engineering, Indian Institute of Technology, Kanpur 208 016, India*

ARTICLE INFO

Article history:
Received 29 August 2011
Received in revised form 29 November 2011
Accepted 18 January 2012
Available online 4 February 2012

Keywords:
Shear rate
Cylinder
Electro-diffusional flow diagnostics
Shear-thinning fluids
Micro-electrodes

ABSTRACT

Micro-electrodes made of platinum have been used to measure the local shear rate on the surface of a cylinder (length-to-diameter ratio of 11–12) exposed to the fully developed laminar flow of power-law fluids in a vertical pipe. Two Newtonian and two shear-thinning solutions are used as model test fluids to ascertain the influence of shear-thinning viscosity on the distribution of shear rate on the surface of the cylinder. The results reported herein encompass a wide range of Reynolds numbers $0.16 \leqslant \mathrm{Re} \leqslant 75$ based on the cylinder diameter and centreline velocity. Over the range of conditions, it is observed that the shear rate is a maximum at about $\theta = 130°$ and it tends to be higher in shear-thinning fluids than that in Newtonian fluids otherwise under identical conditions.

1. Introduction

Over the past 50 years or so, considerable research effort has been devoted to the study of flow of non-Newtonian fluids across a circular cylinder. The interest in such model flow configurations stems from both fundamental and pragmatic considerations. From a theoretical standpoint, the flow past a circular cylinder constitutes a classical problem within the domain of fluid mechanics and transport phenomena. Indeed this prototype flow has provided useful physical insights into the underlying processes of flow separation, wake and vortex shedding characteristics in different flow regimes which have served as useful starting points to understand the corresponding phenomena with complex shapes of bluff bodies. On the other hand, the flow past a cylinder also denotes an idealisation of several industrially relevant applications. Typical examples include the flow in tubular and pin-type heat exchangers, filtration screens used in polymer and paper-pulp related applications. Consequently, over the years, a vast body of knowledge has accrued as far as the flow of Newtonian fluids is concerned [1,2]. In contrast, the analogous body of knowledge for non-Newtonian fluids is much less extensive and coherent as well as is of recent vintage. While detailed reviews of the pertinent literature are available elsewhere [3–5], one can divide the available literature in three sub-categories. Early studies in this field endeavoured to study the flow behaviour of the so-called drag reducing dilute polymer solutions past thin wires and cylinders. While such solutions exhibit almost constant shear viscosities, but their extensional behaviour deviates significantly from that of the solvent (mostly water). This can lead to drag reduction accompanied by reduction in convective heat transfer or drag increase depending upon the flow regime, polymer type and its concentration, etc. [6–8]. Similarly, significant deviations in the wake dynamics stability and vortex shedding characteristics, e.g., see [9–12], in coil-stretch transition [13], etc. have also been observed with such dilute polymer solutions. The second sub-class of studies is motivated by the objective of delineating the role of visco-elasticity on the detailed flow characteristics like streamlines, drag, etc. at zero Reynolds numbers (negligible inertial effects) for a cylinder confined in between two plane walls, though some studies also take into account weak inertial effects. This body of knowledge has been extensively reviewed in [3,4]. Finally, there has been a growing interest in seeking numerical solutions for the flow of purely viscous fluids (power-law and Bingham plastics) past a circular cylinder together with the corresponding convective transport processes in the forced, mixed and free convection regimes. In particular, extensive results are now available on the flow and heat transfer from a circular cylinder immersed in power-law fluids which span wide ranges of governing parameters like Reynolds number, Grashof number, Prandtl number and power law index, but these are mainly restricted to the so-called steady flow regime [14–19] and indeed very little is known about the corresponding phenomena in the laminar vortex shedding regime [20]. Broadly speaking, the wake tends to be shorter in shear-thinning fluids

---

* Corresponding author. Tel.: +33 240172615; fax: +33 240172618.
E-mail address: nour-eddine.sabiri@univ-nantes.fr (N.-E. Sabiri).

0894-1777/$ - see front matter © 2012 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2012.01.021

Nomenclature

A	surface area electrode area
a	numerical coefficient tabulated by Mitschka and Ulbrecht [32]
C_0	concentration
D	diffusion coefficient
d_e	electrode diameter
d	cylinder diameter
F	Faraday's constant (F = 96,485 C/mol)
I_L	diffusional limiting current
k	mass transfer coefficient
μ	dynamic viscosity
m	consistency index
ν	kinematic viscosity
n	behaviour index
θ	angle
R_D	rotating disc radius
Re	Reynolds number
S_w^*	dimensionless shear rate, ($S_w^* = S_w \cdot d/U_{\max}$)
S_w	shear rate
τ	shear stress
$U_{\max}$	centreline velocity
ω	rotation speed
$\dot{\gamma}$	shear rate

than that in Newtonian fluids otherwise under identical conditions. Also, convective heat transfer is promoted by shear-thinning fluid behaviour in all regimes. Indeed, it is possible to augment the rate of heat transfer by up to 100% under appropriate conditions. In contrast, the corresponding experimental information is not only very limited and less coherent, but is also of relatively recent vintage [5,9,10], as reviewed recently [21]. Thus, all in all, while a few numerical studies are available on the cross-flow of power-law fluids past a cylinder, very little experimental results are available, even on drag coefficient. Reliable knowledge of the detailed structure of the flow field as well as of the gross engineering parameters is not only necessary in its own right for the healthy growth of this field, but is also needed to validate the numerical predictions. This work is concerned with the measurement of the local effective shear rate at a point on the surface of the cylinder as a function of the Reynolds number and power-law index which, in turn, can be used to deduce the variation of the effective viscosity in the close proximity of the submerged cylinder.

In this work, the well-known electrochemical polarographic-type method has been used to measure the shear rate on the surface of a cylinder exposed to the laminar flow of power-law fluids. This technique has been used extensively for gleaning similar information for the flow of Newtonian fluids past a circular cylinder [22,23] and subsequently as a diagnostic tool in a range of flow applications including the delineation of flow regimes in porous media [24], swirling flows [25], food processing [26] and microflow devices [27]. It has been also used to study mass transfer from cylinders in visco-elastic liquids [28]. Furthermore, the experimental results obtained in this work have been supplemented by numerical results for the case of an unconfined flow over a cylinder thereby showing the qualitative correspondence between the predictions and observations. We begin with a short description of the electrochemical technique followed by that of the experimental materials, methods and data analysis protocols employed in the study.

2. Elecro-chemical method and shear rate measurements

The technique of micro-electrochemical sensors allows the experimental determination of the wall shear rate, S_w. It is based on a chemical reaction entailing the reduction of ferricyanide ions on a cathodic surface as per the following chemical reaction:

$$\mathrm{Fe(CN)}_6^{3-} + \bar{e} \rightarrow \mathrm{Fe(CN)}_6^{4-}$$

Similarly, the reverse reaction occurs at the anode whose surface area is much larger than that of the cathode. The transport of ferricyanide ions by migration is minimised by using a supporting electrolyte.

Furthermore, the reaction is conducted at sufficiently high voltage between the cathode and anode in order to reduce the ferricyanide ions concentration to zero at the surface of the cathode. Under these conditions, the rate of reaction is controlled by the rate of diffusion of ferricyanide ions in the mass transfer (concentration) boundary layer. The corresponding electrical current is called the diffusion limiting current I_L. Its value is related to the mass transfer coefficient k between the electrolyte and the probe surface by the following relation:

$$I_L = n_e F A C_0 k \tag{1}$$

where n_e is the number of electrons involved in the electrochemical reaction ($n_e = 1$), F is the Faraday's constant (F = 96,485 C/mol), A is the surface area of the electrode and C_0 is the bulk concentration of the ferricyanide ions.

For a circular electrode of diameter, de, embedded in an inert wall, Reiss and Hanratty [22], solved the diffusion-convection equation (neglecting diffusion in the direction of the mean flow) and showed that the mass transfer coefficient is related to the mean wall velocity gradient $\bar{S}_w$ in steady state conditions by the following relation:

$$k = 0.862(D^2\bar{S}_w/d_e)^{1/3} \tag{2}$$

where D is the molecular diffusion coefficient of ferricyanide ions in the solution. Combining Eqs. (1) and (2) leads to the following relation:

$$\bar{I}_L = 0.677 n_e F C_0 (\bar{S}_w D^2)^{1/3} d_e^{5/3} \tag{3}$$

The mean wall shear rate $\bar{S}_w$ can then be calculated from the experimental value of the limiting current intensity from the following relation:

$$\bar{S}_w = \frac{1}{(D^2)(d_e^5)}\left(\frac{I_L}{0.677FC_0}\right)^3 \tag{4}$$

Note that the number of electrons $n_e = 1$ has been used in arriving at Eq. (4); this forms the basis of evaluating the shear rate at the surface of the cylinder from experimental observations. This, however, necessitates the values of the limiting current (I_L), molecular diffusivity (D) and the equivalent diameter of the electrode (d_e); these were determined experimentally in this work as outlined in the next section.

3. Experimental methods and materials

3.1. Experimental set-up

The experimental set-up used in this study is illustrated schematically in Fig. 1a and b. The liquid was circulated in the upward