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Viscoelastic fluid flow past a confined cylinder: Three-dimensional effects and stability

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HIGHLIGHTS

- Laminar flow of viscoelastic fluids past a confined circular cylinder.
- The 3D nature of the flow is assessed for a wide range of aspect ratios.
- Flow visualizations and PIV measurements are presented.
- The onset of flow instability is determined experimentally.

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ABSTRACT

The flow of viscoelastic fluids past a confined cylinder in a rectangular duct was investigated experimentally and numerically in order to assess the three-dimensional effects associated with cylinder aspect ratio (*AR*) and the fluid rheology. The blockage ratio was 50%, the cylinder aspect ratios were $AR = 16$, 8 and 2, and the flow conditions tested varied from creeping flow conditions up to the onset of time-dependent flow. Three viscoelastic fluids were tested, namely a shear-thinning and two Boger fluids, and the results were compared against the numerical and experimental data for Newtonian fluids.

For the shear-thinning fluid, and in the range of Deborah numbers (*De*) studied ($0.025 < De < 0.99$), elastic instabilities appear upstream of the cylinder above a critical Deborah number, that depends on the aspect ratio. In contrast, for the Boger fluids the flow remained symmetric both upstream and downstream of the cylinder in the range of Deborah numbers studied ($De < 1.3$). For all non-Newtonian fluids studied, the streamwise velocity profiles show that the length required to achieve the fully developed velocity downstream of the cylinder increases with *De* and *AR*.

1. Introduction

The flow past circular cylinders is of relevance for industrial applications and can be found in structural design and in the process industries. It is in the latter that typical applications involve fluids with non-Newtonian characteristics, as in heat exchangers, textile coating processes or in wastewater treatment, among others (Nishimura, 1986). In addition, the two-dimensional (2D) flow around a confined cylinder with 50% blockage ratio (*BR*, defined as the ratio between the cylinder diameter and the width of the channel) is a classical benchmark problem in computational rheology (Brown and McKinley, 1994).

There is a wealth of investigations on Newtonian fluid flow past an unconfined cylinder, which are summarized in the reviews of Telionis et al. (1992) and Williamson (1996) and in the books of Zdravkovich (1997, 2003). In contrast, much less is known about the interplay between the far flow field and the cylinder for fluids of complex nature such as the effects upon the flow around the cylinder and the vortex shedding phenomenon, of the aspect ratio (*AR*, defined as the ratio between the cylinder length and diameter), of the blockage ratio (*BR*) and also of the rheology of the working fluid.

The flow of Newtonian fluids past a cylinder in a rectangular channel is characterized by two geometrical ratios (e.g. *AR* and *BR*) and by the Reynolds number, which represents the relative importance of inertial forces relative to viscous forces. Sen et al. (2009) indicate the range $3.2 < Re_D < 7$ for the onset of downstream flow separation. The critical Reynolds number for the onset of laminar vortex shedding is found to be $Re_D \approx 47$ for high aspect ratios and increases when the aspect ratio decreases (Williamson, 1996;

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Sahin and Owens, 2004; Kumar and Mittal, 2006; Ribeiro et al., 2012). The work of Ribeiro et al. (2012) investigated the 3D effects on the laminar flow of a Newtonian fluid past a confined circular cylinder with $BR=50\%$ and showed good agreement between experimental results and numerical predictions. An unusual phenomenon was observed experimentally and confirmed numerically, consisting of intense velocity peaks downstream of the cylinder in the vicinity of the cylinder end walls, which are not reduced even when the aspect ratio of the cylinder increases. For the largest aspect ratios investigated ($AR=16$ and 8) the influence of the end walls on the local velocity peaks was predominant while for $AR<6$ the flow was found to be also influenced by the side walls, due to geometric confinement.

For viscoelastic fluids, the flow past a confined cylinder has also been thoroughly studied experimentally and numerically. Some of the experimental studies of non-Newtonian fluids around a confined cylinder refer only to steady creeping flow conditions (Manero and Mena, 1981; Shiang et al., 1997). Nevertheless, at higher flow rates (or Deborah numbers) when elastic instabilities occur, the flow becomes highly three-dimensional (3D), with steady complex structures developing upstream and downstream of the cylinder. At further higher flow rates, a second elastic instability develops and the flow becomes time-dependent (McKinley et al., 1993). McKinley (1991) investigated elastic instabilities in viscoelastic flow past a circular cylinder using a Boger fluid. The cylinder used in the experiments had a high aspect ratio ($AR=24$); thus the flow in the middle plane could be assumed as quasi-2D at low Deborah numbers. Above $De=1.30$, a cellular structure was observed in the spanwise direction; thus significant 3D effects were found even for such high AR geometry. Shiang et al. (2000) also investigated the flow past a confined cylinder ($AR=12$) with Boger fluids and observed the onset of steady three-dimensional flow, due to the formation of cellular structures in the wake of the cylinder, at a critical Deborah number between 0.14 and 0.21. The Boger fluid used by Shiang et al. (2000) was more viscous and elastic (thus, with a higher elasticity number) than the Boger fluid used by McKinley et al. (1993) and these differences can explain the discrepancy observed in the critical Deborah number. More recently, the experiments of Verhelst and Nieuwstadt (2004) showed the appearance of 3D effects near the walls in the flow past a confined cylinder in a rectangular duct with 50% blockage ratio and aspect ratio $AR=16$.

The onset of 3D effects in the viscoelastic fluid flow past a confined cylinder has also been reported in experimental studies using microfluidic devices (Li et al., 2010, 2012; Kenney et al., 2013). The downscaling of the channel dimensions in microfluidics amplifies the elastic effects, and simultaneously leads to a reduction of inertial effects. Recently, Kenney et al. (2013) investigated the fluid flow past a confined cylinder and identified two distinct elastic instabilities using dilute aqueous solutions of polyethylene oxide (PEO) for increasing flow rates. Initially a time-dependent downstream instability of disorderly streamlines was observed, followed by an upstream instability at higher flow rates, characterized by the occurrence of a detached upstream stagnation point and the formation of an upstream vortex.

Numerical investigations of non-Newtonian fluid flow past a cylinder are usually based on 2D calculations due to the expensive computational resources required for 3D simulations. For some viscoelastic fluids, such simulations showed the steady flow behind the cylinder to be characterized by the appearance of velocity overshoots, which depend significantly on the rheology of the fluid (Phan-Thien and Dou, 1999). Experimental and numerical studies of the viscoelastic flow past a gradual contraction, which can be qualitatively compared with the upstream flow around a cylinder, also show the appearance of velocity overshoots along the centreline and near the end walls upstream of the contraction for 3D geometries (Poole et al., 2007; Poole and Alves, 2009). These velocity overshoots near the walls, which were called the "cat's ears" phenomenon (Poole et al., 2007), are a manifestation of fluid elasticity and were qualitatively captured in the 3D numerical simulations of Poole and Alves (2009).

Despite the smaller number of works reporting 3D simulations, some studies analyzing the viscoelastic flow around a 3D cylinder have also appeared in the literature. Sahin and Wilson (2007) performed 2D and 3D viscoelastic fluid flow simulations around a confined circular cylinder in a channel with 50% blockage ratio, and analyzed the flow patterns up to a Weissenberg number (Wi) of 1.2. The converged 2D numerical results beyond $Wi=0.7$ indicate that the solutions are mesh dependent, at least in a small region in the wake of the cylinder, whereas for the 3D calculations the results at high Weissenberg numbers did not converge, due to the classical high Weissenberg number problem (HWNP) (Fattal and Kupferman, 2004). Sahin (2011) also simulated numerically the 2D and 3D flow of an Oldroyd-B fluid past a confined cylinder and concluded that at $Wi=0.7$ mesh convergence is still achieved in his calculations, even in the wake of the cylinder. However, no steady-state solution was possible for an Oldroyd-B fluid beyond $Wi=0.8$. Richter et al. (2010) studied numerically the 3D viscoelastic flow past a circular cylinder to assess the influence of viscoelasticity on the flow but their simulations were carried out at moderate Reynolds numbers ($100 \le Re \le 300$). More recently, Tenchev et al. (2011) compared 2D and 3D flow simulations of an Oldroyd-B fluid around a confined cylinder and of a Rolie-Poly fluid flowing through a sudden contraction. In both cases, the results for 2D and 3D flows show significant differences, thus emphasizing the need for reliable 3D computations. More recently, Sahin (2013) investigated numerically the 3D creeping flow of an Oldroyd-B fluid past a confined cylinder in a rectangular channel and observed the appearance of a purely elastic instability in the wake of the cylinder, with the formation of cellular structures above a critical Weissenberg number between 1.2 and 1.6, in agreement with the experiments of McKinley et al. (1993).

The practical implementation of the flow of viscoelastic fluids past a confined cylinder is necessarily three-dimensional and it is clear from the previous works that their characteristics can be significantly different from those observed in a simplified two-dimensional geometry. Therefore, the primary goal of this work is the characterization of three-dimensional effects of the flow of viscoelastic fluids past a confined cylinder centered in a rectangular channel with 50% blockage ratio. This is achieved by considering the flows of two Boger fluids and one viscoelastic shear-thinning fluid in three different geometries having aspect ratios of $AR=16$, 8 and 2. The flows analyzed varied from creeping flow conditions (low Reynolds number) up to the onset of elastic induced time-dependent flow, which corresponds to the range of Reynolds numbers between $0.008<Re<3.2$ and Deborah numbers between $0.025<De<0.99$. This work was preceded by a similar investigation involving the laminar flow of Newtonian fluids at low Reynolds numbers (Ribeiro et al., 2012). Numerical predictions were also carried out in order to predict the Newtonian and non-Newtonian fluid flows. These numerical predictions, together with the results of Ribeiro et al. (2012), will be used here to assess and separate the effects of elasticity from those of shear-thinning viscosity.

The remainder of this paper is organized as follows: the experimental set-up and techniques are described in Section 2, while Section 3 presents the rheological characterization of the fluids used. The governing equations and a brief outline of the numerical method are described in Section 4. Section 5 presents and discusses the experimental results and compares them with the corresponding Newtonian fluid flow. In Section 6 the main conclusions are summarized.