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Mechanistic understanding of size-based fiber separation in coiled tubes

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ABSTRACT

Understanding separation of poly-disperse particle suspensions according to the particles size is of great importance to product quality. Previous experimental studies of suspension flow through coiled tubes report different results for spherical and elongated particles, e.g., larger and thus heavier elongated particles are faster than smaller ones.

We use Euler–Lagrange simulations, as well as experiments, to measure the residence time distribution of fibers with different size in coiled tubes with different curvatures. Fluid flow through the coiled tubes was simulated as toroidal flow, i.e., the pitch of the tube was neglected. Fibers are one-way coupled to the fluid, and their movement in the cross section, as well as their orientation is predicted based on the assumption of an infinitely dilute suspension.

We find that in coiled, dilute suspension flow of fibers the ratio of particle settling velocity to the secondary flow speed determines the fiber motion in the tube cross section. For low Reynolds number and thus larger effect of gravitation, fibers are found to concentrate in distinct orbits. Long fibers form flocs propagating through the torus whilst small fibers are well mixed and thus retained in the tube. We found that fiber–fiber interaction and the formation of flocs and not fiber–fluid interaction is key to the size based separation.

1. Introduction

Two-phase solid/liquid suspension flow in tubes and pipes is ubiquitous in the producing industry, including (i) pulp and paper manufacturing (Krogerus et al., 2003; Lundell et al., 2011), (ii) chemical and pharmaceutical industry (Eder et al., 2010), or (iii) recycling of resources (Carissimi and Rubio, 2005; Körkkö et al., 2008; Laitinen et al., 2008). A situation of high relevance is the flow through coiled and bent pipe configurations. Centrifugal forces acting on the fluid lead to (i) a deflection of the velocity maximum towards the outer bend, and (ii) a pressure difference between the inner and outer bend. The latter induces a secondary motion commonly known as Dean flow (Dean, 1928, 1927; Naphon and Wongwises, 2006; Vashisth et al., 2008). This secondary motion increases cross-sectional mixing, and hence reduces axial dispersion of suspended particles. Because the degree of mixedness of particles defines (i) product quality, or (ii) the capability to focus, align or even separate suspended particles (Di Carlo, 2009; Martel and Toner, 2013), a profound understanding of coiled suspension flow is essential. The current paper focuses on the exact mechanism behind the separation of suspended elongated particles, more specifically of fibers. Specifically, we are interested in how the fiber size, shape, and concentration affects the separation process in a coiled tube. Clearly, in case of a pipe with no lateral exit, separation of particles can be only realized in case the residence time of the particles is different from each other. Hence, there is a natural interest in the residence time of suspended particles in coiled tubes.

The influence of curvature and flow conditions on the particle residence time are well investigated for suspensions consisting of spherical particles (Koutsky and Adler, 1964; Palazoglu and Sandeep, 2004; Tiwari et al., 2006). For system involving non-spherical, elongated particles (e.g., fibers) additional modes of particle motion, such as flipping and tumbling, have to be taken into account (Jeffery, 1922; Rosén et al., 2014). Currently, studies on the residence time distribution (RTD) of elongated particles are limited to experimental results (Krogerus et al., 2003; Laitinen et al., 2011, 2006). Findings from literature are that the particle residence time decreases with fiber length. However, these previous studies lack a mechanistic description of the separation process: the current understanding is based on observations from fibers and particles separating in slug tube flow (Johansson et al., 1970; Olgard, 1970).

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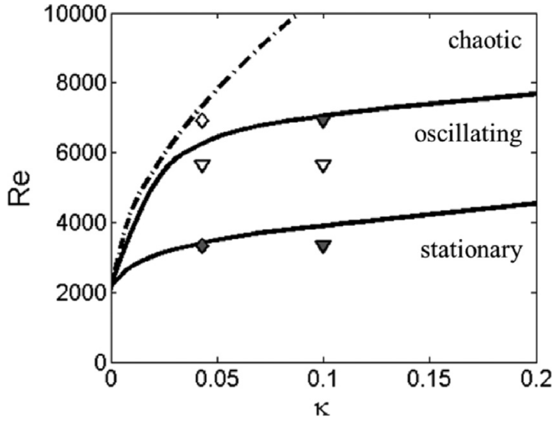

Fig. 1. Regime map for flow through coiled pips (adapted from Di Piazza and Ciofalo (Di Piazza and Ciofalo, 2011). Simulation cases are denoted by triangles, where filled symbols denote two phase fiber/fluid (CFD-DEM) simulations. Diamonds represents cases where both experiments and simulations were performed.

1.1. Objectives

It is the purpose of this paper to provide a mechanistic explanation for size-based separation of fibers in a coiled pipe configuration. The focus is on intermediate Reynolds numbers which correlates with typical operational settings (Laitinen et al., 2006). In this range of Reynolds numbers we deal with steady-state, or oscillating pipe flow in toroidal configurations. We perform experiments to verify the influence of the Reynolds number and the concentration of the fiber pulp suspension on the separation process. The motion on dilute fiber suspension within toroidal fluid flow is then simulated with a recently developed open-source CFD-DEM code (CFDEM®project, DCS Computing GmbH (Goniva et al., 2012)). Figure 1 summarizes the simulation cases and experiments in the flow regime map proposed by Di Piazza and Ciofalo (Di Piazza and Ciofalo, 2011).

Specifically, the questions to be answered in the current paper are:

(1) How is the fiber position and trajectory affected by the fiber aspect ratio and pipe curvature?
(2) What is the fiber residence time distribution?
(3) What is the mechanism responsible for size-based fiber separation in a coiled tube?

1.2. Outline

The outline of the paper is as follows:

In Section 2 we review recent studies on single-phase flow in coiled pipes, and fiber motion in suspension flow. This is to provide adequate background information on the most important flow features that affect particle trajectories.

In Section 3 we present supporting experiments using a fiber separation device, i.e., the tube flow fractionator (TFF). Specifically, experiments with sulfite pulp and mono-sized synthetic cellulose fibers were conducted at different settings of flow rate and fiber concentration. Also, the effect of fiber flocculation on the fiber movement in the channel is discussed.

In Section 4 we present the results of the numerical study. Fibers of different size are introduced into a toroidal tube flow. Fiber position in the pipe cross section, orientation and the resulting residence time of fibers in the pipe are discussed.

In Section 5 we link the simulation study and the experimental study and discuss the results.

In Section 6 we conclude the work and summarize our major findings.

The Appendix presents details related to the post-processing the numerical simulations. The electronical annex (see Electronic Annex in the online version of this paper) presents results of our single-phase simulations of toroidal flow and details on the mesh generation, as well as the validation of DNS simulation results.

2. Theory on toroidal flow and the motion of fibers

2.1. Fluid motion in coiled tubes

In coiled fluid flow, a pressure difference between the outer and inner pipe bend, caused by centrifugal forces, leads to secondary motion within the cross section of the pipe. Dean (1928, 1927) showed that the curvature $\kappa = d/D$, the ratio of the pipe diameter d to the coil diameter D is of major importance to the secondary motion. Hence, the extent of the secondary motion is described by the Dean number Da, i.e., a Reynolds number Re modified by the curvature:

$$Da = \frac{u_{sec} \cdot d}{\nu} = Re \cdot \sqrt{\kappa}. \tag{1}$$

Here ν is the kinematic viscosity of the fluid and u_{sec} is the velocity of the secondary motion which scales with the square root of the curvature and the axial fluid motion, $u_{\mathrm{sec}} = u_{bulk}\sqrt{\kappa}$.

Da characterizes the effect of inertial, viscous and centrifugal forces on the flow. The secondary motion is then often referred to as Dean flow, and the resulting vortices arising at the inner side of the bend as Dean vortices. Re is based on the bulk velocity u_{bulk} and the pipe diameter d.

$$Re = \frac{u_{bulk} \cdot d}{\nu} \tag{2}$$

Recently, direct numerical simulation (DNS) of fluid flow through curved and helically curved pipes were performed to gain a better understanding of the complex phenomena in this flow system (Ciofalo et al., 2014; Di Liberto et al., 2013; Di Piazza and Ciofalo, 2011; Hüttl and Friedrich, 2001, 2000; Noorani et al., 2013). Specifically, it was found that due to centrifugal forces, the velocity maximum is deflected to the outer side of the bend, and the effect increases with the curvature. Consequently, the velocity gradient at the outer bend (i.e., near the outer wall) was observed to be high. Surprisingly, it was found that turbulence is suppressed, and hence the transition to turbulent flow occurred at higher Re. In an extensive numerical study, Di Piazza and Ciofalo (2011) investigated the flow behavior in a toroidal domain for cases below the critical Reynolds number Re_c. They found that for increasing Re the Dean vortices first start to oscillate. The oscillating behavior was also observed in an experiment using a mildly curved torus ($\kappa = 0.049$) (Kühnen et al., 2013). With further increase of Re, the flow becomes chaotic. As already mentioned, this however occurred at a critical Reynolds number larger than that in a straight pipe flow (Fig. 1).

Studies comparing toroidal and helically coiled pipe flow showed, that torsion has only a weak effect on the axial main flow. It was found that peak turbulence is reduced at the outer side, and the pressure drop is unaffected (Ciofalo et al., 2014). However, torsion has an effect on the secondary motion. For high values of torsion the Dean vortex in the upper half of the pipe in relation to the direction of torsion increases, whilst the Dean vortex in the lower half of the pipe decreases (Hüttl and Friedrich, 2001, 2000). Again, for small torsion (ratio of pitch to coil radius smaller 1) the effect is negligible. A torus is hence a good and valid approximation of the industrially more commonly used situation of helically coiled pipes with small torsion.