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Experimental and numerical analysis of an apparatus to apply controlled shear/elongation in fluid flows

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HIGHLIGHTS

- A study of an apparatus to apply controlled shear to fluid flow was done.
- An extensive experimental and numerical analysis of the flow field was given.
- A detailed description of the pathlines inside the flow field was given.
- The shear rate on particles periodically change direction.
- The maximum shear can be controlled by the frequency and amplitude of oscillation.

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ABSTRACT

This paper reports on the detailed flow physics of a device to control shear/elongation in a fluid flow. The device consists of a sphere which periodically moves up and down inside an axisymmetric confinement. Detailed analysis of the flow field inside the setup is reported in this paper and an analysis of the flow structures and the shear rates inside the confinement is made. The flow field is experimentally measured using Time-Resolved Particle Image Velocimetry (TR-PIV) and numerically obtained by a Direct Numerical Simulation. The numerical simulations are validated with experimental data and the numerics were able to capture all the flow features found in the experiments. Shear rate profiles along pathlines are calculated and it was found that the shear rate profiles are very similar for different initial positions in the flow field. Due to the up and down movement of the probe, both positive and negative shear is created, which is not possible with other shear controlled devices such as rotating cylinders, moving plates, and contractions. Therefore, this apparatus is able to simulate more realistic flow conditions as can be found in the processing industry.

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1. Introduction

Applying a controlled shear force in fluid flow is used in many engineering applications. For instance in droplet dispersions, the dynamics of the droplets under a mechanical load is of interest in cosmetics, pharmaceuticals, and polymer blending (Taylor, 1932; Boonen et al., 2009). An understanding of the droplet dynamics in such systems helps in explaining the rheological behavior of the flowing emulsions. Also in the food industry it is widely used to characterize the behavior of gels, liquids and emulsions (Gallegos and Franco, 1999). To study the deformation and orientation of single Newtonian droplets immersed in an immiscible Newtonian liquid, several devices are used in the literature. For instance in sudden contractions, the droplets are subject to shear/elongation caused by convergence of the streamlines as the flow goes through the contraction (Han and Funatsu, 1978; Chin and Han, 1980; VanderReijden-Stolk and Sara, 1986). More controllable devices, such as computer controlled four-roll mills (Bentley and Leal, 1986; Stone et al., 1986) and eccentric rotating cylinder systems (Ottino et al., 1988; Windhab et al., 2005; Boonen et al., 2009), are able to change the magnitude of the shear rate and the elongation in a controlled manner. However, in most processing operations, the sign of the shear rate also changes, which is not possible to realize with the devices mentioned earlier.

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Another application of controlled shear in fluid flow is the in vitro simulation of gastric flow. It is believed that the flow inside a stomach plays an important role in the mixing and digestion of food (Vassallo et al., 1992; Kamba et al., 2000; Marciani et al., 2001; Pal et al., 2004; Ferrua and Singh, 2010). To simulate the mixing in gastric flow, most simple *in vitro* models use end-over-end rotations to mix the digest with stomach juice. However these end-over-end rotations do not take into account the flow structures and vortices associated with periodic contractions of the stomach during gastric digestion (Ferrua and Singh, 2010). A simple device to simulate these periodic contractions of the stomach has been proposed by Chen et al. (2011). Basically, the setup consists of a periodically moving sphere (called a probe) inside an axisymmetric confinement. In this way, mixing is modeled and the controlled application of mechanical forces can help study the influence of shear on the digestion process. However in their paper, only a numerical analysis of the flow was done and no experimental analysis was performed. Only limited data of the flow field are given and therefore a detailed analysis of the physics of the flow field inside the confinement is not included. Moreover, information on the shear rates in the flow field was not given.

In this paper, a detailed analysis of the flow field of this apparatus is made. Such a detailed analysis is currently lacking in the literature. Not only the flow structures are discussed, but also the shear rate in the flow field is studied. The apparatus is not only able to control the magnitude of the shear force, also the direction is changed periodically. Current devices found in the literature to generate controlled shear do not exhibit this property. Therefore, this apparatus is able to study the dynamics of droplets in more realistic flow conditions as can be found in the processing industry.

2. Experimental and numerical model

The apparatus to apply the controlled shear forces is schematically shown in Figs. 1 and 2. The device was developed by Chen et al. (2011) and the dimensions as such were chosen to be a good representation of the flow during digestion in the human stomach. The setup is axisymmetric along the x-axis in a cylindrical (xr) coordinate system. It consists of a spherical probe centered inside a confinement. The internal diameter D of the confinement is 70 mm and the internal height H is equal to 180 mm. The spherical probe has a diameter $D_p = 58$ mm and moves periodically up and down with a frequency $f = 75$ mHz. The amplitude of the motion is 3 cm and the maximum probe velocity U_p is 1 cm/s. This probe velocity was chosen so the velocities in the apparatus are in the same order of magnitude as the ones in the stomach during digestion. As the probe moves up and down, shear stresses are created in the flow field. Because of the axisymmetry of the setup, the only non-zero shear stress in the flow field is τ_{xr} and is given by

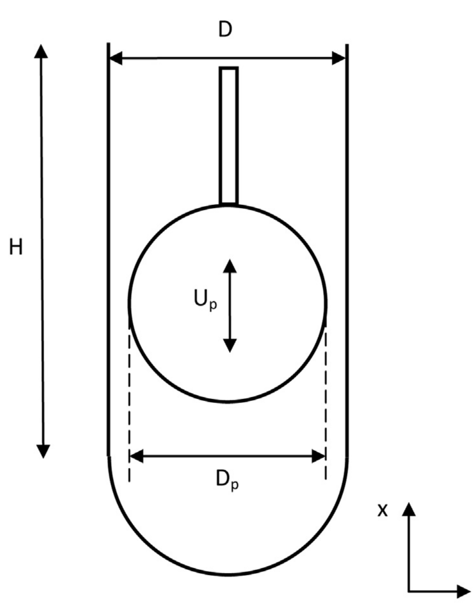

Fig. 1. Schematic view of the dimensions of the apparatus. The probe moves up and down with a velocity U_p.

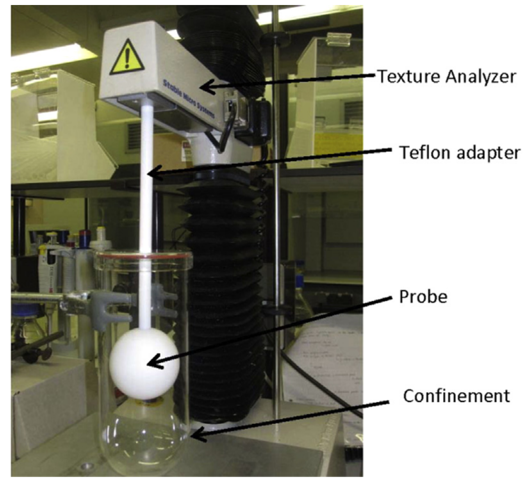

Fig. 2. Photograph of the experimental setup.

$$\tau_{xr} = \mu\left(\frac{\partial U}{\partial r} + \frac{\partial V}{\partial x}\right), \quad (1)$$

where μ is the dynamic viscosity of the fluid, U is the velocity component in the x-direction and V the velocity component in the r-direction. Since the probe moves periodically, the shear stresses in the entire flow field are also periodically changing in a controlled way.

2.1. Experimental setup

The up and down motion of the probe is governed by the load cell of a Ta-XT2i Texture Analyzer (Stable Micro Systems, Surrey, England). Both are connected by a thin Teflon adapter (9 mm thick). The Texture Analyzer can measure the force on the probe and hence the rheological behavior of a fluid can be studied. As working fluids, sugar-water solutions are used with different sugar concentrations. The density of the fluids depends upon the sugar concentration and ranges from 998 to 1290 kg/m^3 and the viscosity varies from 1 mPas (pure water) to 80 mPas (60% sugar solution). The Reynolds number of the flow, based upon the maximum probe velocity and probe diameter ranges from 9 for the high viscosity fluid to 580 for the low viscosity fluid. This ensures a laminar flow, even for the highest Reynolds number.

The flow field inside the confinement is measured by Time-Resolved PIV (TR-PIV). A laser sheet with a thickness of 0.5 mm is generated using a Dual Cavity Nd:YLF Pegasus-PIV laser from NewWave with a wavelength of 527 nm and a pulse energy of 10 mJ @ 1000 Hz. The velocity field is measured in a median plane through the central axis (xr-plane). The flow is seeded using hollow PMMA particles of diameters between 20 and 50 μm. The particles are coated with Rhodamine B. These fluorescent particles increase the signal to noise ratio as the back light of the laser sheet is filtered out using an optical filter. The images are recorded using a 'HighSpeedStar 5' CMOS camera with a resolution of 1024 × 1024 pixels. To correct for refraction, the PIV system was calibrated by placing a calibration plate in the flow field. The calculation of the

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