Turbulent drag reduction by additives

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This section presents general information about techniques used in the experiment. The rheological measurements were made with a Reologica StressTech rheometer and the drag reduction measurements were realized using a horizontal closed-loop system. The counter rotating disks were used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids. This chapter presents a detailed characterization of the rheometer, the horizontal closed-loop system, Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV) and the counter rotating baffled discs techniques.
3.1 Reologica StressTech Rheometer

Knowledge of viscosity is a key factor in understanding the rheological behavior of DR agents. The viscosity was measured using the Reologica StressTech rheometer, which is optimized for stress-controlled rheology measurements. It is equipped with a wide selection of modular cone plates, plate-plates, and coaxial cylinder measurement systems. Different geometries can be used, depending on the fluid being tested.

Figure 1: Reologica StressTech rheometer.

3.1.1 Parallel plate geometry

A parallel plate geometry consists of a fluid placed between two parallel plates. The bottom plate is fixed, while the top plate moves freely under an applied force. This geometry works for fluids that are viscous enough to prevent them from flowing out of the sides of the plate. The shear rate varies from zero (at the center) to $R \omega / D$ (at the edge of the plate), where $R$ is the plate radius [m], $D$ the gap [m], and $\omega$ the rotation rate [rad/s]. A schematic of parallel plate geometry is given in Figure 2, below.
Shear rate (sec\(^{-1}\)): \( \dot{\gamma} = \frac{R \omega}{D} \) 

Shear stress (Pa): \( \tau = \frac{2}{2\pi r^3} \) 

Viscosity (Pa\cdot s): \( \eta = \frac{\tau}{\dot{\gamma}} \)

3.1.2 Cone and plate geometry

A cone and plate system involves placing the sample between a lower fixed circular disk and a rotating angled cone. The plate is rotated and the corresponding torque on the cone is measured. Since the angle is a very small, the shear rate can be considered to be constant. Cone and plate geometry only requires a very small amount of sample. The determining parameters include the disk radius \( R \) [m], the rotational rate \( \omega \) [rad/s], the angle between cone and plate \( \theta \) [rad], and the torque \( M \) [N\cdot m]. A schematic of cone and plate geometry is shown in Figure 3.
Shear rate (sec⁻¹): \( \dot{\gamma} = \frac{\omega}{\sin \theta} \)  \( \quad (4) \)

Shear stress (Pa): \( \tau = \frac{3M}{2\pi r^3} \)  \( \quad (5) \)

Viscosity (Pa·s): \( \eta = \frac{\tau}{\dot{\gamma}} \)  \( \quad (6) \)

### 3.1.3 Bob and cup (Couette) geometry

Bob and cup geometry (or “couette geometry”, after inventor Maurice Couette) was the first rotating device to measure viscosity [1]. For this type of geometry, the resistance to flow is assumed to be in a small gap. The input parameters include the rotational speed [rad/s], the torque \( M \) [N·m], the bob radius \( R_b \) [m], the bob height \( L \) [m], and the internal radius of the cup \( R_c \) [m]. A schematic of bob and cup geometry is given in Figure 4.
Shear rate (sec⁻¹): \( \dot{\gamma} = \left( \frac{2R_c}{R_c^2 - R_b^2} \right) \omega \) \hspace{1cm} (7)

Shear stress (Pa): \( \tau = \frac{M}{2\pi R_c^2 L} \) \hspace{1cm} (8)

Viscosity (Pa·s): \( \eta = \frac{\tau}{\dot{\gamma}} \) \hspace{1cm} (9)
3.2 Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) is the most effective and progressive measurement tool for the quantification of the velocity field in fluid mechanics and aerodynamics. PIV technique is widely used to study turbulence properties of fluids. Measurements using Particle Image Velocimetry are described by Hibberd et al. [2], Warholic et al. [3] and White et al. [4].

Particle Image Velocimetry is an optical method of visualization to measure instantaneous velocity. The PIV system gains information on the particle displacements in the fluid over a known interval of time. The velocity is calculated by dividing the particle displacement by the time:

\[ u = \frac{\Delta X}{\Delta t} \]  

(10)

(where \( \Delta X \) is the average displacement of particles in the fluid over interval of time \( \Delta t = t_2 - t_1 \)).

Typically, the PIV system consists of double-pulse (Nd-Yag type) lasers, a CCD camera (a digital camera with a high resolution), a laser plane (pulse) for illumination of the flow, a particle seeding mechanism, and a computer with image-processing software (DaVis) for data storage and analysis. In the PIV method, the flow is seeded with sufficiently small tracer particles that perfectly follow the molecules of the fluid and scatter enough light from the incident laser beam. In this case, the flow was seeded with glass particles 15 µm in diameter. The density of the glass particles is close to the density of water (between 9 and 11 microns). The flow visualization was performed using Nd-Yag lasers, which each have an output of 45 mJ/pulse and a wavelength of 532 nm. Two laser pulses illuminated the particles, with a short time difference. The time interval between the two laser pulses (\( \Delta t \)) or the duration between two successive illuminations determines the movement of the particles (\( \Delta X \)) between two successive images.

The light scattered by the seeds is collected by an optimized CCD camera sensor. The CCD camera is a key element in the study and in our measurement, we used a high-resolution digital camera (1024x1280 pixels). The image acquisition is based on scanning several pairs of successive images over an interval of time, which are then transferred to the computer for processing. The computer calculates the instantaneous velocity fields by means of algorithm cross-correlation. Finally, the PIV technique yields the mean velocity field and turbulence quantities of
the flow by statistical treatment of the instantaneous data sets. The statistical treatment of turbulent flow requires the calculation of different averages from a set of sufficient instant fields vectors, in order to have a convergence of the statistical properties of the flow (mean, variance, standard deviation, correlation coefficient). The number of instant fields needed for calculation of the average field depends on the experimental conditions, and can be estimated with statistical methods.

Fig 5: Working principle of particle image velocimetry (www.lavision.de).
3.3 Characterization of Horizontal Closed-Loop System

The drag reduction measurements were realized using a horizontal closed-loop system (shown schematically in Figure 6 and Figure 7). This setup was developed at Caen University. The system consists of two main parts: The first part is made from a stainless steel tube equipped with a differential pressure transducer (DRUCK, PDCR 2111) to measure the pressure drop. This pressure transducer is connected to two pressure taps, 6.2 m apart. The pressure taps are controlled by two sensors arranged along the channel to measure the pressure loss and calculate the pressure drop. The measurement range of the pressure sensors is 0-350 bar. The second part is used to visualize the flow of PIV through a transparent glass tube, around 1.2 meters long with a diameter of 22.5 mm. This tube is made from a borosilicate pipe glass, manufactured by the company PRECIVER. The fluid flow is driven by a volumetric pump (PCM, MR13110) from a reservoir tank of 30 liters. To reduce the fluctuations of pressure in the closed system, a pressure damper is installed at the outlet of the pump. On the other side, a magnetic flow meter is placed after a bend of 180° (400 mm radius of curvature) to measure the flow rate. The temperature is measured when entering and exiting the system. Temperature is controlled by a heat exchanger and measured by two sensors (ANALOG DEVICES, AD592CN). A 1.5 m heat exchanger tube is introduced into the loop before the tank. This part of the heat exchange is supplied with a coolant by a large capacity cryostat. The volumetric pump and valve are used to adjust the flow rate. The pump used here can deliver up to 8 bar (for 0.95kW) and the range of flow rate covered is up to 676 [L/min]. This flow rate can be adjusted by changing the frequencies (between 20 to 60 Hz) and opening the valve installed on the outlet of the pump. The reference frequency of the drive can be entered manually or via a computer connected to the driver. A filter on the driver reduces the noise generated. The valve, placed at the outlet of the pump, is used to regulate the flow circulating in the loop system and maintain normal operation of the pump (to avoid operation of the pump at low speeds of rotation, in the case of low flow rates). All data, consisting of pressure gradient, temperature and flow rate, are then processed by computer. Our experiment used a PC with an acquisition system (delivered by LAVISION), with DaVis processing software.
Figure 6: Installation of the camera on the PIV experimental test loop.

Figure 7: Schematic design of the experimental setup.
3.4 Characterization of Counter Rotating Baffled Disks.

The counter rotating disk is an apparatus broadly used in the determination of the turbulent properties of a fluid. Such a set up has been widely used for the examination of turbulence properties in simple fluids as well as in drag reducing complex fluids. Studies on this type of apparatus are reported by Bonn et al. [5], Cadot et al. [6] and Sohn et al. [7]. Cadot et al have found that drag reduction occurs with smooth discs but not with baffled discs. Turbulent flows can be generated between two counter-rotating discs (either with baffles or without baffles). In the present study, we used two counter rotating baffled disks. The experimental set up is also described in more detail in chapter 5. Here, what we examine is the modification of the turbulence properties in the bulk of the solution. The turbulence is generated in the cylindrical cells between two counter-rotating disks at a constant angular velocity, $\Omega$. The counter rotating disc used for the determinations of turbulence properties was equipped with four baffles having a height of 4 cm. These disks are driven by two separate motors which can rotate at different frequencies controlled by two current supplies. Then cylindrical cell was filled with approximately 2.5 litres of the desired solution. The cells have a radius of 7 cm and a height of 20 cm. The design of the measurement cell is shown in Figure 8.

![Figure 8: Schematic of counter-rotating cell apparatus with baffles.](image)
3.5 Laser Doppler Velocimetry (LDV)

Laser Doppler Velocimetry (LDV) produces temporal traces of the velocity of micron sized seed particles in solution and is measured at a fixed location in the cell. The LDV probe was positioned slightly below the centre of the cell so as to have a nonzero mean flow velocity. Visualization is realized by seeding the experimental fluids with glass particles which are 15 µm in diameter. An Nd-Yag type laser is used as a source of illumination and a CCD camera (of 1024x1280 pixels resolution) is used to record flow images. In our experiment, the reference state is water and the complex fluid used is a dilute aqueous solution. The Reynolds numbers examined are defined as

\[ \text{Re} = \frac{\Omega R^2}{v} \]

and range from 5000 to 100000, where \( R \) is the radius of the discs, \( \Omega \) is the angular rotation, and \( v \) the kinematic viscosity of the fluid.

3.6 Taylor’s Frozen Turbulence Hypothesis

In this experiment, we have recast the frequency into a wave number by using the Taylor’s frozen turbulence hypothesis, when representing the power spectra of the velocity fluctuations. Taylor [8] proposed an assumption in which he could deduce the spatial structure of a turbulent velocity field from a single point measurement of its temporal fluctuation. Taylor’s frozen turbulence assumption is often used in laboratory experiments to investigate the large-scale turbulent structures. The Taylor hypothesis for frozen turbulence basically assumes that the velocity of turbulence is insignificant compared to its advection velocity. To examine turbulence from a continuous record of measurements from a single point, the turbulence is assumed to be frozen. This means that the fundamental properties of the eddies remain unchanged, or frozen over a point. The Taylor hypothesis is very valuable since according to this, the frozen turbulence assumption may be used to convert the frequency spectra to wave-number spectra. Such approximation of wave number is given by

\[ k_x = \frac{2\pi f}{U_0} \]

Where \( f \) is the frequency of the fluctuations \( U_0 \) is the relative flow speed, and \( k_x \) is the wavenumber.
Bibliography


