Viscoelasticity and shear-thinning effects on bio-polymer solution and suspended particle behaviours under oscillatory curve Couette flow conditions

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Abstract: Formation of wear particles within total hip replacement is one of the main causes of its failure. In addition to improving the lubrication and wear resistance of materials used as bearing surfaces, understanding of wear particle distribution patterns within lubricants inside an implant gap could be used to improve design parameters and implants' lifespan. In this study, the behaviours of biolubricants (with compositions similar to human joint synovial fluid) and suspended particles were investigated by micro-particle image velocimetry in curved mini channels under oscillatory Couette flow conditions. The studied biolubricants had shear-thinning viscoelastic characteristics. The authors found that increasing shear-thinning, elasticity or motion frequency levels did not affect the trend behaviours of biolubricant flows due to the low strain values of the experimental conditions applied. However, suspended particles formed strings along flow directions and exhibited cross-stream migration to channel walls. Motion frequency, fluid shear thinning and elasticity characteristics and channel dimensions strongly affected particle behaviours.

1 Introduction

The dynamics of non-Brownian suspended particles in non-Newtonian viscoelastic fluid have been recently studied widely due to their numerous biological and industrial applications [1]. One challenging application that has not yet received much attention is related to the distribution of wear particles in total hip replacements (THRs). Synovial fluid (SF), which lubricates human joints, is a viscoelastic fluid with non-Newtonian shear-thinning characteristics. It is composed of proteoglycan (0.05–0.35 mg ml$^{-1}$), hyaluronan (1–4 mg ml$^{-1}$) and surface active phospholipids (0.1 mg ml$^{-1}$), which provide lubricity features [2, 3].

The shear thinning and viscoelasticity of SF is attributed to its hyaluronic acid (HA) composition as a linear biopolymer. HA exists in healthy SF at a molecular weight and concentrations of 6.7–7.6 MDa and 1.45–4.22 mg ml$^{-1}$, respectively [4]. However, characteristics of HA in SF of a patient with THR, which is called periprosthetic SF, is not the same as healthy SF. THR is one of the most successful surgeries in the 21st century. Most conventional THR design consists of a hard ball made of cobalt chromium alloy or ceramics moving against a soft acetabular cup usually made from ultra-high-molecular-weight polyethylene (UHMWPE). Although UHMWPE shows favourable mechanical and tribological properties for reducing friction, wear particles of this material produced during the THR lifetime are the source of bone loss (osteolysis) and implant loosening which eventually cause failure [5]. Distribution patterns of these wear particles within implants' gaps are affected by the special rheological behaviours of the SF, geometrical parameters, particles’ sizes, particles interactions and particle-fluid interactions [6, 7]. Therefore, understanding these patterns can allow one to optimise design parameters to decrease wear particles and third body wear effects on bearing surfaces. Therefore, the lifespans of the implant and patient life quality are increased.

The specific behaviours of particles within the viscoelastic fluid that are not happening in Newtonian fluid include particle migration and string formation along the flow direction. Particle alignment and string formation along the flow direction was first reported by Michele et al. [8]. These authors showed that randomly distributed particles in viscoelastic fluid subjected to shear or pipe flow align and build up strings. They attributed the discrepancy between particle behaviours in Newtonian and viscoelastic fluids to normal stress effects. This behaviour was observed when the Weissenberg (Wi) value (defined as the ratio of normal stress to shear stress) reached at least to ten. Further investigations have focused on understanding the effects of parameters such as shear thinning, wall confinement, particle sizes and flow conditions (shear or pressure driven and steady or unsteady) on the migration and alignment of particles in non-Newtonian viscoelastic fluid flows.

Lyon et al. [9] showed that particles in a fluid flow with an oscillatory motion, cluster rather than forming long strings. Won and Kim [10] conducted studies on both shear thinning and viscoelastic fluids under reciprocating shear flow conditions. They found that though the Wi number may be critical for particle migration, shear thinning is the determinant parameter for particle string structure formation. This observation was later confirmed by Van Loon et al. [7]. The results presented by Van loon et al. showed that while compressive forces originating from normal stress and elasticity effects enhance particle cross-stream migration and particle alignment, shear thinning is necessary for particle strings formation. Moreover, confinement from channel walls was found to improve collision probability levels and facilitate particle alignment. On the other hand, Scirocco et al. [11] showed that when particles are small enough relative to the channel size, gap sizes have no significant effects on alignment. The authors showed that experimental conditions, particle sizes and criteria used to define string formation processes have significant effects on critical Wi number determination (the Wi value at which particle alignment starts), and they confirmed that a critical degree of shear thinning is required to initiate string formation. They also suggested that string formation is a bulk phenomenon that does not necessarily occur along the walls. However, Pasquino et al. [12] suggested that in very weak shear-thinning fluids, particle
alignment is not a bulk phenomenon and occurs near the walls. Particle strings were found to form when the applied shear rate value is higher than the critical shear rate and are enhanced when the shear rate is increased and the gap size is decreased. Once low shear rates and small particle sizes are involved, short strings of particles can align normal to the flow direction. The authors concluded that different parameters might affect string lengths and alignment directions. Particle sizes, fluid characteristics such as colloidal and hydrodynamic forces, kinetics of string formation and particle migration features were listed as some of the parameters involved. In a later work, the same authors defined an alignment factor for quantifying the effects of shear rates and particle concentrations on the duration and length of string formation. Their results showed that increasing both parameters results in faster and longer particle string formation [13]. Numerical and experimental studies on single particle migration under Couette flow conditions between two concentric cylinders conducted by D’avino et al. [14] showed that under the effects of viscoelasticity forces, particles migrate toward the outer cylinder unless they are very close to the inner cylinder. Higher angular velocity and shear-thinning rates were found to increase the migration rate. Numerical simulations of particle migration under reciprocated confined simple shear flows have shown that increasing the frequency ceases particle migration induced by fluid viscoelasticity and wall confinement [15]. This result is partly in agreement with the results of Lormand and Phillips’s [16] study on particle migration within viscoelastic shear-thinning fluids in concentric cylinders with oscillatory motion. Lormand’s results showed that depending on initial particle positions, migration is directed toward the inner or outer cylinder. Inner migration velocity levels were found to increase with frequency. In Lormand’s study, for frequencies larger than 1 Hz, outer migration velocities reached a value of zero and particles did not migrate toward the outer wall. The authors thus proposed that the migration rate is affected by the elasticity parameter [16].

Particles' migration and alignment in non-Newtonian viscoelastic fluid flows are affected by numerous factors: flow conditions (steady state, oscillatory, Couette, Poiseuille etc.), gap and particle sizes and geometries, shear thinning, elasticity degrees, particle concentrations etc.

The main objective of the present paper was to investigate particle-flow interactions within a cylindrical curve channel mimicking a THR configuration. Various viscoelastic shear-thinning HA solutions under an oscillatory Couette flow were investigated via micro-particle image velocimetry (micro-PIV). The effects of HA concentration, protein content, motion frequency and gap size were investigated. Distilled water was used as the reference liquid. Potential improvements for THR design were deduced from the results.

2 Materials and methods

2.1 Experimental setup

Micro-PIV was used to derive velocity profiles of the polymeric fluid flow. The working principle of micro-PIV is the same as that of PIV but for smaller scales. In this method, tracing particles were added to the fluid. Particles were illuminated with a pulsed light [either laser or light-emitting diode (LED)]. Sequences of double frame images were captured by a charge coupled device (CCD) camera mounted on a microscope. The plane of the view was divided into numerous interrogation areas. The displacement of particles between two frames of a double frame image divided by the time difference between each light exposure provided the particle velocity value. According to PIV principles if the density and size of particles are suitable, particles follow the fluid motion and particle behaviours are representative of fluid behaviour [17–19]. Previous studies by the authors have included further information on particle suitability evaluations for studying the steady and unsteady behaviours of polymeric solutions. These studies also include validation process for applying this standard method in investigating the behaviour of polymeric solutions [20, 21].

Fig. 1 shows a schematic view of the experimental setup used. The system included a double-pulsed micro-strobe (LED) and a high-speed double frame CCD camera with a spatial resolution of 1280 × 1024 px/frame mounted on a microscope with four magnifications (5×, 10×, 20× and 40×). The two pulses had the same time duration (70–110 μs) based on the flow speed and channel size. The time between two pulses was set between 150 and 940 μs as a function of the speed amplitude and fluid type. Polystyrene particles (microParticles GmbH, Berlin, Germany) with a density of 1–1.05 g cm$^{-3}$ and a diameter of 4.89 μm were used at a magnification of 10×.

Fig. 1 Schematic view of the experimental setup
2.2 Experimental model

Two curved channels were designed to study particle-flow interactions under constant width and converging–diverging channel conditions. The curved channel consisted of two stainless steel concentric cylinders. To optically access the model, the stainless steel parts were placed inside a Plexiglas frame. The constant-width channel was 1.1 mm wide while the width of the converging–diverging channel ranged from 0.3 to 1.1 mm. The inner wall radius and depth of both channels were set to 21 and 3 mm, respectively. About \( \sim 3 \) ml of fluid was stored in the rectangular storage areas of each model during the measurement period (Fig. 2). The channels were sealed with an upper Plexiglas plate. Hereafter, the constant-width channel is referred to as the Const channel and the converging–diverging channel is referred to as the Conv channel.

2.3 Reciprocal movement

The inner cylinder was oscillated by a rotating disk powered by an electrical motor in combination with four rotating arms and one pushing arm. Fig. 3 presents a schematic view of the oscillatory engine coupled with the experimental model. To determine the

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**Fig. 2** Experimental model

**Fig. 3** Schematic view of the oscillatory engine
angular positioning of the disk, a magnetic encoder and 12 steel teeth (knobs) spaced equally along the periphery of the disk were used. An encoder signal synchronised the micro-PIV and LED, i.e. it acted as a trigger. Images were captured at defined phases. As noted in the previous study, to achieve statistically significant mean velocity profiles, several velocity maps must be averaged [20]. Under oscillatory conditions, averaging is possible only for images captured at almost the same phase. Image phases were defined based on the positioning of the pushing arm and rotating disk phase. The positioning of pushing arm was defined by a distance laser.

A code developed in LabVIEW controlled the frequency of the rotating disk. Three different frequencies were applied: 0.37, 1.02 and 2.03 Hz. The criteria applied to select the frequency are listed in our previous paper [21]. The rotation amplitude of the inner cylinder was set to 15° (total movement of 30°), which is the average hip joint rotation amplitude in the sagittal plane that occurs during walking [22].

### 2.4 Experimental fluid

Distilled Water was used as reference Newtonian fluid. The HA solutions investigated were selected to capture periprosthetic fluid characteristics by using a simple composition. Available data suggest that the periprosthetic fluid has a similar composition to that of normal SF with less viscosity, shear thinning and viscoelastic behaviour [23]. To capture characteristics of the periprosthetic fluid and to investigate effects of the different parameters on flow behaviours, three solutions of HA were studied:

(i) HA with 1.6–1.8 MDa molecular weight (Sigma Aldrich 537474, St. Louis, Missouri, USA) with a concentration of 3 mg ml⁻¹ in phosphate buffer saline (PBS from Sigma Aldrich, St. Louis, Missouri, USA with 0.15 M concentration).

(ii) HA with 3 mg ml⁻¹ concentration in a mixture of 75% PBS and 25% bovine calf serum (Sigma Aldrich 12133C).

(iii) HA with 5 mg ml⁻¹ concentration in PBS.

To minimise bacterial activity, 0.1% (w/v) sodium azide (Sigma Aldrich 71289, St. Louis, Missouri, USA) was added to the HA solutions.

The blending procedures applied to the solutions have been published [20].

Rheological behaviours of the HA solutions were investigated using a Bohlin CVO rheometer at 25°C under shear rate control (0.05–1570 s⁻¹) with coaxial cylinders (C25) to obtain the variation of viscosity versus the shear rate. The viscoelastic behaviour of the HA with 5 mg ml⁻¹ concentration in PBS was investigated using the same rheometer and cone on plate configuration, which consisted of a stainless steel cone of 1° and 20 mm in diameter. Frequency sweep measurement was performed with the strain value of 2% and strain frequency between 0.07 and 10 Hz. Investigating the viscoelastic behaviour of the HA solutions with 3 mg ml⁻¹ was not possible due to the calibration range of the rheometer used. Table 1 provides a summary of the experimental conditions applied.

### 3 Theory

A shear flow induced by a flat plate with harmonic oscillatory motion in its own plane is known as Stokes’ second problem [24]. Viscous waves generated at the moving wall penetrate into the fluid with a velocity perpendicular to the wall and a penetration depth calculated from the equation below [25]:

\[
\delta = \sqrt{\frac{2v}{\omega}}
\]

\(\delta, v, \omega\) represent the penetration depth or Stokes boundary layer thickness, the kinematic viscosity and the frequency of oscillation in rad s⁻¹, respectively.

| Fluid name | Fluid |
|------------|-------|
| distilled water | DW |
| PBS + HA 3 mg ml⁻¹ solution | H3A |
| 75% PBS + 25% serum + HA 3 mg ml⁻¹ solution | HA3S |
| PBS + HA 5 mg ml⁻¹ solution | HAS |

**Table 1a** Experimental conditions

| Channel width in mm (h) | Channel name |
|-------------------------|--------------|
| 1.1                     | Const channel |
| 0.3–1.1                 | Conv channel |

**Table 1c** Experimental conditions

| Flow frequency, Hz | Frequency acronym |
|--------------------|--------------------|
| 0.37               | Fr-0               |
| 1.02               | Fr-1               |
| 2.03               | Fr-2               |

Fig. 4 shows a two-dimensional (2D) view of the experimental model and measurement location. The measurement location was set at 45° with respect to the symmetrical axis of the model. For the Conv channel, the ratio of the widths of the largest to smallest measurement sections width in a complete cycle was more than 2 at this location. The maximum curvature ratio (ratio of the width of the channel to the inner cylinder radius) of both channels was 0.05. Owing to the small field of view and small curvature ratio, it was assumed that curvature effects were negligible in our analytical analysis. The half-circle part (Fig. 4) is subjected to oscillatory motion in its own plane at a velocity of \(v = \omega \cos(\omega t)\). Assuming a negligible effect of the curvature on the flow, the governing equation for the conservation of momentum for both Const and Conv channels is given by equation below:

\[
\rho \frac{\partial u}{\partial t} = \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) - \frac{\partial P}{\partial x}
\]

where \(\rho, \mu, P\) represent density, dynamic viscosity and pressure, respectively.

In (2), \(\partial P/\partial x = 0\) for the Const channel and Conv channel \((\partial P/\partial x) > 0\) for contraction phases and \((\partial P/\partial x) < 0\) during expansion phases.

### 4 Data analysis

The velocity profiles were derived by applying cross-correlations between two frames of a double frame image. On the basis of the criteria described in our previous publication [20], the interrogation area size was set to 16 × 128 px. The border of the analysis was set at two particle diameters from the wall to prevent the large error region.
The distance laser determined the position of the pushing arm at each instant. Connections between the arms were assumed to be solid and sinusoidal movement was transferred to the moving cylinder. The sinusoidal velocity of the moving cylinder was derived from the distance laser signal. The zero phase was defined as the middle position of the pushing arm when moving backward. At least 120 images were captured at each phase. Derived velocity maps were phase resolved and averaged at each phase, i.e. angular resolved. Sinus curves were fitted at angular resolved velocities along the width of the channel, thus describing the profile in time for the Const channel. The amplitude and phase of the fluid velocity used in the analysis were derived from the sinus curves. The phase difference between the moving wall and fluid was calculated from the equation below:

\[ u_{\text{cylinder}} = \text{Amp}_{\text{cylinder}} \sin (2\pi f + \phi) \]
\[ u_{\text{fluid}} = \text{Amp}_{\text{fluid}} \sin (2\pi f' + \phi') \]
\[ \Delta \phi = \phi - \phi' \]

where \( u \), \( \text{Amp} \), \( f \) and \( \phi \) represent the measured velocity, calculated amplitude, frequency and phase of motion, respectively. The velocity was made dimensionless by dividing it by the maximum amplitude. As the phase acquired for the moving wall was \( \phi = -90^\circ \), the cylinder velocity can be written in cos from the equation below:

\[ u_{\text{cylinder}} = -\text{Amp}_{\text{cylinder}} \cos (2\pi f) \]

Channel width variations in the Conv channel made it impossible to use the same procedure for the data analysis. Therefore, results were compared at each phase.

It was noted in [20] that at least 300 images are required to have mean velocity variations of <0.5%. For this set of measurements, due to CCD camera memory limitations, 120 images were captured at each phase. The relative difference (RD) between the mean velocities obtained from 120 and 300 images was investigated (5). Fig. 5 shows RD along the channel width. The RD is presented for the case of distilled water at a frequency of 2.03 Hz and for the phase with the cylinder maximum velocity.

\[ \text{RD} = \left( \frac{\bar{u}_{120} - \bar{u}_{300}}{u_{\text{cylinder}}} \right) \times 100 \]

where \( \bar{u}_{120} \) is the mean value of the velocity calculated using 120 images, \( \bar{u}_{300} \) is the mean value of the velocity calculated using 300 images and \( u_{\text{cylinder}} \) is the cylinder velocity of the specific phase. The results show that the maximum RD along the channel is <1% of the cylinder velocity.

5 Results and discussion

5.1 HA rheology

Fig. 6 shows the viscosity versus the shear rate for the three HA solutions investigated. The HA solution with protein content...
showed higher viscosity compared with the HA solution without protein at low shear rates. As noted by Zhang et al. [26], the rheological behaviour of these two solutions is actually the same, and the difference is attributed to the interfacial effects of rheological measurements.

The most frequent equation applied for quantifying polymer behaviour in the shear-thinning region is the power law model as (6) [27]

$$\mu = m\dot{\gamma}^{n-1}$$

The above equation is a line fitted on the shear-thinning region of the double-logarithmic plot of the viscosity-shear rate. ‘n = 1’ is the slope of the line and ‘n’ is called the power law index. ‘m’ is the consistency index, which is the intercept of the fitted line with a shear rate of 1 s\(^{-1}\). The intersection of the fitted line with the line of zero shear viscosity, on the experimental measurements, defines the critical shear rate ($\dot{\gamma}_{\text{critical}}$) [28, 29]. $\dot{\gamma}_{\text{critical}}$ is the shear rate at which the disentanglement of the HA solutions and shear-thinning behaviour begins. The inverse of $\dot{\gamma}_{\text{critical}}$ is equal to the longest relaxation period. Table 2 includes the value of the rheological parameters which shows that the relaxation periods of the higher and lower HA solution concentrations were 0.168 and 0.077 s, respectively.

Fig. 7 shows the dynamic moduli versus the strain frequency for the HA solutions with 5 mg ml\(^{-1}\) concentration. The crossover frequency is at 1.1 Hz. At frequencies lower than the crossover frequency, viscosity controls the flow behaviour while at higher frequencies the elasticity dominates the viscous effects. For lower HA solution concentrations, the dynamic moduli were not measurable due to instrument limitations. However, it is known that by decreasing the HA concentration, the crossover frequency increases [30].

Fig. 8 shows the dynamic moduli variation as a function of strain at a frequency of 1.02 Hz. In the linear viscoelastic region, the dynamic moduli stay constant as the strain increases. The dynamic moduli decrease as the strain increases in non-linear viscoelastic region.

### Table 2: Rheological parameters for HA solutions

|       | n (power law index) | m (consistency) | $\dot{\gamma}_{\text{critical}}$, s\(^{-1}\) | Crossover frequency, Hz |
|-------|---------------------|-----------------|-----------------------------------------------|--------------------------|
| HA3   | 0.618 ± 0.011       | HA3             | 0.26                                          | 13                       |
| HA5   | 0.443 ± 0.012       | HA5             | 1.75                                          | 6                        |

Fig. 7 Elastic and viscous moduli ($G'$ and $G''$) versus strain frequency (f) for HA solution with 5 mg ml\(^{-1}\) concentration in PBS

Fig. 8 Viscous (filled marks) and elastic (hollow marks) moduli versus strain% at frequency of 1.02 Hz for HA with 5 mg ml\(^{-1}\) concentration in PBS for HA solution
5.2 Channel with constant width

5.2.1 Water behaviour: Fig. 9 shows the results for the amplitude and phase difference profiles along the non-dimensional channel width for distilled water at difference frequencies.

For frequencies of 2.03, 1.02 and 0.37 Hz, Stokes lengths (Stokes boundary layer thickness) were 0.4, 0.56 and 0.93 mm, respectively. Figs. 10 and 11 show the velocity profiles along Const channel width for various phases of cylinder motion. At Fr-2, the Stokes length was smaller than the width of the channel (1.1 mm). The viscous waves generated at the moving wall only dominated the fluid behaviour in the vicinity of the moving wall. With increasing distance from the inner cylinder, the phase difference increased and as a result at some phases (e.g. $\phi = 303^\circ$) the flow direction in the vicinity of moving wall was opposite to that of the middle of the channel.

At a frequency of 0.37 Hz, the Stokes length was comparable with the channel size. Therefore, viscous waves generated at the moving wall only dominated the fluid behaviour in the vicinity of the moving wall. With increasing distance from the inner cylinder, the phase difference increased and as a result at some phases (e.g. $\phi = 303^\circ$) the flow direction in the vicinity of moving wall was opposite to that of the middle of the channel.

![Fig. 9](image-url) Amplitude (Amp) and phase difference ($\Delta \phi$) of distilled water in the Const channel for

- a, b Frequency of 2.03 Hz
- c, d Frequency of 1.02 Hz
- e, f Frequency of 0.37 Hz

![Fig. 10](image-url) Velocity profiles along the Const channel width for distilled water at frequency of 2.03 Hz.
wall (due to shear-induced flow) could control the flow across the entire channel width, and therefore the fluid velocities at all phases near the constant and moving wall have same directions.

5.2.2 HA behaviour: Fig. 12 shows velocity profiles along the non-dimensional channel width for the lower concentration of HA solution (HA3) at the highest frequency: \( f = 2.03 \) Hz. The HA viscosity at the highest achievable shear rate was roughly 40 times that of distilled water (Fig. 6). The penetration depth of the viscous wave was much greater than the width of the channel and viscous forces controlled fluid behaviour. At each instant, the velocity profiles maintained steady-state conditions.

Fig. 13 shows the non-dimensional amplitude and phase difference profiles along the non-dimensional channel width for HA solution with 3 mg ml\(^{-1}\) concentration in PBS (HA3) at different motion frequencies. Different behaviour from that of distilled water was observed, as the frequency of motion did not affect the amplitude or phase difference.

For a polymeric solution and under oscillatory motion, the Deborah number (fluid characteristic time to flow characteristic time ratio) shows how viscoelasticity affects the flow. At a Deborah number of close to 1 or higher, elastic forces affect the solution behaviour. At the middle of each cycle, the flow direction and thus the stresses direction applied to the fluid changes. Therefore, half of the cyclic frequency is chosen as the fluid characteristic time (7) [21]

\[
De = \frac{\lambda \omega}{2}
\]

The Deborah number for lower HA solution concentrations under the different frequency of motion conditions is presented in Table 3. Although the Deborah number was large at frequencies of 1.02 and 2.03 Hz, the polymeric solution did not show any variations in behaviour. This suggests that a different mechanism dominated and controlled the flow behaviour.

The same behaviour was observed for HA solutions with and without protein content at frequencies of 1.02 and 2.03 Hz. A comparison of amplitudes and phase differences of HA solutions of different concentrations at different frequencies (Fig. 14) shows that almost the same behaviour was observed for Fr-0 and Fr-1. Differences between the non-dimensional amplitude profiles shown in Figs. 13a and 14a for Fr-0 and Fr-1 were <1% [as expected based on the Section 4. Data Analysis (Fig. 5)]. However, the difference between non-dimensional amplitude profiles for HA5 at Fr-2 near the moving wall in Fig. 14a relative to other amplitude profiles was roughly 4%. At higher HA solution concentrations (5 mg ml\(^{-1}\)) and at the highest frequency (Fr-2), a different behaviour near the rotating wall was observed (see Fig. 15). This suggests that in contrast to previous findings [21], under these conditions the De number did not describe the
flow behaviour and other fluid characteristics dominated the flow behaviour.

Previous experiments were performed on an unsteady Poiseuille flow [21]. In an earlier paper, the HA molecular weight was slightly lower (1.4–1.5 MD) than the present paper (1.6–1.8 MDa). While the reciprocal frequency and geometric parameters applied in the current and previous experiments were the same [21], the strain had different values (8)

\[ \dot{\gamma} = \omega \gamma \]  

where \( \gamma \), \( \dot{\gamma} \) and \( \omega \) are the shear strain, shear rate and strain frequency, respectively.

A maximum strain value of 8 was reached in the present paper, which was much lower than the strain values of 23–60 in previous experiments [21]. Therefore, the strain gradient along the width of the channel was smaller.

The critical concentration (the concentration at which entanglement formation starts) for an HA solution with a molecular weight of 1.5 MDa in PBS has been reported to be 2.4 mg ml\(^{-1}\) [31]. This suggests that for all tested HA solutions, HA chains were entangled and formed temporary networks. Applying strain resulted in network disentanglement. On the other hand, the Brownian motion acted toward forming new entanglements. The disentangled chains tended toward aligning with the flow. This combination of opposing forces applied to the HA chains resulted in net force creation on the polymer chains. On the basis of the coordinated system shown in Fig. 4, the contributions of this force to the normal stress in the flow direction (\( \sigma_{xx} \)) were more significant than contributions to the normal force in the \( y \)-direction (\( \sigma_{yy} \)) [32]. The difference between these two normal stresses is known as the first normal stress difference [\( N_1 \) in (9)] which is representative of elasticity in viscoelastic fluids

\[ N_1 = \sigma_{xx} - \sigma_{yy} \]  

Therefore, anisotropy in the HA solution was actually induced by the strain [32, 33]. In a previous study [21], higher strain generated a higher degree of disentanglement and gave rise to the elasticity effect. Moreover, under such high strain values, the viscoelastic behaviours of the HA solutions were non-linear [34].

Under Poiseuille flow conditions [21], the pressure difference applied to the fluid produced flows that also contributed to the

| Fluid | Frequency | Wi | De |
|-------|-----------|----|----|
| HA3   | Fr-0      | 0.23 | 0.35 |
|       | Fr-1      | 0.63 | 0.99 |
|       | Fr-2      | 1.25 | 1.97 |
| HA5   | Fr-0      | 0.49 | 0.77 |
|       | Fr-1      | 1.36 | 2.16 |
|       | Fr-2      | 2.72 | 4.30 |

Table 3: Wi and Deborah number values for HA3 and HA5.
normal force in the flow direction ($\sigma_{xx}$) and could increase the first normal stress difference and enhance the elastic effects. However, when the flow was induced by a moving surface, this pressure effect was not present.

In characterising viscoelastic non-Newtonian behaviours of a fluid, two non-dimensional parameters are usually evaluated: the Deborah and Wi numbers. The Wi number defines the effect of elastic forces relative to viscous forces. Two equations are...
typically used to define this parameter (10) and (11) [35]

\[
Wi = \frac{\dot{\gamma} \lambda}{\sigma_{xy}}
\]  

(10)

\[
Wi = \frac{N_1}{\sigma_{xy}}
\]  

(11)

where \( \lambda \) is the fluid characteristic time, which is usually considered to be the longest relaxation time (inverse of \( \dot{\gamma}_{\text{critical}} \)). \( N_1 \) and \( \sigma_{xy} \) represent first normal stress and shear stress, respectively. \( \dot{\gamma} \) is the amplitude of the strain rate in an unsteady oscillatory flow. Table 3 shows the Wi number of fluids 2 and 4.

As the Wi number is proportional to the strain value, the present results had considerably lower Wi values in comparison with the previous measurements on unsteady Poiseuille flows [21]. The small Wi and strain values show that the disentanglement density was not considerable.

Discrepancies between Newtonian and non-Newtonian flow velocity profiles under Poiseuille flow originated from variations in the strain along the width of the channel. Variations in the strain value along the width of the channel could be an effective parameter for obtaining different velocity profiles under different measurement conditions as well. However, for the present measurements, variations in strain values along the width of the channel were not significant.

![Fig. 16](https://example.com/fig16.jpg)

**Fig. 16** HA solution with 5 mg ml\(^{-1}\) concentration flowing at frequency of 2.03 Hz

a. Particle-depleted layer and particle alignment

b. Particle trajectories in the plane of view
channel were not considerable. Strain values changed from 1.5 at the outer stationary wall to 8 at the inner channel wall. Therefore, there was not a considerable strain distribution to cause strong velocity deviations between different measurement conditions.

Previous studies on particle migration within viscoelastic fluid flows show that elasticity contributes to the migration of particles toward lower shear rate regions and that the migration rate increases with the velocity gradient while shear-thinning drives particles in the opposite direction [1, 14, 36]. This behaviour was observed in the present measurements with HA5 at a frequency of 2.03 Hz (the most elastic solution with the highest velocity gradient). Therefore, non-dimensional amplitude profiles near the moving wall, in this case, deviated from the other measurements (Fig. 14). The migration of particles resulted in the formation of a particle-depleted layer in the vicinity of the moving wall. This layer formed gradually and caused a gradual decrease in velocity values. As noted in Section 4, Data analysis, velocity profiles were derived by averaging several velocity maps to obtain reliable velocity fields for each phase. The velocity amplitude based on an average of 60 images is compared with that obtained from 120 images for HA5 and DW (Fig. 15). HA5 variations are explained by gradual particle migration.

For HA5 flow at a frequency of 2.03 Hz, particles aligned near the moving wall and formed strings. These strings were distributed along the width of the channel by flow circulation within the plane of study. Fig. 16a shows the random distribution of particles as small white dots and formed strings as white lines and Fig. 16b shows the particle trajectories during the measurement period. Fig. 16b was derived by extracting the maximum pixel values for a series of images (image accumulation) and shows that particles followed a specific trajectory. Particle alignment is a known phenomenon found in non-Newtonian shear-thinning fluid. Previous studies by Scirocco et al. [11] and Van Loon et al. [7] show that particle alignment is mainly dependent on the shear-thinning characteristics of the fluid and that normal stresses create better conditions for particles to approach one another.

Particles in a Newtonian fluid subjected to shearing, rotate to maintain a zero torque balance on their surfaces [1]. To keep the particles in a string directed along a flow direction, each particle must maintain its rotation and zero torque conditions. In a Newtonian fluid, as two particles are drawn closer, the fluid leaves the gap between the particles. These two particles, in turn, attached to one another and tumble, which prevents them from maintaining their rotation. The torque applied to them is non-zero, which results in the separation of the two particles. In shear-thinning fluid, as two particles are drawn closer to each other, the shear rate inside the small gap increases, resulting in viscosity decline and pressure build up. The squeezing effect due to built-up pressure prevents the two particles from getting too close and maintains a thin layer of fluid between them. This condition helps particles maintain their rotation and zero torque conditions. The formed strings, in turn, remain stable within the fluid along the flow direction [7].

According to Scirocco et al. [11], once a sufficient degree of shear thinning is achieved, strings form, which may be affected by other parameters thereafter. The critical shear rate value of HA5 was the lowest relative to the other fluids. Within the gap between the two concentric cylinders, the shear rate increased toward the inner cylinder (the moving cylinder). It seems that a frequency of 2.03 Hz provided the sufficient degree of shear thinning for particles to start forming strings in HA5 near the moving wall.

5.3 Channel with variable width

5.3.1 Water behaviour: Variations in channel width at the measurement section of the Conv channel regarding the phase of movement (φ) are shown in Fig. 17. The measurement section width decreased from φ = 270° to 90° and increased from φ = 90° to 270°, 90° and 270° corresponded to a zero angular velocity when the inner cylinder changed direction. Fig. 18 shows the velocity profiles along the width of the measurement section of the Conv channel at different phases of motion. The measured velocities at phases close to φ = 90° and 270° were close to zero and presented very high levels of deviation. Therefore, they are not included in this figure. Δφc and Δφs represent the phase differences between each phase and that of the smallest and largest measurement sections, respectively. Fig. 17 shows variations in measurement section width and velocity at the moving wall versus the phase of the movement, and Δφc and Δφs are also shown in this plot.

Fig. 18 presents velocity profiles along the width of the measurement section at different phases of movement. A comparison between the positive and negative velocity profiles with similar Δφc and Δφs values shows that the flow behaved asymmetrically under contraction and expansion modes.

This behaviour originated from the pressure gradient (2) along the flow direction. During contraction, (∂P/∂x) > 0, which produced pressure resistance against the flow and resulted in back flow. However, under the expansion mode, (∂P/∂x) < 0, which contributed to the induced flow. However, a complex final flow behaviour could be due to the 3D nature of the flow inside the channel.

5.3.2 HA behaviour: Figs. 19 and 20 show the velocity profiles at frequencies of 2.03 and 1.02 Hz, respectively, for water in comparison with HA solutions for measurement section widths exceeding 0.4 mm. At these phases, HA solutions affected the asymmetry of the flow during contraction and expansion. By increasing the HA concentration, the viscosity increased and the effect of the pressure gradient decreased (2). Therefore, for the HA solution with a concentration of 5 mg ml⁻¹ and a viscosity of

![Figure 17](image-url)
roughly two orders of magnitude of the viscosity of water, the asymmetry between the velocity profiles disappeared as the width of the measurement section increased or decreased.

For measurement section widths of <0.4 mm and for HA3 at all frequencies and HA5 at frequencies of 0.37 and 1.02 Hz, particles depleted the region near the moving wall and created large deviations in derived velocity profiles. Figs. 21a and b show the particle distribution along the 0.35 mm measurement section for HA3 at start and end of the measurements, respectively. Particles were depleted from the region near the moving wall, which
resulted in large deviations in the derived velocity profile of that region (Fig. 21c).

As noted in a previous section, elasticity caused particle migration to the lower shear rate region. Fig. 22 shows a variation of shear rates along channel width for HA3 and HA5 for two measurement sections. For measurement sections smaller than 0.4 mm, the shear rate increases along the channel width from the stationary to the moving wall. However, shear rate decreases along the channel width from stationary to moving wall for measurement sections larger than 0.4 mm.

One parameter that affects particle migration is wall confinement [1, 14]. Studies performed by D’Avino et al. [14] show that particle cross-streamline migration is heavily affected by curvature in the shear rate and by interactions with confining walls. The results published by Van Loon et al. [7] also show that more confinement (a smaller gap size) enhances both particle migration and string formation. A shear rate distribution around particles forms as a result of different distances from the confinement wall, which in turn results in normal force imbalances and particle migration. When decreasing the channel size, the velocity gradient increases and shear rate variations around particles are enhanced [7]. Therefore, after decreasing the width of the channel in comparison with the Const channel, particles migrated in both HA fluids at all frequencies. At all frequencies, the width of the depletion layer varied from 0.031 to 0.105 mm for different phases of motion (Fig. 23).

However, HA5 at a frequency of 2.03 Hz showed a different particle migration mechanism. At all phases, particles formed strings that travelled to the channel walls. Fig. 24 shows the particle distribution in the Conv channel along the width of the measurement section for HA5 under different conditions. Figs. 24a and b show the particle distributions at the start and end of the measurements at a frequency of 2.03 Hz, respectively, for a measurement section width of 0.7 mm. Random particle distribution was visible at the start of the rotation period. However, after 120 cycles (roughly 1 min), particle strings formed and migrated toward the inner and outer walls. The same behaviour was observed for other phases and at smaller measurement section widths (Fig. 24c). At the end of the measurement period, for HA5 at Fr-2 in the Conv channel, almost all particles participated in string formation, which did not occur for the constant-width channel. Decreasing the channel size affected particle string formation in two ways, which in turn resulted in more particle string formation: (i) increased particle

![Fig. 21](image-url)  
Particle distribution along the Conv channel for HA solution with 3 mg ml$^{-1}$ concentration along 0.35 mm width measurement section at frequency of 1.02 Hz at

a Start of the measurement period
b End of the measurement period
c Obtained velocity profile for the measurement sections of (a) and (b)
collision and (ii) increased shear-thinning effects. Fig. 24 shows that for HA5 at a frequency of 1.02 Hz, shorter particle strings formed. By increasing the frequency, the shear rate increased and shear-thinning characteristics improved, which in turn directly affected and facilitated particle string formation. Particle alignment was not detected for HA5 at a frequency of 0.37 Hz and for HA3 at all frequencies.

Different behaviours investigated during these measurements are in agreement with previous study results. Lormand and Phillips [16] studied particle migration in viscoelastic fluid subjected to flows in concentric cylinders as the inner cylinder moved at a square wave velocity and induced flow. Compared to materials used in the present study, Lormand’s fluid was higher in viscosity and had shear-thinning characteristics similar to those of HA5. Their results show that for oscillatory flows, particles generally migrate toward the walls and away from the channel centre. However, this behaviour is strongly dependent on flow characteristics. In Lormand’s study, once oscillation frequencies

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**Fig. 22** Shear rate along channel width at two different measurement phases for HA solution with 3 mg ml$^{-1}$ concentration (blue line) and HA solution with 5 mg ml$^{-1}$ concentration (black line)

**Fig. 23** Wall depletion width of different measurement conditions at two different phases of motion
exceeded 1 Hz, outward particle migration ceased and particles remained in regions close to the outer cylinder. This behaviour in our study was observed for HA3 at all frequencies and for HA5 at frequencies of 0.37 and 1.02 Hz. Particle migration showed similar behaviour for HA5 at a frequency of 2.03 Hz for all phases. However, for other measurements, migration was only detected across small measurement section widths. This may be attributable to 3D effects and vorticity within the flow. The results did not show that the formation of a particle-depleted layer near the moving wall resulted in increasing particle density in other channel sections in the plane of view (Fig. 24/d). This suggests that the migration pattern was 3D and that understanding the complete mechanism requires 3D study.

6 Conclusion

HA solutions and suspending particle behaviours were investigated under unsteady Couette flow conditions within curved channels of constant and variable widths. Micro-PIV was used as the quantitative flow measurement method. For the unsteady Couette flow measurement inside curve channels, particles did not necessarily follow fluid behaviour and showed cross-streaming migration. The selection of fluid and experimental model configurations was designed to simulate flows within THR. The aim was to investigate and understand wear particle distributions within the THR. Our results showed particle alignment/cluster formation and particle migration toward channel walls, which

Fig. 24 Particle distribution along the Conv channel for the HA solution with 5 mg ml$^{-1}$ concentration

- a along the 0.7 mm wide measurement section at frequency of 2.03 Hz at Start of the measurement period
- b along the 0.7 mm wide measurement section at frequency of 2.03 Hz at End of the measurement period
- c Along the 0.36 mm wide measurement section at frequency of 2.03 at the end of the measurement period
- d Along the 0.32 mm wide measurement section at frequency of 1.02 at the end of the measurement period
increased by decreasing the distance between walls. Dependent on HA concentrations, particles migrated toward the outer wall alone or to both inner and outer walls. However, the density of particles migrating toward the outer walls was always higher than that of the inner walls. The outer wall in the present paper corresponds to the UHMWPE linear surface rather than in the metallic/ceramic paper suggest that at hip implant frequency of movement (0–0.37 Hz) wear particles are mostly concentrated in regions close to the UHMWPE surface rather than in the metallic/ceramic femoral head. The particle aggregation mechanism near walls can increase third body wear of the implant bearing surfaces, and confinement effects (smaller gap) increase aggregation and wear rates. However, 3D measurements must be carried out to validate the observed phenomena.

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8 References

[1] D’Avino, G., Mafléttone, P.: ‘Particle dynamics in viscoelastic liquids’, J. Non Newton Fluid Mech., 2015, 215, pp. 80–104
[2] Chiou, V., Mosneagu, V., Munteanu, L., et al.: ‘On a micromorphic model for the synovial fluid in the human knee’, Mech. Res. Commun., 2010, 37, pp. 246–255
[3] Ghosh, S., Choudhury, D., Das, N.S., et al.: ‘Tribological role of synovial fluid compositions on artificial joints – a systematic review of the last 10 years’, Lubr. Sci., 2014, 26, pp. 387–410
[4] Dahl, L.B., Dahl, I.M., Engstrom-Laurent, A., et al.: ‘Concentration and molecular weight of sodium hyaluronate in synovial fluid from patients with rheumatoid arthritis and other arthropathies’, Ann. Rheum. Dis., 1985, 44, pp. 817–822
[5] Ingham, E., Fisher, J.: ‘Biological reactions to wear debris in total joint replacement’, Proc. Inst. Mech. Eng. H, J. Eng. Med., 2000, 214, pp. 21–37
[6] Li, G., McKinley, G.H., Ardakani, A.M.: ‘Dynamics of particle migration in channel flow of viscoelastic fluids’, Journal of Fluid Mechanics, 2015, 785, pp. 486–505
[7] Van Loon, S., Fransen, J., Clasen, C., et al.: ‘String formation in sheared suspensions in rheologically complex media: the essential role of shear thinning’, J. Rheol., 2014, 58, pp. 237–254
[8] Michelet, J., Pätzold, R., Doins, R.: ‘Alignment and aggregation effects in suspensions of non-Newtonian media’, Rheol. Acta., 1977, 16, pp. 317–321
[9] Lyon, M., Mead, D., Elliott, R., et al.: ‘Structure formation in moderately concentrated viscoelastic suspensions in simple shear flow’, J. Rheol., 2003, 45, pp. 881–890
[10] Won, D., Kim, C.: ‘Alignment and aggregation of spherical particles in viscoelastic fluid under shear flow’, J. Non Newton Fluid Mech., 2004, 117, pp. 141–146
[11] Scirocco, R., Vermant, J., Mewis, J.: ‘Effect of the viscoelasticity of the suspending fluid on structure formation in suspensions’, J. Non Newton. Fluid Mech., 2004, 117, pp. 183–192
[12] Pasquino, R., Snijkers, F., Grizzuti, N., et al.: ‘The effect of particle size and migration on the formation of structures in viscoelastic suspensions’, Rheol. Acta, 2010, 49, pp. 993–1001
[13] Pasquino, R., Panariello, D., Grizzuti, N.: ‘Migration and alignment of spherical particles in shear: a viscoelagitation simulation’. A quantitative determination of the flow-induced self-assembly kinetics’, J. Colloid Interface Sci., 2013, 394, pp. 49–54
[14] D’Avino, G., Mafléttone, P., Greco, F., et al.: ‘Viscoelasticity-induced migration of a rigid sphere in confined shear flow’, J. Non Newton Fluid Mech., 2010, 165, pp. 466–474
[15] Lombard, B.M., Phillips, R.J.: ‘Spherice migration in oscillatory Couette flow of a viscoelastic fluid’, J. Rheol., 2012, 51, pp. 215–234
[16] D’Avino, G., Mafléttone, P., Greco, F., et al.: ‘Viscoelasticity-induced migration of a rigid sphere in confined shear flow’, J. Non Newton Fluid Mech., 2010, 165, pp. 466–474
[17] Raffel, M., Willert, C.E., Wereley, S.T., et al.: ‘Particle image velocimetry: a practical guide’ (Springer, Berlin, 2007, 2nd edn.)
[18] Vennemann, P., Lindken, R., Westerweel, J.: ‘In vivo whole-field blood velocity measurement techniques’, Exp. Fluids, 2003, 34, pp. 471–478
[19] Lindken, R., Rossi, M., Grobe, S., et al.: ‘Micro-particle image velocimetry (micro-PIV): recent developments, applications, and guidelines’, Lab Chip, 2009, 97, pp. 2551–2567
[20] Safari, A., Enami, N., Cervantes, J.M.: ‘Bio-lubricant fluid behaviour in mini-channels’, Lubr. Sci., 2016, 28, pp. 221–242
[21] Safari, A., Cervantes, J.M., Enami, N.: ‘Viscoelastic behaviour effect of hyaluronic acid on reciprocating flow inside mini-channel’, Lubr. Sci., 2016, 28, (8), pp. 521–544
[22] Johnston, R.C., Smidt, G.L.: ‘Measurement of hip-joint motion during walking’, J. Bone Joint Surg., Am., 1969, 51, pp. 1083–1094
[23] Urb, B., Bryant, J.T., Kontopoulos, M.: ‘Rheological properties of synovial fluids’, Biochemistry, 2007, 44, pp. 59–74
[24] Vafai, K.: ‘An overview of recent studies’ second problem for non-Newtonian fluids’, J. Non-Newton. Fluid Mech., 2005, 47, pp. 955–980
[25] Yakhot, A., Arad, M., Ben-Dor, G.: ‘Numerical investigation of a laminar pulsating flow in a rectangular duct’, J. Non-Newton. Fluid Mech., 2000, 99, pp. 315–350
[26] Zhang, Z., Barman, S., Christopher, G.: ‘The role of protein content on the steady and oscillatory shear rheology of model synovial fluids’, Soft Mat., 2014, 10, pp. 5965–5973
[27] Kontopoulos, M.: ‘Applied polymer rheology: polymeric fluids with industrial applications’ (John Wiley & Sons, New Jersey, 2011)
[28] Vazquez, M., Schmalzing, J., Matsudaira, P., et al.: ‘Shear-induced degradation of linear polyacrylamide solutions during pre-electrophoretic loading’, Anal. Chem., 2001, 73, pp. 3035–3044
[29] Bingöl, A., Lohmann, D., Püschel, K., et al.: ‘Characterization and comparison of shear and extensional flow of sodium hyaluronate and human synovial fluid’, Biochemistry, 2010, 47, pp. 205–224
[30] Yam, F., Kontopoulos, M., Bryant, J.: ‘Effect of concentration and molecular weight on the rheology of hyaluronic acid/bovine calf serum solutions’, Biochemistry, 2009, 46, pp. 31–43
[31] Krause, W.E., Bellomo, E.G., Colby, R.H.: ‘Rheology of sodium hyaluronate under physiological conditions’, Biomacromolecules, 2001, 2, pp. 65–69
[32] Gupta, R.K.: ‘Polymer and composite rheology’ (CRC Press, Boca Raton, 2000), pp. 19–47
[33] Dealy, J.M., Wang, J.: ‘Viscoity and normal stress differences, melt rheology and its applications in the plastics industry’ (Springer, Dordrecht, 2013), pp. 19–47
[34] Safari, A.: ‘Time dependent flow of biolubricant and suspended particles behavior within total hip replacement’, Luleå University of Technology, 2017
[35] Phan-Thien, N.: ‘Understanding viscoelasticity: basics of rheology’ (Springer Science & Business Media, Berlin, 2013)
[36] Jeffs, M., Zahed, A.: ‘Elastic and viscous effects on particle migration in plane-Poiseuille flow’, J. Rheol., 1989, 33, pp. 691–708