Turbulence statistics and flow structure in fluid flow using particle image velocimetry technique: A review

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Abstract
Particle image velocimetry (PIV) measurement technique provides an excellent opportunity for investigating instantaneous spatial structures which are not always possible with point measurements techniques like laser Doppler velocimetry. In this review, it was shown that PIV technique provides an effective means of visualizing important structures of Newtonian and drag-reducing fluid flows. Such structures include large-scale-events that constitute an important portion of the Reynolds stress tensor; shear layers of drag-reducing flows, which have been suggested to constitute the mechanism of drag reduction (DR); and near wall vortices/low speed streaks which constitute the mechanism of turbulence production. PIV investigations of turbulence statistics in Newtonian and drag-reducing fluid flows were reviewed with the view of providing explanation to DR by additives. Results of turbulence statistics, for Newtonian fluid flow, showed that streamwise velocity fluctuations and turbulence intensity had peak values close to the wall, in a region of high mean velocity gradient, while radial fluctuating velocity and Reynolds stress tensor had peaks further from the wall and at approximately the same detachment from the wall. In single- and two-phase flows in horizontal channels, the velocity profile of polymer solution, in the turbulent regime, show asymmetric behavior. This review highlighted important interfacial characteristics in gas-liquid flows such as S-shaped velocity profile as well as the turbulences statistics in each phase and across the interface region. Drag-reducing agents (DRAs)-imposed changes on turbulence statistics and flow structures were also examined. PIV studies of drag-reducing flows showed that DRAs act to dampen wall-normal-, streamwise fluctuating velocity, and Reynolds stress tensor. The reduction in Reynolds stress tensor is higher than the reduction of both wall-normal and streamwise velocity fluctuations and this discrepancy has been associated with the decorrelation of the component of fluctuating velocity. Furthermore, the addition of DRA produces a shift of the peak of wall-normal velocity fluctuations further from the wall due to increased buffer layer thickness. DRAs not only act to reduce drag but also to modify the flow structure. The major influence of DRAs on flow structures is seen in the...
reduced strength and population of vortices close to the wall, increased spacing between low-speed streaks, reduced frequency of large-scale events and reduced concentration of small eddies. Effect of DRAs on flow structures depends not only on the level of DR but also on the concentration and molecular weight. The effect of concentration is linked to the elastic properties of the DRA. The influence of DRA on oil-water flows in similar to its effect on single phase water flow with regards to changes in near wall structures and turbulence statistics. A few research gaps and limitations of the PIV techniques were also highlighted.

**KEYWORDS**
particle image velocimetry (PIV), polymer drag reduction, surfactant drag reduction, turbulence statistics, velocity profile

## 1 | INTRODUCTION

The application of drag-reducing agents (DRAs) for improved fluid transport efficiency, operational safety, and two-phase flow regime control has been investigated for over 60 years. Despite the significant amount of research interest in this area, understanding of the physics of the process remains incomplete. Most of the early studies of drag reduction (DR) have focused on the macroscale physics of the process. Therefore, measurements have mostly been on parameters like pressure drop, wall, and interfacial stress in addition to visual observations. Extensive reviews in this area can be found elsewhere. These macroscale measurements have failed to provide explanation to certain characteristics of drag-reducing solution flows such as asymmetric velocity profile and transient structural characteristics of such flows. Recent studies have sort to understand the microscale influence of DRAs on fluid flow and also link the micro- and macroscale observations with the view defining a more global mechanism of DR. To this end, measurement of turbulence statistics, flow profiles and secondary flow characteristics of drag-reducing solution flow have been carried out. Thanks to the availability of high-precision nonintrusive measurement techniques, further light has been shed on the effect of DRAs at microscale. Notwithstanding the improved measurement techniques, reports are still fragmented and conclusions are inconsistent. Therefore, the focus of this review is to put some perspective into available literature in this area of studies. The review focuses on experimental studies where nonintrusive measurement techniques (particularly particle image velocity) is used to investigate the turbulence statistics and velocity profiles of Newtonian- and drag-reducing fluid flows. Extensive studies have been carried out on the numerical simulation of drag-reducing fluid flow with the view of fully understanding the physics of the flow. These studies include those of Graham and coworkers and those of Dubief and coworkers. Numerical simulation of drag-reducing flows has also been extended to curved conduits with reasonable success. These include the works of Mompean and coworkers on drag-reduced flows in straight and curved conduits.

### 1.1 Common noninvasive techniques applied to fluid flows

Noninvasive techniques for measuring flow fields include point (eg, laser Doppler velocimetry, LDV, laser Doppler anemometry, LDA), plane (eg, particle image velocimetry, PIV) and volume (eg, holographic particle image velocimetry, HPIV) and nuclear magnetic resonance velocimetry, NMRV) techniques. The LDA/LDV relies on the laser coherent property to create interference between intersecting beams in the flow under investigation. For LDA to measure a flow profile, the flow is seeded with fairly small particles capable of following the fluid flow accurately, yet large enough for scattering incident when the particles passing through the test section. Phase Doppler anemometry is an improvement on LDA which has the capability of measuring the particle size of seeds. NMRV is a noninvasive technique that has been employed widely in hospitals. In NMRV technique, the media to be measured is positioned in a static magnetic field and a strong magnetic pulse is then applied to it. The recovery is measured from the disruption of the spin of the nuclei. If single plane magnetic pulse is applied to flowing fluid media, flow development after stepwise time increment can be measured, similar to particle tagging using dye tracers and subsequently following the bands.
In this review, attention is given to PIV studies of single- and two-phase flows. The review begins with a brief overview of the PIV technique. This is followed by a review of PIV investigations in Newtonian fluid flows. Finally, review of PIV investigations on drag-reducing fluids is presented.

1.2 Particle image velocimetry

This is a nonintrusive measurement method that provides quantitative and instantaneous whole-field velocity vector maps. Particle image (or tracking) velocimetry (PIV or PTV) and holographic particle image (or tracking) velocimetry (HPIV or HPTV) both record images of fluid flow seeded with particles and use coupled images which have a definite time interval to compute the velocity within test section. PIV and HPIV are able to compute velocity field in two-dimensional and three-dimensional space, respectively. For PIV setup (Figure 1), a section of the flow is illuminated by a sheet of laser light and the scattered light is captured on camera. Here it is difficult to determine component of velocity which is out-of-plane but this may be resolved by using more than one camera. The component of the velocity that is out-of-plane is determined by comparing in-plane measurements. In HPIV, the laser light illuminates the entire volume of flow with a reference beam intersecting with the scattered light. This interference is captured with either electronic imaging devices or conventional holographic materials. After reconstruction, focusing on any point in the 3D space accurately is possible. When seeding density is low and it is possible to track individual particles, the technique is referred to as PTV, and when the concentration is very high such that distinct particle observation in a flow image is not possible the term laser speckle velocimetry is used. Other PIV techniques include stereoscopic PIV and Tomographic-PIV. Stereoscopic PIV involves the use two cameras and stereoscopic reconstruction for obtaining three components of the velocity field. In other words, stereoscopic PIV gives two-dimensional-three component PIV data. Tomographic-PIV gives a full 3D time-resolved information of the velocity field, albeit with lower spatial resolution compared to stereoscopic PIV. This is due to the introduction of noise from flow field data reconstruction and ghost particles especially in the high velocity gradient region. Three-dimensional information is obtained by simultaneous recording of multiple views. Details of stereographic and Tomographic-PIV techniques can be found in the articles of Stanislas and coworkers.

**FIGURE 1** Illustration of particle image velocimetry experimental setup. Source: Reproduced from Kumara et al with permission from [Elsevier]
In the application of PIV for obtaining information on flow field, careful estimation of uncertainties is important. The uncertainties resulting from PIV data acquisition can be broadly grouped into systematic errors (associated with the measurement technique) and random errors (associated with measurement statistics). In general, these uncertainties result from; uneven distribution of tracer particles, out of plane displacement of particle, nonconformity of tracer particles with flow, image distortion, pixelization, illumination, background intensity, CCD noise as well as reflections from the wall and interface in the case of two-phase flow. Systematic errors are generally higher close to the wall and at the interface of two-phase flow due to:

- Higher velocity gradient close to the wall.
- Lower velocity close to the wall.
- Reflection from the wall and interface.

Uncertainty analysis is sometimes presented in terms of the divergence of the instantaneous velocity field, probability density function of fluctuating velocity, mean velocity profiles, and power spectra of velocity. Systematic errors can be reduced by optimization and preprocessing while random error can be reduced by increasing the measurement runs. Further highlights on sources of uncertainties and steps taken by various investigators to minimize these uncertainties is provided in various sections of this article and further information on uncertainty analysis can be found elsewhere.

1.2.1 PIV image recording and processing

The recording technique for PIV is generally categorized into two; single-frame multiexposure and multiframe single-exposure PIV. In general, temporal sequence data of illumination pulses are not retained during implementation of single frame multiexposure technique resulting in displacement vector directional ambiguity. A number of schemes are, however, available for resolving this direction ambiguity such as those based on displacement biasing, pulse tagging, and image shifting. In the case of multiframe single exposure PIV, particle images temporal order is inherently preserved. However, this technique is limited by the camera frame rates, especially for high flow velocity measurements. Where the technical limitations are met, the multiframe single exposure technique is generally the preferred approach (see figs. 4.1 and 4.2 of Reference 40 for illustration of both methods). Current day cameras used for PIV measurements have high frame rates and thus PIV recording is possible even for high velocity flow using multiframe single-exposure PIV technique. The overall experimental setup design for PIV requires certain trade-offs. The general considerations include; spatial/temporal resolutions of the flow field, velocity fluctuation resolution, time interval between each PIV measurement as well as hardware-imposed limitations. In general, exposure time should be small relative to the time scale of the flow to obtain accurate whole field data and the spatial resolution should also be small relative to flow field length scale. Traditionally, time delay between images is set by flow rate, size of interrogation area, and optical device limitations.

The choice of recording system determines the approach used for resolving directional ambiguity and for image processing. While autocorrelation analysis is usually used for single-frame multiple exposure system, crosscorrelation is generally applied to multiframe PIV recording. The crosscorrelation function, for example, is a pattern-matching function which computes the displacement shift that best overlaps the first and second field views. Figure 2 shows the stages typical of image processing routines like the fast Fourier transforms (FFTs) often used for computing the crosscorrelation coefficient. Large correlation peak is obtained where several particles match up with corresponding displaced pairs and low correlation peaks results when there is significant mismatch. The former and later are sometimes referred to as true and random correlations, respectively. Tracer particles entering or exiting the field view between capturing of first and second images does not form part of the true correlation because either the initial or final position is unknown. However, they constitute random correlation and results in reduced signal to noise ratio. Notwithstanding, the highest correlation peak usually gives a good representation of the matching particle pairs. The mean particle displacement within the field of view is associated with the highest peak in the correlation plane. When this displacement is scaled by camera lens magnification and divided by the time interval between the successive image frames the mean fluid velocity within the field view is obtained. In image processing (eg, using FFT) it is important to identify erroneous vectors and also use suitable schemes to eliminate and replace them. Fortunately, most of the current day PIV systems are accompanied with software
packages to perform this task. Various techniques are used to identify, remove and where necessary replace spurious vectors fields. Vector field validation using median filter is quite common. Further information on PIV technique such as laser source, seeding particles, light filters, mapping functions, and profile detection can be found elsewhere.

2 | PIV STUDIES OF SINGLE-PHASE NEWTONIAN FLUID FLOW

PIV technique has been used to investigate turbulence statistics, mechanism of turbulence production, and turbulence structures of wall-bounded Newtonian fluid flows. A review of some of these investigations is provided next and serves as a base of comparison with drag-reducing solution flows. The brief review here focusses on wall-bounded flows and is by no means exhaustive. The application of PIV in boundary layer flows has also received significant attention and some of the contributions of note in this area include those of Stanislas and coworkers.

2.1 | PIV measurements of turbulence statistics for single phase Newtonian fluid flows

The turbulence statistics of single-phase liquid flow can be computed reliably from instantaneous velocity measurements obtained by PIV technique. Comparisons of turbulence statistics of PIV and LDA for single phase flow in pipes has shown that PIV and LDA gave similar. In general, for Newtonian fluid flow in pipes, axial velocity fluctuation $u_{rms}$, and turbulence intensity $Tl(u)$ have peak values near the pipe walls where the average streamwise velocity gradient is at a maximum. This may be explained by the linkage between turbulence generation and the mean shear flow which produces the axial intensity $u_{rms}$ (Figure 3A). The turbulence statistics results presented in the PIV studies of Kumara et al was presented in dimensional form.

The wall-normal stress tensor $v_{rms}$ is produced by the redistribution of the intensities from the axial flow component and generally falls below values of $u_{rms}$. The peak values of $v_{rms}$ is somewhat shifted from the wall and two notable peaks are observed far from the wall. This is because the wall suppresses the radial component of turbulence, hence the shift in the position of peak $v_{rms}$ away from the wall (Figure 3B). Though there is basically no turbulence production at the center of the pipe $u_{rms}$ and $v_{rms}$ values remain fairly high due to vigorous eddy mixing by momentum transfer from surrounding fluids. PIV measurements of Reynolds stress show that two distinct peaks (at approximately the same position as $v_{rms}$) occur close the pipe wall where axial gradients are large (Figure 4A). The shifting of the peaks for Reynolds stress further from the wall can again be explained by the suppression of wall-normal turbulence components by the impenetrable wall. An approximation of the Reynolds shear stress is given by Boussinesq’s definition of eddy viscosity (Table 1). For hydrodynamically developed flow scenarios, the second term in the bracket is negligible and by symmetry the Reynolds stress becomes zero at the center line where the stress changes its sign.

Figure 4B shows profiles of axial turbulence intensity with peak values occurring near the pipe walls and the lowest at the center of the pipe. Similar to streamwise velocity fluctuations, the peak values of turbulence intensity are found at a region of significant shear gradient near the wall and the same mechanism can be associated with both. The effect of drag-reducing polymers and surfactants on Newtonian turbulence statistics is examined in later sections of this review.
Although, PIV measurement of turbulence statistics for Newtonian fluid flow gives similar profiles to well established point measurement techniques such as LDA and hot wire anemometry (HWA), uncertainties in PIV measurements are relatively high in the region of high shear gradient close to the wall and near the axis of mean flow. This is more pronounced at high flow rates. Recent improvements in PIV cameras, pre- and postprocessing techniques, tracer application etc, have significantly reduced uncertainties in PIV measurements.

2.2 | PIV studies of the characteristics of wall turbulence

The mechanism of wall turbulence has been described in terms of hairpin vortex packets hierarchy. There are three important elements in this mechanistic model description of turbulence production and chief among them is the hairpin vortex. The other two are the auto-generation process (by which newer or younger hairpins are spawned by older ones in a sequence) and the hairpins packet.\textsuperscript{51} The heads of the hairpins sequence that constitute a packet is at angle to the wall
### TABLE 1 Mathematical nomenclature

| Parameter                                | Mathematical expression | Definition of terms                             |
|------------------------------------------|-------------------------|-------------------------------------------------|
| Mean streamwise/axial velocity           | $\bar{u} = \frac{1}{N} \sum_{i=1}^{N} u_i$ | $u_i$ instantaneous streamwise velocity         |
| Mean spanwise/radial velocity            | $\bar{v} = \frac{1}{N} \sum_{i=1}^{N} v_i$ | $v_i$ instantaneous spanwise velocity           |
| Root mean square streamwise velocity     | $u_{rms} = \frac{1}{N} \sqrt{\sum_{i=1}^{N} u_i'^2}$ | $u'_i = u_i - \bar{u}$ $u'_i$ is the velocity fluctuation at each point of measurement and $\bar{u}$ is the corresponding mean velocity |
| Root mean square spanwise velocity       | $v_{rms} = \frac{1}{N} \sqrt{\sum_{i=1}^{N} v_i'^2}$ | $v'_i = v_i - \bar{v}$ $v'_i$ is the velocity fluctuation at each point of measurement and $\bar{v}$ is the corresponding mean velocity |
| Streamwise turbulence intensities        | $TI(u) = \frac{u_{rms}}{\bar{u}} \times 100\%$ |                                                |
| Spanwise turbulence intensities          | $TI(v) = \frac{v_{rms}}{\bar{v}} \times 100\%$ |                                                |
| Reynolds stress tensor                   | $\rho \bar{u}' \bar{v}' = \frac{1}{N} \sum_{i=1}^{N} (u_i - \bar{u})(v_i - \bar{v})$ |                                                |
| Reynolds stress tensor correlation coefficient | $C_{uv} = \frac{-\rho \bar{u}' \bar{v}'}{u_{rms} v_{rms}}$ |                                                |
| Instantaneous streamwise shear strain rate | $\dot{\gamma}_{xy} = \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{u}'}{\partial y}$ |                                                |
| Instantaneous 2D vorticity               | $\omega_z = \left( \frac{\partial \bar{v}}{\partial x} - \frac{\partial \bar{v}'}{\partial y} \right) + \left( \frac{\partial \bar{v}'}{\partial x} + \frac{\partial \bar{u}'}{\partial y} \right)$ |                                                |
| Momentum thickness Reynolds number       | $R_\theta \equiv U_e \theta / \nu$ | where $\theta$, $U_e$, and $\nu$ are momentum thickness, free-stream velocity and kinematic viscosity, respectively |
| Boussinesq eddy viscosity hypothesis     | $\rho \bar{u}' \bar{v}' = \mu_\tau \left( \frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{u}'}{\partial y} \right)$ | $\mu_\tau$ is the turbulence eddy viscosity |

and this angle was reported to have an average value of 12° in the PIV measurement of Adrian et al.\(^{52}\) DNS computations of Zhou et al\(^{53}\) puts the angle between 12° and 20°. The evolution of vortex packets is linked to the bursting events in wall turbulence. Vortex packet spacing is determined by bursting events frequency.\(^{51}\) Furthermore, near wall ejection of low-momentum fluids (second quadrant Q2 events) are linked to the flow imposed by the neck and head of a hairpin vortex, and the high speed sweeps towards the wall (fourth quadrant Q4 events) occurs in a downwash section of a hairpin vortex located upstream.\(^{52}\) Overall, most of the turbulent transport and all of the turbulence kinetic energy are linked to the bursting events associated with ejections and sweeps.\(^{54}\)

Several PIV investigations have been conducted to study the possible universality of turbulence (ie, the independence of turbulence structure on Reynolds number). The relationship (if any) between the distribution of turbulence energy and Reynolds number provides a bases for assessing turbulence structures. The distribution and structure of turbulent energy and transport can be assessed using the two-point correlation function given by Equation (1).

$$\rho_{u_i u_j}(dx, dy, y_{ref}) = \frac{u_i(x, y_{ref}, t)u_j(x + dx, y_{ref} + dy, t)}{\sigma_i(y_{ref})\sigma_j(y_{ref} + dy)} \quad (1)$$

where $\sigma_i$ is the rms value of the $i$th-component of fluctuating velocity. In the early work of Townsend,\(^{55}\) he reported that large-scale-motions structures were independent of Reynolds number of the flow. As shown by Liu et al,\(^{56}\) the correlation contours for various Reynolds number flows show qualitative similarity, and to the limits of qualitative description agree with the report of Townsend.\(^{55}\) However, there is a difference in the span of the axial velocity correlation. Close to wall, the span of the correlated region is longer for the higher Reynolds number flow compared to lower Reynolds number flow (see figs. 1 and 2 of Liu et al\(^{56}\)).
A PIV study for flow over wavy surface was carried out by Nakagawa and Hanratty,\textsuperscript{57} they obtained streamwise and spanwise autocorrelation as well Reynolds stress crosscorrelation similar to that of Liu et al.\textsuperscript{56} It has been reported that the span of the axial velocity autocorrelation is a reflection of the organization of eddies close to wall into packets along with the ensuing correlation of the streamwise fluctuations imposed by the consecutive eddies. With increasing Reynolds number, length of each packet increases due to increase in number of eddies per packet. When the reference point is not on the centerline, autocorrelations of the streamwise component give a characteristic shape that is tilted slightly to the wall and elongated in the streamwise direction.\textsuperscript{57} The angle of inclination is reported to be a weak function of Reynolds number.\textsuperscript{56} It was reported that the strength of bursting events determines the angle of inclination of the low-momentum region.\textsuperscript{51} In general, the height and length of the high positive correlation region increases with increase in distance of the reference point from the wall. This also applies to autocorrelation of wall-normal (radial) velocity tensor, however, the $v$-component correlations contours appear more circular compared to the elliptical contours of streamwise $u$-component correlations. Plots of $u$-$v$ crosscorrelation point to the fact that, large-scale motions carry significant amount of the Reynolds stress tensor and a smaller fraction of the $v$-component energy. Also, with increase in Reynolds number, the contribution of small-scale structures to Reynolds stress increases slightly. The reviewed studies reveal a Reynolds number dependence of turbulence structures. This dependence is linked to increased number of eddy packets at higher Reynolds numbers. As stated in Section 1.2, PIV measurements in the region of high velocity gradient close to the wall are associated with high levels of uncertainties. Recent advances in acquisition hardware, pre/postprocessing techniques and tracer application have greatly improved the reliability of PIV measurements. However, the relative uncertainties compared to techniques like LDA and HWA are still significant and therefore calibration of PIV with other measurement instrumentation is sometimes necessary, especially for investigations in the near-wall region. Some recent numerical simulation \textit{NS} studies have highlighted important characteristics of flow. As will be discussed in subsequent sections of this article, these studies classified the spatiotemporal characteristics of fluid flow into \textit{active} and \textit{hibernating} turbulence regimes. The duration of each regime is characterized by the Reynolds and Weissenberg number of the flow.\textsuperscript{18,58}

### 2.3 PIV application for vorticity field measurement and imaging of coherent structures

In flow description, information on velocity is sometimes of secondary interest. In general, parameters such as fluid properties, velocity fields as well as pressure are required to find parametric solution to Navier-Stokes equation (Equation (2)). However, the simultaneous determination of these quantities is not feasible at the moment.\textsuperscript{40} Velocity tensors gotten from PIV measurements provide a means of estimating some important fluid flow quantities. One such quantity is the vorticity, for example, in the studies of turbulent boundary layers, complex vortical flows and wake vortices.

\[
\rho \frac{dU}{dt} = -\nabla p + \mu \nabla^2 U + F, \tag{2}
\]

where $F$ is the contribution of body force.

The vorticity equation for incompressible flows ($\nabla \cdot U = 0$) may be written as;

\[
\frac{dw}{dt} + U \cdot \nabla w = w \cdot \nabla U + \nu \nabla^2 w. \tag{3}
\]

Equation (3) is written after eliminating the pressure term from Equation (2) for $F = 0$ and the term $\nabla^2 w$ is difficult to estimate from actual PIV data. However, this quantity is frequently used in fluid mechanical description and various differentiation schemes are available for solving the vorticity equation. The velocity gradient tensor is often decomposed into symmetric and antisymmetric tensors. The strain tensor is represented by the symmetric part with elongational strain and shearing strain, whereas the antisymmetric part represents the vorticity. 2D PIV gives velocity gradient tensor sampled on 2D uniformly spaced grids and in this case finite difference \textit{FD} scheme may be used in estimating spatial derivatives of the velocity gradient tensor. Some of the \textit{FD} implementation approaches include forward difference, center difference, backward difference, Richardson, and least squares. According to Pino et al,\textsuperscript{59} an undesirable effect of differentiation of noisy field can be avoided if least-square spline approximation is used in calculating the vorticity.

2D3C image capture of hairpin legs inclined towards the wall in wall-bounded flows was done using stereoscopic PIV measurements by Li et al.\textsuperscript{60} Their PIV measurements revealed that antisymmetric hairpin vortices are the most predominant vortex structures in wall bounded flows.\textsuperscript{60} They reported that about 90% of the computed velocity field in the
crosssectional plane showed antisymmetrical single (or paired) vortex core. However, a counter-rotating vortex pair was observed in the mean velocity vector field riding on the conditional event point. Reported conditionally average vortex pair was almost symmetrical about its center point in the spanwise direction and both pairs had equivalent magnitude of vorticity. In addition, vortex pair greatly elongates in the streamwise direction creating vortex cores having narrow elliptical shape. Inspection of a counter-rotating vortex pair reveals that, close to the wall, the vortex tubes crosssection are almost oval in shape. Li et al.\cite{60} highlighted the close association between turbulent events close to the wall and vortex structures in a turbulent channel flow. Between a pair of counter-rotating vortex tubes, negative $u$ associated with low-momentum fluid was reported to accompany positive $v$. This indicates low-momentum turbulent fluid ejections from the wall.

By reconstructing PIV data of instantaneous velocity vector field, Li et al.\cite{51} extracted vortex structures close to the wall and measured inclination angle of the low-momentum region (vortex growth angle) for wall-bounded single phase liquid flows. Figure 5 is an illustration of the extracted coherent structure where the circles signify the vortex head location. Between the vortex heads and the wall lies the locally formed low-momentum regions. A coherent structure is determined by; low-momentum region close to the wall (which is roughly ramp-shaped) visible in contour maps of axial velocity; appearance of vortex structures bothering the low-momentum zone; and apparent ejections and sweeps over and in the low-momentum region.\cite{51} More recently, Martins et al.\cite{26} carried out Tomographic-PIV (3D data) study of coherent structures near the wall for boundary layer flow at high Reynolds number. Similar to previous investigations, they reported vortical structures close to the low momentum regions and these vortices induce ejection and sweep events. Another coherent structure, hyperbolic structures, have been reported in NS study of Pereira et al.\cite{18} In general, vortices (and hyperbolic structures) are responsible for energy dissipation in the self-sustaining turbulent process and the PIV technique provides an excellent platform for visualizing coherent structures.

2.4 Large-scale events and their effect on Reynolds stress tensor

There are large-scale-motions that appear as bulges of the turbulent boundary layer. These structures are associated with plumes emanating from the bottom wall.\cite{61} These large-scale motions travel at velocities that fall just short of the mean axial velocity and their span and length are between 1-2 and about 2 boundary layer thicknesses, respectively. Another form of large-scale motion occurring in low Reynolds number pipe flow, for smooth entry conditions, are low speed puffs.\cite{62} In general, these large-scale motions differ from the low-speed streaks occurring in the buffer layer of wall-generated turbulence. Low-speed streaks have long dimensions in the streamwise direction but are very thin in comparison with the large scale motion described above.\cite{56,63} Several experimental investigations have provided data that support the view that large-scale events carry a significant amount of the kinetic energy $K.E.$ in streamwise direction.\cite{22,55} Other studies have focused on quantifying the influence large-scale-motions on Reynolds stresses.\cite{56} Deductions from stochastic estimates indicates that a large fraction of the time that flow vectors spend in the second quadrant (Q2) or fourth quadrant (Q4) is due to long length-scale motions (large time-scale events). Experimental approaches like laser-Doppler and hot-wire velocimetry provide one-dimensional spectral analysis and thus are not able to adequately resolve flow structures in anything but the axial flow direction. With these techniques, it is difficult to separate the contributions from long/thick structures resulting from large-scale-motions from that of long/thin structures (eg, near-wall streaks). Such analysis requires the use of two- or three-dimensional analysis such as is possible with the use of PIV.\cite{56}
In the implementation of PIV for investigating the contributions of various motion scales on the kinetic energy and Reynolds stresses, a number of authors have used the proper orthogonal decomposition method. This method is a generalization of the conventional Fourier power spectral analysis and is used for evaluating energy distribution in relation to the scale for statistically inhomogeneous flow. In the PIV studies of Liu et al., it was shown that largest-scale events in both axial and radial directions contribute the most to the turbulent $K.E$. Their results are in agreement with experimental results of Grant and Townsend. Liu et al. further reported that these large-scale structures carry about two-thirds of the Reynolds stress tensor and away from the centerline ($y/h = 0.6$), most of the streamwise kinetic energy. On the contrary, most of the wall-normal $K.E.$ isthe result of small-scale motions. At the centerline, contributions to both components are almost the same. This is because only few large-scale structures extend to the centerline. The contribution of large-scale structures to Reynolds stresses was obtained to be high even at the centerline. This has been attributed to the intermittency of Reynolds stress events at the centerline. A study by Nakagawa and Hanratty, where both PIV and direct numerical simulation were used, also revealed that velocity structures which have large dimensions in the axial and wall-normal directions and appeared intermittently contained major contribution to the Reynolds stress tensor. Liu et al. concluded that the large-scale events are very energetic in producing turbulence above the buffer layer but near the wall their contributions are much less.

Figure 6 shows the projection of the instantaneous turbulence velocity vector field showing motions like ejection and sweeps which are significant in a region at $35^\circ$ inclination to the wall. These motion scales contribute strongly to the average Reynolds stress tensor. According to Liu et al., second and fourth quadrant flows create between themselves a inclined shear layer. The aggregative effect of this shear layer, a rotation about wall-normal direction, and an inclined zone of Q2 (ejections) vectors (with a local maximum Q2 event) were identified by Adrian et al., as a flow characteristic that contributes greatly to Reynolds stress tensor associated with turbulent boundary layers. The projected fields of Figure 6A ($Re_h = 5378$) and Figure 6B ($Re_h = 29 935$) contain two structures that possess the signature of Reynolds stress event. The lower half of Figure 6A shows fluid ejection (Q2 event) from the wall spanning about $1.6 \times h$ in the axial flow direction and a significant sweeping motion (Q4 event) of fluid from the channel's outer section. This pair of motion generates a stationary point and a corresponding shear layer inclined to the wall. The length of patterns in Figure 6A scales with channel height. This is not considered significantly large with reference to the viscous length scale for lower Reynolds number flow. The projection shown for higher Reynolds number flow in Figure 6B provides stronger indication that these structures could be comparable to the outer length scale. Characteristics of large-scale events are visible close to the top and bottom walls. Similar to earlier studies, Martins et al. in their Tomographic-PIV investigation of boundary layer flow, also identified Q2 and Q4 events as the predominant contributors to turbulence production. In general, large scale eruptions contribute significantly to turbulent $K.E.$ and Reynolds stresses.

2.5 | PIV studies of turbulent structures away from a wavy boundary

The mechanism of fluid flow over smooth surfaces is associated with flow oriented near-wall coherent structures while that of flow over wavy walls have been associated with the shear layers formed behind the crest. Therefore, the
mechanisms that sustain turbulence over smooth and rough surfaces is thought to be quite different. However, at some distance away from the wall, turbulence has some form of universal character.\textsuperscript{57}

The influence of wavy boundary layer is limited to an area near the wall where the difference in the mechanism of turbulence generation significantly influences flow pattern. Overall, the effect of wavy wall on flow patterns spans a greater spanwise length in comparison to smooth surface effects. Notwithstanding, at sufficient large distances from the wall, both smooth and wavy surfaces show intermittent large-scale-motion contributions to Reynolds stresses\textsuperscript{57} but this effect is more pronounced for wavy boundaries close to the wall (see PIV results of Reference 68 shown in fig. 27 section on DRP). Figure 7 shows the vector field for flow over a wavy bottom surface. A low momentum flow region extending almost to the point of maximum average streamwise velocity ($y_{\text{max}}$) in the spanwise direction and over around one channel height in the axial direction is visible. The high uncertainties in PIV measurements in the high velocity gradient region close to the wall have limited PIV application in discriminating between turbulence characteristics in wavy and smooth surfaces. In this regard, proper validation of PIV data using other measuring technique as well as comparison with already validated NS data is required. Questions such as the dynamics of turbulence (active and hibernating turbulence) near wavy walls remain and this question can be addressed by PIV technique. Another question future PIV investigation might answer is the possible existence of hyperbolic structures away from wavy walls as has been reported in NS studies of flow in smooth conduits.

3 | PIV MEASUREMENTS OF TWO-PHASE FLOW CHARACTERISTICS OF GAS-LIQUID WALL-BOUNDED FLOWS

The interfacial shear, pressure fluctuations, turbulent fluid motion, and other effects observed in gas-liquid flows produce interfacial instabilities and wave structure formation. A number of the PIV studies for gas-liquid flows have reported difficulty in defining the precise position of the interface and in taking measurements close to pipe walls due to reflection at the interface and wall respectively.\textsuperscript{69} Various techniques have been employed to improve PIV measurements at the interface such as camera orientation, optical filters, fluorescent seeding, and the use of complementary measurement instrumentation such as pulsed shadow technique (PST) and planar laser-induced fluorescence (PLIF) among others.\textsuperscript{70-72} Another challenge often encountered in taking PIV measurements just below gas-liquid interfaces is the occurrence of images pairs of which one is a mirror image of the other and separated by the surface.\textsuperscript{48} One common means of eliminating vectors fields that are outside the flow area (ie, mirrored images) is masking.\textsuperscript{46,73}

3.1 | Application of PIV in investigating stratified gas-liquid flows

Stratified gas-liquid flows may be categorized into stratified wavy and stratified nonwavy flows. In both cases, PIV investigations have been focused on the interfacial characteristics and the interaction between interface-induced characteristics and wall-induced characteristics.
3.1.1 Stratified wavy gas-liquid flow

One of the areas of research interest in gas-liquid flows is the characteristics of interfacial waves. The layer, down to the first millimeter below the water surface, where viscous transport processes exceed the turbulent transport is of particular interest. Some parameters of the transport processes within this layer can be obtained from mean velocity profiles of the layer. Measurements in this section of the flow are few because velocities are high with regards to the area of interest and the presence of waves further complicates measurements. When gas flowing over a liquid layer imposes shear on it but the surface is kept free from waves, a liquid layer with high velocity is formed just below the interface. In the event of strong shear, instability of the layer results in the formation of coherent structures similar to what is observed in wall generated turbulence.

The existence of waves at the interface results in significant variations in the velocity field inside the layer. In general, average streamwise velocity near the interface decreases and the mean axial velocity near the wall increases (thereby assuming a characteristic S-shape profile for liquid layers of low depth) in comparison with that without wave. The S-shape profile is produced by the interaction between mean flow vortices and the orbital flow imposed by the waves. In the case of deep liquid layer, the profile remains logarithmic near the wall but the coefficients of the log-law changes. Also, spanwise and streamwise velocity fluctuations increase with increase in height of waves but the turbulent fluctuation near the wall is not significantly affected (especially if it is scaled with friction velocity). The Reynolds stress tensor no longer has a linear profile and now has pointedly lower values in the bulk fluid when the wave height is sufficiently high. This is associated with the secondary currents in the layer resulting from interactions between wave-induced velocity field and the mean flow. It has been reported that, due to the crosswise changes in liquid depth in pipes (when compared to channels), there is difference in distribution of wave amplitude from the center to the wall for pipe flows. The implication of this is that different amplitudes exist in pipes when compared to channels.

To effectively resolve particle motion in the viscous sublayer of wind-forced wavelets, measurement instrumentation should be capable of resolving length scales of 10 μm to 100 mm and have time scales in the range of 2 to 250 milliseconds. Study of wave characteristics using PIV dates back to the work of Gray and Greated who made effort to investigate the internal flow structure of nonwind-forced waves. Another report on the application of PIV to nonwind-forced waves is that by Lin and Rockwell who generated some useful data on vorticity and velocity fields over a range of gravity wave steepness. A few early reports are available on the application of PIV to wind-forced waves. These early researches demonstrated the potential for the application PIV in the studies of wave characteristics. They also highlighted some of the constraints in the application of PIV such as difficulty in making precise measurement within the linear sublayers very close to the surface and difficulty in making suitable choice of tracer particles. For example, in the application of PIV for study of wave characteristics, the high fluid acceleration sometimes observed in the wave troughs requires that suitable tracers be employed. It should be stated that the acceleration at the wave troughs is a highly localized phenomenon and is limited to capillary waves.

The characteristic of capillary waves (formed with laminar liquid and turbulent air flow) was investigated by Birvalski et al using PIV. It was reported that; the waves showed 2D behavior, the waves are uniform, wave amplitude is highest at the pipe center, and wave amplitude decrease towards the wall. Birvalski et al also investigated the wave characteristics of gas-liquid stratified wavy flow (turbulent gas and turbulent liquid flow) and reported that peak wave amplitude was located close to the wall rather than at the middle. Furthermore, they reported that wave amplitude on one side of the wall was usually higher than that at the other side and the variation in amplitude alternates from one wall to the other. During the changes in amplitude, similar wave amplitude occurs on both sides of smaller magnitude relative to the nonsymmetric regimes. After phase averaging procedure was carried out on their PIV data, they reported that (for all scenarios studied): waves were nonsinusoidal with troughs having higher amplitudes than crest; the crests were longer than the troughs and; the windward side of the wave has longer length than the leeward side. Wavelength increased with increase in phase velocity but this effect is more pronounced with changes in gas superficial velocity. Increased liquid velocity (at constant gas velocity), decreased the wave height (difference between crest and troughs). The of mean axial velocity profile reported was S-shaped in the liquid layer due to the combined influence of interfacial waves and turbulence on the liquid as described earlier. They also reported a higher mean radial velocity for wavy flows in comparison to smooth flows.

The interaction between the circulating motion of the nonsymmetric wave field and the mean shear in gas-liquid stratified wavy flow results in secondary flow which can be upward or downward directed. The crosswise variation of wave amplitude has been reported as a driving mechanism for secondary flows. In general, if wave peak amplitude is at the center, secondary flow along the center plane projects downwards (ie, towards the waves) and the reverse effect is observed if peak wave amplitudes are close to the wall.
The axial, radial, and Reynolds stress tensors for gas-liquid stratified wavy flow was investigated by Birvalski et al.\textsuperscript{46} for both laminar (F) and turbulent (H) liquid superficial velocities (Figure 8). The fluctuations in case F is due to waves while that of H is due to both waves and turbulence. The axial and radial stresses in the case of laminar liquid layer approach zero at the wall and are maximum in the region where wave-imposed motion is most significant. For this case, the Reynolds stress tensor is almost zero. In the case of turbulent liquid layer, Reynolds stress tensor, axial and radial fluctuations show the effect of waves (near the interface) and turbulence (in the near wall region). The Reynolds stress tensor profile for this case is nonlinear, been less in the bulk fluid. This nonlinear characteristics appear to be limited to cases with very high wave amplitudes.\textsuperscript{46}

Wave motion on a liquid surface reduces the velocity below the trough and raises the velocity below the crest (Figure 9). The magnitude of the decrease in velocity under the trough and the increase in velocity below the crest are not the same. The negative streamwise velocity at the trough is larger relative to the positive streamwise velocity at the crest. The waves also impose strong radial (wall-normal) motion under the slope of the wave profile (Figure 9). The radial motion on the leeward side is generally stronger relative to that of the windward side. This has been attributed to wave asymmetry.
absolute values of wave-imposed axial and radial velocities are stronger for case F and this is associated to the greater slope and height of various parts of the wave profile. 46

3.1.2 Stratified nonwavy gas-liquid turbulent flow

The interfacial characteristics of gas-liquid flows, where the interface is free from waves, have also been a subject of investigation using PIV technique. The effect of the interface is such that it dampens the radial velocity fluctuations and also results in an increase in the axial fluctuation when these quantities are normalized using friction velocity. Birvalski et al 46 reported that streamwise fluctuations have a small peak near the interface while the wall-normal and shear fluctuations approaches zero (Figure 10) due to the dampening effect of the interface. 82

Although we did not exhaust all the PIV investigations of stratified gas-liquid flows, the review demonstrated the suitability and limitations of PIV technique in the measurement of some important characteristics of such flows. More importantly, the studies reviewed lead to the following important projections: 1. In gas-liquid stratified wavy flows with shallow liquid layer, an S-shaped streamwise velocity profile is formed within the liquid layer below the interface. This changes the log-law profile close to the wall. Since, DRAs is known to change the characteristics of the log-law region, application of DRA is expected to influence flow profile of gas-liquid stratified wavy flows; 2. DRA could have significant influence on the secondary flow motion resulting from the interaction between orbital motion of wave field and that of the mean shear flow; 3. Reynolds stress tensor reflects the influence of wave above and wall turbulence below. Again, it could be interesting to see the influence of DRA on Reynolds stress tensor generated by wavy gas-liquid flows. The absence of interfacial waves means that the average streamwise velocity of the liquid layer follows the log-law in the region that belongs to the logarithmic regime. 46, 82

3.2 Application of PIV technique to slug and bubbly gas-liquid flows

As with stratified gas-liquid flow, a particular short coming of PIV measurements in slug and bubbly flows is the difficulty in determining the precise position of the gas-liquid interface due to reflections at the interface and bubble shielding. PIV technique has been applied with reasonable success to dispersed flows such as bubbly flow. Typically, the flow is seeded with tracers of particle size significantly smaller than the size of the dispersed phase. Both the tracer particles and the dispersed phase appear as bright spots in PIV recordings. However, their optical signals differ due to the difference in surface properties and size. This difference can be used in differentiating between the phases in PIV recordings and reduce uncertainties in measurements around the interface. Techniques used for phase discrimination includes; image intensity/intensity gradient, color, spot geometry, spatial frequency as well as characteristics of correlation peaks among others. 83 Another means of reducing uncertainties in PIV measurements close to the interface resulting from bubble shielding is by the use of stereo-PIV (2D-3C) or Tomographic-PIV (3D) as these techniques gives access to 3C or 3D vector field. This, however, increases the computational cost required in post processing. PIV data preprocessing using suitable filter applied to the interrogation area close to the interface reduces errors resulting from reflection at the interface. Therefore, it is sometimes required to apply different filters to different regions of the flow. In addition, recent improvements
in data acquisition hardware, like shutter rate and frame rate, have gone a long way in improving PIV measurements especially in for high velocity two-phase flows.

A few studies of gas-liquid flow have opted to use complimentary techniques for determining the position of the interface and the geometry of bubbles and slugs. Nogueira et al.71 for example, used PST (to compliment PIV) in their studies of slug characteristics in risers. Unlike PIV, the light source of PST is LEDs that emit light at 650 nm. One short coming of this technique is that a careful selection of optical filters must be made so that both lights emitted by tracer particles and that from LEDs are recorded on the PIV camera. Also, processing PIV (flow field) and PST (bubble or slug shape) are carried out separately. The processing for PST is done in stages. Figure 11 is an example of image captured by combined PIV and PST.

The tracer particles in the flow, for PIV measurements, produce a noisy pattern in the grey scale and so a median filter was used to process the image (Figure 11B). Figure 11D is gotten by the subtraction of the Figure 11B from a reference image (Figure 11C) while Figure 11E is the binarized image of Figure 11D with a selected threshold. This last stage of the processing becomes necessary when carrying out PIV post processing.

In the PIV/PST investigation for the motion of gas slug through a stagnant liquid film, Nogueira et al.71 observed that the velocity of the liquid at the nose was around 5% higher than the bubble velocity (Figure 12). In general, the liquid velocity around the nose of the slug is expected to be the same as the velocity of the slug. This deviation could be partly linked to bubble expansion occurring at liquid velocity head. Though the influence of the slug in their report is felt up to a distance of 0.36D ahead of the bubble (D is the pipe diameter), this distance varies depending on the relative magnitudes of inertia and viscous forces. As the liquid begins to move, it gains radial velocity while accelerating downwards along the gas slug thereby forming a thin liquid film. For any film crosssection, the highest liquid velocity gradually approaches the interface. Acceleration along the gas slug continues until constant slug radius and, by implication, film thickness is attained. At this stage, the flow is hydrodynamically developed and there is zero net force acting on the liquid film. There is increase in the streamwise velocity component along the film until thickness of the film stabilizes and the flow is hydrodynamically developed. The radial velocity component decreases in the film down to zero and increases around the nose for fully developed film.71

Figure 12 depicts the geometry of the bottom of a gas slug gotten from PST, and the PIV instantaneous flow field in the wake zone. The geometry of the slug wake zone is not plane as shown in PST output, but rather concave. Flow emerging from the liquid film reaches the bottom of the bubble and then starts to decelerate occupying the whole pipe crosssection. The length required to realize deceleration is related to the relative magnitudes of the radial diffusion of momentum as well as the streamwise convection. The bubble wake region occurs even when the wall-normal diffusion is very high. The mean velocity inside the wake is of equal magnitude as the bubble velocity. The wake region is more obvious in Figure 12B, depicting fluid flow downwards (with increasing wall-normal velocity) close to that emanating from the film and fluid close to the tube axis flowing upwards at a higher rate relative to bubble.71 Simultaneous measurement of 2D velocity of both phases for dispersed bubbly flow in a rectangular channel was also carried out by Hassan et al.,84 using PIV. Vector field data obtained by the PIV system were used by them to obtain the vorticity fields and liquid streamlines.

Another investigation where PIV technique was complimented by an auxiliary measurement technique for measurements of gas-bubbly characteristics is the work of Zhou et al.72 They measured the mean velocity profiles of single phase and gas-liquid bubbly flows in a riser using PIV-PLIF. The introduction of small bubbles into liquid flow tends to flatten (reduce the slope) the velocity profile relative to single phase liquid flows. It was further obtained that there is an increase in turbulence intensities with bubble injection for a majority of the test conditions. In one of the runs carried out in the
work of Zhou et al, it was reported that the turbulence intensity for single phase liquid flow was higher than that for a particular low void fraction gas-liquid flow measurement. This suggests that the bubble injection does not necessarily result in increased turbulence intensities. This behavior can be associated with the fact that high concentration of bubbles near the wall can act as energy sinks because of the bubble interaction.

4 | PIV STUDIES OF LIQUID-LIQUID FLOWS

Liquid-liquid flow systems occur frequently in various industrial applications one of such is subsea pipelines in petroleum production. In subsea petroleum reservoirs water occurs either in the form of connate water or from injected water for the purpose of enhancing oil recovery. Despite the frequency of occurrence of liquid-liquid systems, the approach used for the design mostly relies on intuition and general rule of thumb as opposed to first principles. This is because of the complexity in local flow structure and the relationship between micro- and macroscales is yet to be well understood. By extension, understanding of the various hydrodynamic complications associated with liquid-liquid systems remains fragmented. In particular, the inadequate dynamic and structural information at the microscale and the computational complexities involved in analyzing the dynamics of the flow are some of the reasons these flows cannot be treated purely from a theoretical basis. Nevertheless, the ability to determine liquid-liquid flow characteristics accurately remain fundamentally important. Based on the foregoing discussion, an effective experimental approach would be such that can measure simultaneously all the components of liquid-liquid flow systems. This will shed more light into the coupling effects between both phases and also provide useful data for the CFD model validation. Also, multiphase flow measurements require the ability to obtain full-field microscopic and macroscopic scale instantaneous fluid dynamic information. This full-field information provides greater insights into the phase coupling of the various flow components. The transient behavior of liquid-liquid flow systems has been identified to be of great importance in determining the system performance. Phase regime, thermo-physical properties of fluids, channel geometry, and flow configurations are parameters that govern liquid-liquid flow behavior. Analogous to gas-liquid flow measurement, application of PIV to liquid-liquid flow measurement is limited by interfacial and near-wall reflections. For single phase flows, wall reflection can be minimized by filling a rectangular jacket with the fluid to be measured. Various approaches have been used to reduce interfacial and near-wall reflections for liquid-liquid flow systems. Kumara et al, for example, filled the rectangular jacket with water when measuring the water phase and filled it with oil when taking measurements for the oil phase. This approach does not allow for the simultaneous measurements of both phases. To counter the effect of interfacial and wall reflections, Morgan et al used two liquids with similar refractive index as well as pipe material with similar refractive index to that of the liquids. Similar to PIV studies in gas-liquid flows some PIV investigations of interfacial behavior of liquid-liquid flows used complimentary instrumentation (eg, PLIF—a spectroscopic technique) to compliment PIV. Regardless of the approach used suitable calibration and image correction algorithms are required to correct image distortions and this image correction has been investigated extensively by Bicen, Boadway and Karahan.

FIGURE 12 Velocity profile around a gas slug ascending in stationary liquid column. A, Fixed reference frame. B, Moving reference frame. Source: Reproduced from Nogueira et al with permission from [Springer Nature]
4.1 PIV measurements in horizontal liquid-liquid flows

The pipe wall and the interface region in liquid-liquid flows significantly influence the turbulence statistics in such flows. In general, higher values of Reynolds stress tensor, root mean square axial and radial velocities are reported in large mean velocity gradient regions. This suggests there is a connection between turbulence production and shear mean flow. Combined LDA and PIV measurements of turbulence statistics and velocity profile of horizontal oil-water flow was done by Kumara et al., for various oil-water input conditions. They reported a good agreement between both measurements at reduced mixture velocities where the flow regime is mostly stratified. At higher flow rates (eg, dual continuous regime) where interfacial mixing is significant and the thickness of the interface region is large, strong reflections from interfacial waves and dispersed bubbles limit PIV measurements due to strong interfacial reflections. The LDA was, however, able to provide a complete velocity profile with only minor disturbances at the interface region. As opposed to PIV, which provides whole field measurements, LDA only provides point measurement thus requiring a huge amount of time to resolve the entire flow field. One other limitation of point measurement is the difficulty in relating single-point data to the physical mechanism controlling the hydrodynamics between both phases in two phase flow systems.

Overall, at higher velocities, the maximum values of mean velocities and Reynolds stress tensor are higher with LDA compared to PIV especially in the oil phase. Also, the position of the peaks for LDA appeared near the wall relative to

**FIGURE 13** LDA and PIV measurements at $U_m$ of 0.68 m/s and water cut of 0.5 (A) average axial velocity (B) rms velocity and Reynolds stress tensor. Source: Reproduced from Kumara et al. with permission from [Elsevier]
PIV measurement though the overall shapes of the profiles for both were similar. Results of average streamwise velocity profile and turbulence statistics of Kumara et al.\textsuperscript{50} at mixture velocity $U_m$ of 0.68 m/s and water cut of 0.5 are shown on Figure 13A, B, respectively, and that at $U_m$ of 1.06 m/s is shown in Figure 14A, B.

Results of Figures 13A and 14A show that the maximum mean axial velocity is in the oil phase for both mixture velocities measured using LDA and PIV. Similar results were reported by Kumara et al.\textsuperscript{23} in their PIV studies using the same fluid combination. Given that the oil phase used in these investigations are more viscous than water, it would be expected (based on the classical laminar flow theory) that the maximum axial average velocity would be in the water phase. The reason for this discrepancy is unclear. However, unlike in laminar flow where viscosity plays dominant roles in determining interfacial behavior, both viscosity and density have significant effect on interfacial characteristics in turbulent flows.\textsuperscript{50} Therefore, the classical laminar flow theory cannot be employed for predicting the position of the peak average axial velocity for oil-water flows. Also, in the interface region, the average streamwise velocity profile is fairly flat (especially at higher water cuts) due to low turbulence production and gravity stratification which dampens the wall-normal (radial) stress tensor.

The peak values of $u_{rms}$ occur near the wall and those for $v_{rms}$ and Reynolds stress tensor were shifted further from the wall (Figures 13B and 14B). The peak value of $u_{rms}$ occurs in the oil phase. It was obtained that the lag observed between axial and radial velocity fluctuations indicates that turbulence production is characterized by large axial fluctuations.\textsuperscript{23} The radial intensity is produced by redistribution of intensity from the axial component and is therefore less. This difference between the axial and radial intensities also suggests anisotropic turbulence in oil-water flows. Near the interface, the axial velocity fluctuation increases because of interfacial shear stress and that of radial velocity increase slightly because of interfacial waves.\textsuperscript{23} The turbulence burst produced at the interface is projected downwards ($v' < 0$) resulting to

**FIGURE 14** LDA and PIV measurements at $U_m$ of 1.06 m/s and water cut of 0.5 (A) average axial velocity (B) rms velocity and Reynolds stress tensor. Source: Reproduced from Kumara et al.\textsuperscript{50} with permission from [Elsevier]
a positive \((u' > 0)\) in the axial velocity tensor. Hence, the peak value of average velocity in the water phase occurs near the interface and the Reynolds shear stress in negative in the water phase. Reynolds stress tensor changes sign at the normalized position where the peak value of average streamwise velocity occurs in the oil phase. Beyond this point, turbulence burst projects upwards \((v' < 0)\) resulting to a positive \((u' > 0)\) axial velocity tensor and here the Reynolds stress tensor is positive. The Reynolds stress tensor is suppressed by stable density stratification near the interface. Reynolds stress tensor values around the interface were observed to be higher for higher mixture velocities and there is greater turbulence production near the interface at enhanced mixture velocities thereby limiting gravity stratification. The wall-normal turbulence fluctuations are more suppressed at reduced mixture velocities than at enhanced mixture velocities. This wall effect on radial intensities is the result of kinematic blocking due to the impenetrability of the walls.\(^{23}\) Therefore, peak values of \(v_{\text{rms}}\) are observed at some distance from the wall in comparison with \(u_{\text{rms}}\). In the PIV investigation of Kumara et al.,\(^{23}\) it was obtained that both \(u_{\text{rms}}\) and \(v_{\text{rms}}\) gradually decrease with distance from their respective peak values near the wall of the pipe. This has been associated with diffusion and enhanced turbulence transport with distance from the wall. It was also reported that, both \(u_{\text{rms}}\) and \(v_{\text{rms}}\) have finite values at the point of maximum average streamwise velocity where turbulence production is zero. This has been linked to energy transport from surrounding regions where turbulence is produced rather than turbulence production at the point of peak mean axial velocity.

Morgan et al.\(^{70}\) investigated oil-glycerol/water flow in circular 1-in ID pipe using simultaneous PLIF and PIV. Unlike the aforementioned studies, the oil used in their research was less viscous than the water (glycerol/water) phase and the refractive index of both liquids was the same, that is, 1.444. The matching of the refractive index for both liquids and the glass pipe was done purposely to minimize image distortion both at the liquid-liquid interface at near wall region. In that work, PLIF was used primarily to delineate the phases and determine in-situ volume fraction. This aspect of the work is not discussed here since it does not contribute significantly to the focus of this review. It is important to state here that they used microbubbles, as opposed to suspended solid particles or liquid droplets, as tracers in their PIV measurements. It has been reported elsewhere that microbubbles result in reduction in frictional drag. DR is usually accompanied by changes in flow structures, particularly in the buffer layer. Therefore, there is a possibility that using microbubbles as tracers may result in biased results or result misinterpretation. The use of mixture velocity for the normalization of mean axial velocities in the PIV study of Morgan et al.\(^{70}\) resulted in fairly generalized mean axial velocity profiles (ie, velocity profiles that were quite independent of mixture velocity). However, the interface regions showed some mixture velocity dependence and this was attributed to flow regime transition with changes in mixture velocities. In that study, the velocity profile showed a maximum in the oil phase. This is expected given that both density and viscosity of the oil phase were smaller than those of the water phase (Figure 15). Also, at lower mixture velocity there appears to be a sudden change (step change) in mean axial velocity at some point in the interface region between both phases. It was obtained that the slip ratio at lower mixture velocity is higher than those at higher mixture velocity. This could result in interfacial instability and interfacial wave formation which are characteristic of flow regime transition, hence the jump in mean velocity profile between both phases around the interface region at lower \(U_m\). Edomwonyi-Otu and Angeli,\(^{89}\) recently carried out PIV drag-reduction study of oil-water in horizontal pipe of 14 mm ID using both HPAM (hydrolyzed copolymer of polyacrylamide and sodium acrylate) and PEO (polyethylene oxide) as DRAs. Similar to the above studies, the peak of the velocity profile was always in the water phase. Considering the limited PIV investigations in liquid-liquid flows in straight conduits, no general conclusion can be drawn at this time. The limited literature in this area, however, highlights the potential of PIV techniques in this area. Questions that can be answered in future PIV investigations include; the effect of interface on coherent structures, characteristics of coherent structures in both phases, and turbulence dynamics in both phases. It should be stated that, since liquid-liquid flows demonstrate complex 3D dynamics, future PIV studies will be required to use PIV techniques such as stereo-PIV or Tomographic-PIV in flow field measurements.

### 4.2 PIV studies inclined liquid-liquid flows

Pipe inclination has significant influence on the overall turbulence statistics and flow structure of liquid-liquid flows. Parameters such in-situ velocity, slip ratio, water hold-up, interfacial wave characteristics, and interfacial mixing are affected by changes in pipe inclination. It has been obtained that upward inclination increased flow mixing and results in lower water and higher oil in-situ velocities compared to horizontal flows.\(^{23}\) Inclination of the pipe has a significant effect on mean streamwise velocity of oil-water flow.\(^{23}\) Figure 16 are results of Kumara et al.,\(^{23}\) showing comparisons of mean axial velocity at various inclination for oil-water flow in pipes.
It has been reported that inclination of the pipe has significant effect on the streamwise velocity profiles. Mean streamwise oil phase velocity is a little higher than that of water in horizontal flow scenario and the increase in upward inclination further increases the oil phase velocity relative to water. The implication of this is decrease in water velocity with increase in upward pipe inclination. Also, the mean streamwise velocity increases abruptly across the interface for upward inclination. The opposite effect is observed in downwardly inclined flow where water velocity becomes higher and the relative velocity increased with increase in downward inclination. The position where maximum streamwise velocity occurs in the water phase for downward inclination moves close to wall with increased downward inclination. It was also obtained that the maximum streamwise velocities in the water phase for downward inclinations (−3° and −5°) were generally lower than that of the oil phase for upward inclinations (+3° and +5°). As is evident in Figure 16B, variation in velocity profile is reduced with increased $U_m$ from 0.50 m/s to 1.0 m/s, though the overall shape in both cases are similar. This is linked to increase in momentum transfer with increase in flow rates which suppresses the effect of gravitational forces on the flow. For pipe inclination of −1° the mean axial oil phase velocity at mixture velocity of 0.50 m/s increase towards the surface while for that at 1.0 m/s mean axial oil phase velocity profile has a peak value. Also, the peak values of the streamwise velocity profile in both phases are approximately equal for −1° inclination and $U_m = 1.0$ m/s. With increase in downward inclination to −5° streamwise velocity in the oil phase tends to increase around the interface for $U_m = 0.5$ m/s while it remains relatively constant for $U_m = 1.0$ m/s. Also, the position of the maximum water phase velocity does not vary between horizontal and downward inclined flow at $U_m = 1.0$ m/s in contrast to what is observed at $U_m = 0.5$ m/s.

The effect of pipe inclination of Reynolds stress distribution was also studied by Kumara et al’23 using PIV technique. Figure 17A, B shows plot of Reynolds stress profiles at various inclinations and for $U_m = 0.5$ m/s and 1.0 m/s.
At $U_m = 0.5$ m/s, it was obtained that the Reynolds stress tensor increases close to the wall in the oil phase with increase in upward inclination. This is linked to the increased mean axial velocity in the oil phase with increase in upward inclination of the flow. Similar observation was made for water phase Reynolds shear stress in downward inclination. The value of Reynolds stress tensors reported in their work at $U_m = 0.5$ m/s was generally lower in the interface region for horizontal and flows at small inclinations (−1° to +1°) because of stable density stratification. The slight interfacial waves observed for +1° inclination translated to slightly higher Reynolds stress compared to horizontal and −1° inclination. At higher downward and upward inclinations (−5° and +5°) the interfacial wave becomes significant and these generate fluxes of Reynolds stress tensors of comparative magnitude to those generated by wall turbulence. Also, peak values of Reynolds stress tensor in both phases were located near the wall for higher pipe inclinations and at $U_m = 0.5$ m/s. With increase in flow to 1.0 m/s, Kumara et al. reported increased Reynolds stress due to increased shear rates. Again, stable gravity stratification effects in the interface regions were more pronounced for horizontal and near horizontal scenarios but less so at higher inclinations (−5° and +5°). The peak values of Reynolds stress in both phases were reported near the pipe wall for the case of $U_m = 1.0$ m/s contrary to observations at $U_m = 0.5$ m/s. This was associated with increased turbulence production and transport near the wall at higher $U_m$. Therefore, the higher velocity gradients near the wall at higher mixture velocity and pipe inclination of −5° and +5° results in peaks of Reynolds stress tensor profiles near the wall in both cases. Again, considering the very limited PIV investigation in this area no conclusion can be drawn at this time. However, the reviewed PIV studies in this area highlight the suitability of PIV technique. Similar perspective and future study recommendations to horizontal pipe flow apply to inclined pipe flows. In addition, future PIV investigations on liquid-liquid flows in inclined conduits could answer questions such as the effect of inclination on wave characteristics and mean velocity profile close to the interface.
5 | PIV INVESTIGATIONS OF DRAG-REDUCING FLOWS

DR is a process of reducing pressure losses associated with flows. Additives like heavy molecular weight polymers and various surfactants called DRAs are often used for DR. Turbulent DR using low concentration of polymer additives in liquid flow was first investigated by Tom,\textsuperscript{90} hence the phenomenon is sometimes called the \textit{Tom’s effect}. This drag-reducing phenomenon has far reaching benefits in industrial applications like in reducing of pumping power requirements among others. Drag-reducing polymers and surfactants often possess viscoelastic characteristics. The implication of this property is that stresses in these DRAs do not immediately return to zero when the applied force is removed but rather decays over a time period called \textit{relaxation time}. As mentioned earlier, all the turbulent \textit{K.E.} along with higher percentage of turbulent momentum transport is the result of bursting events which are themselves linked to low-speed ejections from the wall and high-speed sweeps. The Reynolds number effect on turbulence quantities, average flow scales, vortex structure and wall pressure fluctuations for Newtonian fluid flow has a different connotation to its effect on drag-reducing flows.\textsuperscript{42} The effectiveness of DRAs in reducing drag has been linked with their effect on bursting events and vortex structures.\textsuperscript{51,60,91} In this section, effort is made to review some of the PIV studies on the influence of polymer and surfactant DRAs on turbulence characteristics.

5.1 | PIV investigations of the effect of drag-reducing polymers on single phase flows

DR by addition of drag-reducing polymers, DRPs, to Newtonian fluid flows have been studied widely but an understanding of underlying mechanism of DR remains incomplete.\textsuperscript{92-94} Near-wall vortices is a key component in the self-sustaining mechanism of wall-generated turbulence. Therefore, the interaction and modification of turbulence structures near the wall is expected constitute an important component of the mechanism responsible for DR.\textsuperscript{44,95,96} DRP-induced DR can be categorized into homogeneous and heterogeneous DR depending on distribution of the DRP in the flow media.\textsuperscript{97} Virk,\textsuperscript{3} published an extensive review on DR in straight conduits. The work highlighted a number of important aspects of DR such as the mechanism of polymer DR and the effect of DRP on turbulence structure and velocity profile. The article also pioneered the concepts of maximum drag-reduction asymptote (MDRA) and drag-reduction envelop. The Virk’s envelop for polymer DR in straight pipes is shown in Figure 18 on the Prandtl-Karman coordinates. Equations (4) to (6) are equations for laminar flow, turbulent, and MDRA. The maximum DR law holds irrespective of polymer specie used, its concentration or molecular weight.\textsuperscript{3}

\begin{equation}
\frac{1}{\sqrt{f}} = \frac{N_{Re} \sqrt{f}}{16}
\end{equation}

\begin{equation}
\frac{1}{\sqrt{f}} = 4 \log_{10} N_{Re} \sqrt{f} - 0.4
\end{equation}

\begin{equation}
\frac{1}{\sqrt{f}} = 19 \log_{10} N_{Re} \sqrt{f} - 3.24
\end{equation}

\textbf{FIGURE 18} Virk’s envelop in Prandtl-Karman coordinates for drag reduction in straight pipes (author’s sketch)
Studies have shown that phenomenological models for MDRA, developed for polymers, are not necessarily applicable to drag-reducing surfactants (DRSs). An interesting characteristic of DRS is their higher shear viscosity compared to DRP solutions. This makes DRS solution more shear rate dependent and makes the definition of the Reynolds number more complex. Zakin et al showed that fanning friction factor curves of most DRS in straight pipes lie below the Virk MDRA. They proposed an MDRA for surfactant solutions in straight conduits given by:

\[ f = 0.32N_{Re}^{-0.55} \]  

Their work did not account for how viscosity depends on the shear rate in DRS. Aguilar et al used surfactant with viscosity similar to that of the solvent and recorded friction factors slightly lower than those given by the Zakin MDRA. They proposed a new correlation for MDRA given by:

\[ f = 0.18N_{Re}^{-0.50} \]  

A number of PIV studies aimed at investigating the drag-reduction phenomenon have been carried out. In general, PIV investigations have revealed that: polymer elasticity weakens coherent structures by the application of counter forces to that which maintains these structures; polymer elasticity dampens ejection and sweep events; polymer chains store energy in both of these processes which involve polymer stretching and subsequently releases the energy in the streamwise direction, directly or indirectly, when it relaxes in the bulk flow; and polymer stretching is maximum and minimum in the buffer region and the center of the conduit and is significant near the wall.

5.1.1 Effect of DRPs on mean velocity profile in single phase flows

A lot of data have been published to demonstrate the influence of DRPs on the average streamwise velocity profile, however, most of these data were acquired using techniques other than PIV. Notwithstanding, the reports on mean axial velocity profiles based on PIV are consistent with those obtained using other techniques. In general, the addition of DRP results in the upward sifting of the log law zone and increased buffer layer thickness. In the PIV studies of Warholic et al in channel flow, the log-law region was absent. This behavior is synonymous with very high levels of DR or maximum DR. White et al carried out PIV measurements of average velocity profile over a flat boundary layer for water at \( Re = 1475 \) and polymer solution at DRs of 33, 45, and 67%. They normalized their mean axial velocity data by friction velocity and the reported velocity profile for water followed the logarithmic profile as expected. At lower value of DR, there is an upward shift in the log-law region (at constant slope of the log law line) and an increased thickness of the buffer layer. However, at higher DR the profile differs entirely from the Newtonian profile. Their results were consistent with other studies such as that of Zadrazil et al, who carried out PIV measurements of mean streamwise velocity for water and three different molecular weight PEO solutions in horizontal pipe flow (Figure 19). This velocity profile distortion is synonymous to the average velocity profile asymmetry reported by Edomwonyi-Otu and Escudier et al. For single phase horizontal straight channel flow, the velocity profile of polymers in the turbulent regime shows asymmetric behavior. Both the magnitude and location of the peak asymmetry change with streamwise distance until flow fully develops. Escudier et al reported a symmetrical velocity profile for drag-reducing polymers for laminar flow along the horizontal crosssection for majority of cases tested. There was, however, a case of slight asymmetry noted for small value of Ekman number, suggesting significant effect of the Earth’s rotation. No perceptible asymmetry in turbulent flow regime occurred along the horizontal crosssection. However, the degree of asymmetry varied with angle from the vertical (in the transition regime for DRP solution) showing a maxima/minima at 45°/225° especially at higher concentration. Edomwonyi-Otu reported similar findings in his PIV study of HPAM solution flow in 14 mmID horizontal pipe (though they studied only the vertical [0°/180°] two-dimensional velocity profile) (see fig. 3 of Reference 102). Asymmetry varies both axially and azimuthally. Edomwonyi-Otu and Escudier et al concluded that, the asymmetry does not depend on geometric imperfection and inadequate mixing respectively. The sighted works failed to explain the physical mechanism which triggers asymmetry. While Escudier et al suggested that the observed asymmetry is the consequence of fluid-dynamic mechanism, Edomwonyi-Otu concluded that the cause of the asymmetry is inherent in the polymer irrespective of the concentration. Polymer DR is a complex phenomenon involving both viscous and elastic effects on flow structures. PIV data on spatial distribution and propagation of coherent structures such as elliptical vortices and hyperbolic structures may shed more light into mean velocity profile distortion reported in the aforementioned investigations. The application of 3D-PIV could provide...
better understanding of the effect of DRP on mean velocity profile of drag-reducing flows at high and low DR. Therefore, future PIV investigations using stereo-PIV or Tomographic-PIV techniques could lend valuable information on mean velocity profile of drag-reducing flows. In addition, NS studies into this observed behavior of drag-reducing flows are necessary.

### 5.1.2 Effect of DRPs on turbulence statistics

Research into the influence of DRPs on turbulence statistics can be grouped in two: (a) wall-bounded flow and (b) boundary layer flows. In the later, DR varies in the streamwise direction along the boundary surface due to difference in boundary layer parameters with streamwise distance. Some results of investigations into the influence of DRPs on turbulence statistics (ie, axial and wall-normal fluctuating velocity, Reynolds shear stress tensor and turbulence intensity) have been presented in terms of friction-velocity-normalized values of these quantities ($u'_{rms}$ or $v'_{rms}$, $\overline{u'v'}$). It should be stated that the friction velocities of drag-reducing flows are generally lower than that of Newtonian fluid and this makes normalization smeared. Some PIV investigation present velocity fluctuations simply in terms of their rms values ($u'_{rms}$ and $v'_{rms}$) while others present them simply as fluctuating velocity ($u'$, $v'$). Some studies of the influence of DRPs on boundary layer flows have presented their velocity fluctuations measurements as free-stream velocity normalized fluctuating velocities. Overall the choice of normalization (or the lack of it) is important only to the extent of how data are interpreted and are more obvious when interpreting streamwise velocity fluctuations.
In general, when streamwise velocity fluctuations have been reported in terms of friction-velocity-normalized rms fluctuating velocities, the results showed an enhancement in streamwise fluctuating velocity and a shift of the peak fluctuation from the wall with increase in DR. This applies to both wall-bounded flow as well as boundary layer flows. However, when the streamwise fluctuating velocities are presented without normalization with friction velocity, suppression of streamwise velocity fluctuations are reported upon the addition of DRPs. These results are by no means contradictory and both dimensional and dimensionless streamwise fluctuating velocity were presented by Warholic et al.\textsuperscript{101} in their PIV investigation of DR in channel flow. They reported increased friction-velocity-normalized fluctuating velocity and a shift of the peak from the wall at enhanced DR. While there was decrease in the dimensional streamwise velocity fluctuations (especially further from the wall) with increased DR. By implication, the increased streamwise fluctuations reported for friction-velocity-normalized velocity fluctuation can be interpreted to mean an increased unidirectional streamwise fluctuating velocity resulting from the addition of DRP. Also, the reduced axial velocity fluctuations reported when the measured velocity fluctuations are not normalized using friction velocity can be interpreted to mean less disparity between instantaneous velocity and the average velocity due to addition of DRP.

Results of friction factor normalized rms velocity profile of axial ($u^+$) and radial ($w^+$) components of White et al.\textsuperscript{44} for water and DRP in turbulent boundary layer flow on flat plate are shown in Figure 20 at $R_\theta = 1410$. With increasing DR, resulting from the addition of DRPs, the maximum in the axial velocity profile increased and moved away from the wall. This result is in agreement with an earlier investigation by Warholic et al\textsuperscript{107} using LDV technique. In contrast, when the dimensional streamwise velocity profile is used, Liberatore et al\textsuperscript{68} and Warholic et al\textsuperscript{101} reported reduced axial velocity fluctuations with increase in DR in channel flow and the reason for this difference have been explained in the preceding section. Zadrzil et al\textsuperscript{45} recorded increased magnitude and frequency of unidirectional $u^+$-fluctuation structures near the wall after adding DRP to water in pipe flow. Streamwise velocity fluctuations can either be positive or negative and it has been reported that negative velocity fluctuations tend to have larger magnitude (ie, lower frequency) than positive velocity fluctuations for both Newtonian and DRP solution flows.\textsuperscript{101} This skewness in axial velocity fluctuations is depicted on Figure 21 for water and DRPs solution. There was an increase in the negative skewness when DRP is added though this increase in not proportional to changes in DR.

Notwithstanding the type of flow or the normalization method, the radial fluctuations are lower for DRP solution than those of water and decreases with increase in DR as well as polymer concentration.\textsuperscript{44,45,68} However, the decrease in dimensional radial or spanwise velocity fluctuations are quantitative larger than the nondimensional one.\textsuperscript{101} In a PIV investigation of the effect of wall-blown DRPs (heterogeneous DR) on turbulence statistics, Motozawa et al\textsuperscript{100} argued that the availability of polymer near the wall is most essential to DR. Their argument was based on the understanding that polymers work to suppress turbulence eddies close to the wall. Similar to PIV studies in homogeneous DR Motozawa et al\textsuperscript{100} reported an increase in friction factor normalized rms value of axial fluctuating velocities with increase DR. However, unlike other studies, the shift of the maximum streamwise fluctuating velocity further from the wall reported in most DRP studies of homogeneous DR was not reported in their work. The increase in dimensionless streamwise fluctuating velocity was associated with the suppression of axial pressure strain which is responsible for flow redistribution. It was further obtained that nondimensional wall-normal fluctuating velocities decreased and there was a shift of the peak of the nondimensional wall-normal fluctuating velocities further from the blower wall with increase in DR. This result is in agreement with results of PIV measurement for homogeneous DR described above.

**FIGURE 20** rms values of fluctuating velocities plotted against normalized spanwise position. Closed symbols represent axial fluctuations $u^+$ while open symbols represent radial fluctuations $w^+$. Open and solid circles water at $R_\theta = 1475$; open and solid squares 33% DR; open and solid diamonds 45% DR; open and solid triangles 45% DR; solid line.\textsuperscript{100} The dashed lines with DR represent polynomial fit. Reproduced from White et al\textsuperscript{44} with permission from [Springer Nature]
Warholic et al\textsuperscript{101} and Liberatore et al\textsuperscript{68} recorded a substantial drop in dimensional Reynolds stress tensor with increase in DRP concentration and DR (Figure 22). Warholic et al\textsuperscript{101} highlighted the fact that the large changes in Reynolds shear stress were not proportional to small increase in DR. Therefore, the DRPs did not only induce DR but also imposed significant structural changes on the flow. In fact, DR can be regarded as a secondary effect of adding DRA resulting from the effect of DRA on flow structures.

In the case of heterogeneous DR by wall-blown polymer solution, Motozawa et al\textsuperscript{100} reported a reduction in the peak of the Reynolds stress and a shift of this peak away from the pipe wall. This effect was more obvious close to the wall and this suggests an interaction between DRP and turbulence eddies close to the wall. The reported displacement of the peak Reynolds stress tensor was associated with the increase in buffer layer thickness for polymer solution flows. Motozawa et al\textsuperscript{100} also presented data on Reynolds stress tensor correlation coefficient $C_{uv}$ at the two Reynolds number studied. Similar to Reynolds stress tensor, the peak of the reported $C_{uv}$ for DRP solution was less than that for water and the value is even much less with increase in DR. Their results led them to conclude that turbulent motion is reduced by the polymer acting near the blower wall.

A common limitation of the above PIV investigations is the use of 2D-PIV to describe the 3D turbulence statistics of drag-reducing flows. For example, the mean velocity profile asymmetries reported in drag-reducing flows are the results of the action of DRP on turbulence statistics. Therefore, the effect of DRP on turbulence statistics may demonstrate a similar spatial skewness. This could be an interest area for future PIV investigations.
5.1.3 Effect of DRPs on turbulence structures

Coherent structures of wall generated turbulence include the quasi-streamwise vortices and the low-speed velocity streaks which are both important in the mechanism of wall generated turbulence. Considering the effect of DRAs in suppressing wall generated turbulence, it is expected that the addition of DRAs will have an influence on these structures. To study the effect of DRPs on interstreak separation of low-speed turbulence streaks, White et al.\textsuperscript{44} carried out PIV measurements in the horizontal plane at different distance ($y$) from a flow channel bottom. Streak spacing was obtained from a two point spanwise ($z$-direction) correlation function of the streamwise velocity, $C(r) \equiv \langle (u(z)(u(z + \Delta z)))^2 \rangle / \langle u(z)^2 \rangle$, where $\Delta z$ and $u$ are the separation distance in the $z$ direction and streamwise velocity; the minimum $C(r)$ is reported at approximately $1/2$ the streak spacing. Figure 23A shows $C(r)$ at $y^+ \approx 15$ for water and DRP solutions corresponding to 33% and 67% DR. The streak separation in the $z$-direction $\lambda^+$ (obtained from $C(r)$ and normalized by the streak spacing measured for water flow at the equivalent normalized distance from the wall) plotted against DR is shown in Figure 23B. Streak spacing normalized by wall units increased with increase in DR. The low-speed streak is seen in Figure 24 as areas of axial velocity correlated across the image in the axial direction (blue streaks). The coarsening of streak spacing with DR is quite apparent in Figure 24B.

Also, PIV measurements in the $x$-$z$ planes at various distances from the bottom wall were carried out by Warholic et al.\textsuperscript{101} A number of streaks of large negative velocity fluctuations separated by swirls are observed as shown in

![Figure 23](image1.png)

**Figure 23**

Crosscorrelation function $C(R)$ computed at $y^+ \approx 15$ (A) at DR of 0% (open circle), 33% (open square) and 67% (open triangle). Streak separation computed from $C(r)$ vs DR (B), White et al.\textsuperscript{44} (solid circle), Oldaker & and Tiederman\textsuperscript{108} (open circle). Dashed line represents curve fit of Oldaker and Tiederman.\textsuperscript{108} Source: Reproduced from White et al.\textsuperscript{44} with permission from [Springer Nature]

![Figure 24](image2.png)

**Figure 24**

PIV vector map of the velocity fluctuation for: (A) water and (B) 50% DR. The figure represents top-to-bottom flow. Source: Reproduced from White et al.\textsuperscript{44} with permission from [Springer Nature]
Figure 25. A, Shading signifies zones where \( u < -0.2 \) m/s. B, 1.24 ppm solution, shading signifies zones where \( u < -0.1 \) m/s. C, 50 ppm solution, shading signifies zones where \( u < -0.05 \) m/s. Source: Reproduced from Warholic et al.101 with permission from Springer Nature.

Figure 25A. According to Warholic et al.101 these streaks may be the result of a combination of a number of flow structures and their spacing appears to scale with channel dimension. It has been suggested that these streaks are footprints of large-scale events as seen from the x-z plane. As depicted in Figure 25B the frequency of small-scale swirling motions has reduced significantly and thereby streaks of negative velocity fluctuations becomes clearer to the view (this may not be obvious because this measurement was taken at \( y = 1.8 \) mm from the bottom as against 1.0 mm in Figure 25A) with addition of DRP. In the case of 55% DR (Figure 25c), though PIV measurements were carried out at a plane location \( y = 3.8 \) mm away from the channel wall the streaks remain clear enough to view. One limitation of the work of Warholic et al.101 is that the effect of DRP on streak width and streak spacing were not investigated.

The effects of DRPs on near-wall vortices have also been investigated by PIV technique and results show a general weakening of vortices close to the wall and the reduction in magnitude and frequency of small-scale vortices with increase in DR. This reduced number of small scale swirls upon addition of DR was highlighted by Warholic et al.101 and Liberatore et al.68 in separate PIV investigations of wall-bounded flow. White et al.44 identified wall-normal vortices using low-pass filters on the velocity field obtained from PIV for water and DRP solution in boundary layer flow over flat plate. The fluctuating velocity field for water and for the case of 50% DR are depicted in Figure 26A, B respectively. Color scales of the vector are indicative of the magnitude of velocity relative to the average and the color scale of the contour represents the square of the magnitude of the wall-normal vorticity. It can be deduced from Figure 26A, B that the strength and number of vortical structures close to the wall decrease significantly with DR. It was suggested by White et al.44 that these vortical structures represent a crosssectional projection of the wall-inclined quasi-streamwise vortices which are abundant in the near-wall region. If this is the case, the action of polymer would mainly be to dampen spanwise fluctuations (by weakening quasi-streamwise vortices which contributes primarily to redistribution of energy between the axial and wall-normal directions) and increase unidirectional streamwise fluctuations.45 According to White et al.44 an appropriate explanation of the mechanism of polymer DR would incorporate this effect. Zadrazil et al.45 also reported reduction in numbers (or nonexistence) of vortex pockets after adding DRP as well as reduced swirling strength in the shear layer as indicated by the noncircular vortex core characteristic of vortex pockets.

The contributions of large-scale events (which appear intermittently in turbulent flows) to Reynolds stress tensors have been well established in the previous sections. Here the effect of DRPs on these large-scale motions is discussed. Overall, addition of DRPs reduces both the frequency and magnitude of these large-scale eruptions. In the PIV investigation of Liberatore et al.68 in a rectangular flow channel with oscillating bottom and flat top, it was reported that adding DRP resulted in decreased frequency and extent of large scale eruptions (Figures 27 and 28). Figure 28C depicts
Figure 26  PIV vector field of the velocity fluctuation for flow of (A) water and (B) DRP solution at 50% DR. Vector color represents the magnitude and the contour color scale represents the square of the magnitude of the vorticity. The plots represent top to bottom flow. Source: Reproduced from White et al. with permission from [Springer Nature]

Figure 27  PIV velocity vector field for water. Source: Reproduced from Liberatore et al. with permission from [Elsevier]

A large less-active zone of negative velocity fluctuations near the center. The velocity fluctuation in this region is nearly rectilinear because of large decrease in spanwise velocity fluctuations. An interesting observation from PIV data of Figure 28 is the possible 2D asymmetry of intermittent large-scale eruptions. Investigations into any possible asymmetry in these large-scale eruptions could provide answers to the mean velocity profile asymmetry reported in drag-reducing flows.

The effect of DRPs on large scale motion and small eddies was also extensively investigated by Warholic et al. Figure 29A shows a region of large negative fluctuations at the bottom wall which spans from $x = 20$ mm to $x = 50$ mm and outwards from the wall nearly up to channel center. PIV data indicate that negative velocity surges are jet-like extending over small distances in the $x$-$z$ (horizontal) plane. Figure 29 shows PIV fluctuating velocity vector map in the vertical plane for the flow of DRP in channel flows as presented in the report of Warholic et al. It is obvious from Figure 30 (42% DR) that there is reduced activity in the central region of flow due to reduced dimensional streamwise and wall-normal fluctuating velocity. The activity of the DRP is seen in the reduced number of small-scale eddies and dampening of wall-normal fluctuating velocity. Also, adding DRP reduces the frequency of large scale eruptions as is evident when comparison is made between Figures 29A and 30A. PIV measurements of fluctuating velocity vector field for 55% DR (not shown here,
**FIGURE 28**  PIV velocity vector fields for polyacrylamide, PAM, at DR = 58%. DR refers to DR measured using bottom wall shear stress. *Source:* Reproduced from Liberatore et al.\(^6\) with permission from [Elsevier]

**FIGURE 29**  Vertical plane PIV velocity vector field for flow of water. Segments with \(uv > \overline{uv}\) (at \(y/H = 0.5\)) are bounded with solid lines (\(u < 0\)) and the dashed lines (\(u > 0\)). *Source:* Reproduced from Warholic et al.\(^{101}\) with permission from [Springer Nature]

**FIGURE 30**  Vertical plane PIV velocity vector field for flow of 1.24 ppm DRP solution. Segments with \(uv > \overline{uv}\) (at \(y/H = 0.5\)) are bounded with solid lines (\(u < 0\)) and the dashed lines (\(u > 0\)). *Source:* Reproduced from Warholic et al.\(^{101}\) with permission from [Springer Nature]
see Warholic et al.\textsuperscript{101} there is further decrease in the contribution of large-scale motions which made significant contributions to Reynolds stresses in water flows. The regions where the flows are nearly parallel to the wall are more ubiquitous at 55\% DR than for 41\% DR as shown by thick layers of large unidirectional velocity fluctuations.

In the case of heterogeneous DR with wall-blown DRP solutions it appears that the influence of DRPs on large-scale motions is primarily to reduce the frequency of these events near the wall. Unlike homogeneous DR, for example, Warholic et al.\textsuperscript{101} where DRPs result in a less active center region, wall-blown polymer DR data of Motozawa et al.\textsuperscript{100} shows significant intermittent large scale events near the pipe center. This disparity is likely because of low polymer concentrations around the channel center. Since these large-scale events contribute significantly to Reynolds stresses (in the bulk fluid and near the wall with coherent structures) their absence in the central region of wall-blown polymer DR will likely result in reduced overall DR. It should be stated here that the highest DR reported by Motozawa et al.\textsuperscript{100} was less than 20\%. Motozawa et al.\textsuperscript{100} also highlighted the contribution of large-scale motions to Reynolds stresses and the effect of DRPs on these large-scale structures by the use of scatter plots. Figure 31A, B shows scatter plot for water and DRP solution flow in wall-blown heterogeneous DR studies of Motozawa et al.\textsuperscript{100} In turbulent flows, Reynolds stress tensor contributes to the second and fourth quadrants and so these quadrants are dominant for water as indicated in Figure 31A. Conversely, the size of the second and fourth quadrants decreases for drag-reducing flow as depicted in Figure 31B. Also, the plot for water shows symmetric shape and the axis is inclined to the $u' - v'$ axis. The axis of the elliptical shape for shape for drag-reducing flows becomes almost parallel to the $u'$ axis.

Further studies into the influence of DRPs on flow structure were done by Zadrazil et al.\textsuperscript{45} In their PIV study using three different molecular weight PEO solutions, they reported an intermittent flow characteristic which they called shear layer resulting from the addition of DRP (Figure 32). Upon the addition of DRP, they obtained an sharp change in the instantaneous velocity field and the appearance of: (a) thin filament-like layer characterized by large values of negative instantaneous axial shear strain rate $\dot{\gamma}_{xy}$; (b) thin filament-like layer characterized by large values of instantaneous 2D vorticity $\omega_z$; and (c) increased regions of unidirectional velocity fluctuations, relative to water flow at same Reynolds number, which implies a degree of coherence (similar to the report of Warholic et al.\textsuperscript{101} The occurrence frequency of these features and their intensities increased with increase in molecular weight and concentration of polymer. For the test case where the highest molecular weight and concentration was used these features were reported to be almost continuous over time. These features points to a separating layer between the low velocity flow near the wall and the high velocity flow near the pipe center. The high and low momentum zones are separated by thin filament-like layers of intense shear and 2D vorticity.

Although, this review focuses on PIV application to flow field measurement of drag-reduced flow, there is significant literature on numerical simulation of drag-reduced wall-bounded flows\textsuperscript{4,4-6,8,16,17,58}. Similar to PIV studies, the effect of DRP is seen in the weakening of vortical structures and their elongation in the streamwise direction for low Reynolds number quasi-streamwise vortices. Polymer stresses oppose vortical motion resulting in the weakening of vortices.\textsuperscript{58} More recent numerical simulation studies have revealed important coherent structures such as hyperbolic structures (in addition to elliptical vortices) which are significantly weakened by the counter-stretching action of DRP.\textsuperscript{18} These important findings require experimental validation and PIV technique could be used to validate these results.
5.1.4 PIV studies of polymer degradation and mechanism of DR

Under sufficient shear polymer degrades either by the unwinding of aggregates or by polymer chain scission and this results in the DRP losing its drag-reducing ability. The susceptibility of polymer chain to mechanical degradation generally increases with length of polymer chain. The effect of shear on DRP solution flow is shown by increased turbidity of the solution. Rheooptical measurements of three samples of PAM that have undergone various degree of mechanical degradation by recycling through a centrifugal pump was presented by Liberatore et al. as a plot of transmittance against time. The first sample (PAM60, 4 minutes of circulation time) showed increased turbidity with increase in shear rate. According to Liberatore et al., this behavior is linked to the formation of coherent scattering structures under shear flow. With decreased drag-reducing capability, the propensity to demonstrate flow-induced turbidity reduces or is lost completely. In that study, though the molecular weight (and its distribution) of PAM 60 and 62 were similar after circulation for 4 and 43 minutes, the reported DRs were 58% and 42%, respectively. It should be stated that the decrease in scattering structure formation at fixed molecular weight is in agreement with the report of Liberatore et al. for HPAM solution after partial degradation at similar conditions. Since there was no chain scission, the loss of drag-reducing ability from PAM 60 and 62 was associated with the loss of the solution's ability to form large scale coherent scattering structure under shear. Though this explanation is reasonable it does not explain the loss in drag-reducing capability between PAM 63 (88 minutes circulation) and 66 (925 minutes circulation) with DRs of 34% and 11%, respectively. For this case, Liberatore et al. suggested that there is a breakdown of aggregates hence the loss of drag-reducing capability. It is well established that, polymer aggregation contributes significantly to DR and the loss of it translates to loss of drag-reducing capabilities. It is important to state here that the ability to form aggregates of PAM is very limited. Hence it is likely that the observed loss in drag-reducing ability between the two PAM solutions, having similar molecular weight and polymer disparity, is linked to straining of polymer chains beyond their elastic limits without chain scission. This view will, however, require suitable experimental investigation to verify. In other results of Liberatore et al., where there was decrease in molecular weight, for example, PAM 64, loss of drag-reducing ability was linked to polymer chain scission. It has been reported elsewhere that flow-imposed structuring in DRP solution was linked to molecular weight. Liberatore et al. concluded that both polymer chain scission and destruction of DRP aggregates resulted in the loss of drag-reducing ability and the latter is an essential component in the mechanism of DR.
In the PIV study of White et al. for boundary layer flows, they reported an increase in separation between spanwise streaks as well as reduced strength and numbers of wall-normal vortices and concluded that any attempt to explain the mechanism of polymer DR must take these into consideration. The observation of near zero Reynolds stress tensor across the flow crosssection at very high DR led Warholic et al. to suggest that, for hydrodynamically developed flows, turbulence is not generated by the same mechanism as with Newtonian fluids. They argued that polymer imposes an additional stress which is the sum of an average I and a fluctuating I component. The product of the fluctuating polymer stress and the fluctuating velocity gradient is a scalar quantity P. In the case of zero Reynolds stress tensor, the time average of P is positive and turbulence is driven by the fluctuating polymer stress. According to them, the resulting flow field is not just a perturbation of the turbulence observed in Newtonian fluid flows but rather connotes of another stationary state. In this state the energy is supplied to the fluctuating flow by the DRP chain stresses is dissipated by the viscosity of the solvent, that is .. I P I = I P I , where I P represents the fluctuating stress of the solvent.

Mechanism of polymer DR has also been associated with the formation of a shear layer (region of high negative shear strain and high 2D vorticity) formed by the addition of DRP. This shear layer recorded in instantaneous PIV vector field is reported to separate the flow into high and low momentum zones. Figure 33 shows the instantaneous velocity of water gradually increases from the wall to the pipe center. Adding DRP results in the separation into high and low momentum zones, which is shown by an abrupt velocity change at the intermittent interface created by the shear layer. The shear layer thickness increased with polymer concentration and molecular weight but decreased as Reynolds number increased. The similarity of this characteristic of shear layer thickness and the qualitative effects of DRPs led Zadrazil et al. to suggest that there might be a link between shear layer and the underlining mechanism of DR. Similar to Zadrazil et al. Graham and coworkers reported a transient characteristic of drag-reduced flow as well as Newtonian fluid flow in their numerical simulation study of the dynamics of turbulent DR. They identified two turbulence regimes; hibernating and active turbulence regimes for both Newtonian and drag-reduced flows. The hibernating turbulence regime (which is less frequent in turbulent Newtonian fluid flow compared to drag-reduced flow) showed MDR characteristics such as near-zero Reynolds shear stresses, weak vortices and streamwise streaks. Graham suggested that this dynamic characteristic of turbulence was responsible for the weak dependence of MDR on polymer properties. Also, the longer duration of hibernating turbulence or the complete suppression of active turbulence (at MDR conditions) led to the conjecture that DRP results in the unmasking of the hibernating turbulence. Pereira et al. reported striking similarities between Newtonian laminar-turbulent transition and drag-reduced turbulent flows and attempted to explain the cycling mechanism behind the time-space dynamics (alternating hibernating and active turbulence) of these flows. In the transition regime of Newtonian fluid flow, one half of the cycle involves the amplification of perturbations until the active turbulence state is reached. In the active turbulence state, the formation of coherent structures is accompanied by increased velocity gradient (more so close to the wall). The implication of this is increased viscous stresses which subsequently suppresses turbulence by the weakening of the coherent structures. Velocity gradient is again decreased and the hibernating turbulence state rediscovered. This state is synonymous with reduced viscous stresses thereby increasing the potential for increased perturbation. The similarity between Newtonian laminar-turbulent transitional flows and drag-reduced turbulent flows led to the conjecture that viscous effects (Lumley’s theory) was more pronounced than elastic effects in the complex mechanism of DR. Other numerical studies have highlighted the important role of polymer elasticity and a description of elastic-inertia turbulence. Although, these investigations were based on numerical simulation, a validation of the findings by experiment such as the use of PIV technique could shed more light into the mechanism of DR.

5.1.5 Influence of DRP on mean velocity profile and turbulence statistics in liquid-liquid flow

Very limited investigations have been carried out on the effect of DRPs on liquid-liquid flows using PIV technique. Although, literature have been published on liquid-liquid DR, most of these studies have focused macroscale effects (DR, flow patterns and holdup) and mean velocity. Information on turbulence statistics of liquid-liquid flows to which DRP has been added is limited. Even more limited is information on coherent structures of such flows. PIV technique has the potential to fill this gap. A review of the effect of DRPs on liquid-liquid DR, flow pattern and holdup is available elsewhere.
In the PIV oil-water flow drag-reduction studies of Edomwonyi-Otu and Angeli,89 in horizontal pipe of 14 mmID, both HPAM and PEO were used as DRPs. In their oil-water experiments without polymer the peak of the velocity profile was always in the water-occupied pipe section and away from the interface. With increase in oil velocity the peak velocity approaches the interface. After adding DRP, the maximum streamwise water velocity increased by 12% to 30% relative to water flow, at all test conditions reported (Figure 34A). Adding either DRPs had significant influence on the turbulence statistics of oil-water flows (Figure 35B-D). As with single phase flow, the predominant influence of the DRP is seen in the reduction in Reynolds stress tensor. When the HPAM was used, Reynolds and wall-normal stress tensors reduced across
FIGURE 35 Friction factor and DR vs Reynolds number. A, cationic surfactant CTAC \( (Re = U_b H/\nu) \), \( U_b \) is bulk fluid velocity, \( H \) is channel height, and \( \nu \) is the kinematic viscosity of the fluid. Source: Reproduced from Li et al\(^{42} \) with permission from [Physics of Fluids]. B, nonionic surfactant AROMOX \( (Re = \rho U_b d/\eta) \), where \( \rho \) and \( \eta \) are density and dynamic viscosity of water, respectively, \( \lambda \) is friction factor. Reproduced from Tamano et al\(^{111} \) with permission from [Physics of Fluids].

the entire pipe crosssection while the axial stress tensor decreased at the interface and near the wall but was enhanced in the bulk flow. They also demonstrated that the influence of DRP on turbulence statistics is dependent of polymer molecular weight.

5.2 PIV studies of influence of drag-reducing surfactants DRS on single- and two-phase flows

Surfactants are surface-active chemical agents of relatively (compared to drag-reducing polymers) low molecular weight which alters the surface tension of the liquid in which it dissolves.\(^{112} \) They assume various structures in solution such as spherical micelles, rod-like micelles, crystals, emulsions, and vesicles depending on the concentration, temperature, salinity, etc.\(^{113} \) Gadd\(^{114} \) was the first to publish a work on the use of surfactants as DRAs. The classes of surfactants are ionic (examples; anionic, cationic, and zwitterionic) and nonionic surfactants. In comparison to polymer they have higher resistance to mechanical degradation\(^ {91,115} \) and are thermodynamically stable.\(^ {116} \) This is due to their ability to self-repair after degradation.\(^ {98,117} \) The efficiency of surfactants in reducing drag depends on its concentration, temperature, geometry of flow channel, size of micelles, and bond strength.\(^ {118,119} \) Also, the turbulent DR level of surfactant solutions are strongly Reynolds number \( Re \) dependent. The onset of DR is linked to the formation of the so-called shear-induced structure (SIS) in the case of cationic surfactant additives and the surfactant viscosity at this point has a peak value. After onset of turbulent DR, which occurs at some threshold value of \( Re \) in wall-bounded flows, the level of DR increases with \( Re \) up to the threshold Reynolds number \( Re_c \) is reached. Critical (threshold) Reynolds number of DRS increases monotonically with increase in DRS concentration as does the maximum DR (Figure 35B). In the region of flow between onset of DR and \( Re_c \), the flow is not exactly laminar but is drag-reduced turbulent.\(^ {111} \) This is seen in the slight deviance between the relation \( \lambda \) and \( Re \) and the Hagan-Poiseuille laminar flow relationship (Figure 35). Above the critical Reynolds number, the level of DR drops steadily to zero at a sufficiently high value of Reynolds number (which is concentration dependent), indicating a total loss of drag-reducing capability by the DRS. The apparent gross characteristics of the flow of DRS is the ensemble of turbulence structures which are determined by the turbulence statistics and are closely linked to fluid rheological properties.\(^ {42} \) In this review, we shall categorize the drag-reducing behavior of DRS into four regimes (Figure 35A) according to the categorization of Li et al.\(^ {42} \) Though, this categorization was done originally for cationic surfactants, nonionic surfactant behavior (Figure 35B) can be roughly categorized into these four regimes. Regime I is the laminar flow regime where there is no DR; regime II is a region of increasing DR with increase in \( Re \); regime III is a region of decreasing DR with \( Re \); regime IV is a region of no DR due to loss of drag-reducing capability of the surfactant solution. The line separating regimes II and III signifies the point of maximum DR corresponding to the most effective network configuration of the SIS for cationic DRSs. Attention will be focused on the last three regimes for wall bounded flows. For
boundary layer flows over flat plates, DR increases in the streamwise direction downstream of the leading edge and also increases with momentum-thickness Reynolds number \( Re_\theta \). It is also pertinent to note that unlike DRPs, a certain minimum threshold concentration of DRS must be attained for DR to occur regardless of the type of flow. In general, DRS surfactants have been reported to result in turbulence suppression, alteration of quasi-streamwise/hairpin vortices and low-speed streaks, and are responsible for difference between the sum of turbulence and viscous shear stresses and the total shear stress.\(^{42,51,60,91,107,120}\)

### 5.2.1 PIV measurements of average streamwise velocity profiles for surfactant solution flow

The influence of DRS on average streamwise velocity in wall-bounded flows is seen in the lift of the log-law region with steeper slope away from the wall and a downward shift near the wall with a gentler slope compared to water.\(^{42,60}\) The mean streamwise velocity profile in regimes II and III has been shown to be different even when there is comparative level of DR.\(^{42}\) This suggests that the solution may possess different characteristics at different Reynolds number even when the levels of DRS are similar. Comparing C1 (Figure 36A) with C3 (Figure 36B) (corresponding to flow regimes II and III respectively) it can be seen that the average streamwise velocity profiles differ, that is, different degree of upward shift and different slopes in the log-law layer even though they both have similar percentage DR (49% and 43%, respectively). Also, the mean axial velocity profile in regime IV, where the solution has lost its drag-reducing capability, does not overlap with water flow (Figure 36C). This suggests that there is a difference in the characteristics of water and cationic DRSs solution that has lost its drag-reducing capability.

For boundary layer flows, the friction velocity normalized mean streamwise velocity profiles shows that for small negative or positive DR, the log-law profiles shifted downward or upward, respectively, but the profile was similar to that of water. However, at higher positive DR the upshift increases and the slope of the profile increases for both ionic\(^{119}\) and nonionic\(^{111}\) surfactant additives (Figure 37). When the free-stream-velocity-normalized mean streamwise velocity is

![Figure 36](image-url)  
*Figure 36* Average axial velocity profiles for water \( W \) and DRS solution \( C \) in rectangular channel flow: regime. A, II, B, III, C, IV.  
*Source:* Reproduced from Li et al\(^{42}\) with permission from [Physics of Fluids]
plotted against the boundary-layer-thickness-normalized distance further from the wall for water and DRS the profile for DRS lie between that of water and the laminar flow profile (Figure 37B). This is a fingerprint of partial laminarization of the flow by DRS additives.

Kawaguchi et al.\textsuperscript{91} in their PIV determination of velocity profile generated a velocity profile for surfactant solution. Though their study was not aimed at determining flow symmetry/asymmetry, the velocity profile given in their work appeared symmetrical. Research on the influence of DRAs on velocity profile distribution in curved pipes is required as this could provide more explanation to this behavior observed in straight pipe flows. This could also provide useful insights into the effects of DRAs in the laminar flow regime in curved pipe flows.

PIV studies of multiphase drag-reducing flows are few and data on mean axial velocity profiles of such flows are limited. Dieter et al.\textsuperscript{74} used PIV-flow visualization method to measure mean axial velocity profiles within the viscous boundary layer of air-water/air-surfactant solution flows. Their results show higher mean axial velocities in the viscous boundary layers for air-surfactant solution flow compared to air-water flow. Though no explanation was provided for this in that report, this behavior can be associated with suppression of wall-normal turbulence and flow redistribution.

In summary, DRS promotes parabolic mean profiles and reduces the velocity gradient in the near-wall region. Information on possible 2D or 3D mean velocity profile distortion is limited. Future PIV investigations could shed more light on the effects of DRS on mean velocity profile.

### 5.2.2 PIV studies of turbulence statistics for the flow of DRS solution

The turbulence statistics for polymer and surfactant DRAs show a number of similarities particularly in the regime of surfactant flow that fall into regime II, that is, where DR increases with the Reynolds number of surfactant solution. Similar to polymer DR, PIV reports on turbulence statistics of DRSs flows have been presented either in dimensional or normalized form and again a number of similarities exist between the actions of both drag-reducing additives DRAs. In general, dimensional fluctuating velocities in the axial and wall-normal directions are dampened in DRS flows compared to that of the solvent, but this decrease is smaller than the suppression of Reynolds stresses by DRS. This difference has been associated with decorrelation of the axial and radial velocity fluctuations and this has also been related to the overall manifestation of DR.

PIV data of Li et al.\textsuperscript{42} in channel flow show that dimensional (or in this case bulk-velocity normalized) streamwise velocity fluctuations in regime II is dampened (ie, lower) for flow of cationic DRS solution compared to that of water. The streamwise velocity fluctuations in regime III for flow of cationic surfactant solution shows different behavior as shown in Figure 38B. Near the wall fluctuating streamwise velocity appears to increase while it decreases close to central
region of the flow (C3—high DR, 43%) or it remains similar to that of water (C4—low DR, 12%). This has been linked to degradation of SIS of the cationic DRS close to the wall at higher Reynolds numbers (regime III). Again, though the level of DR of C1 and C3 are similar their fluctuating streamwise velocity profiles are different which show that there is Reynolds number dependence on flow characteristics. Figure 38C compares the bulk-velocity-normalized fluctuating streamwise velocity of water and DRS solution that has lost its drag-reducing ability. The curves do not coincide and this suggests that though the cationic DRS solution has lost all its drag-reducing ability its characteristics are different from that of water. This has been associated with the viscoelasticity contribution of the DRS which is present even after the DRS has completely lost its drag-reducing capabilities. In a separate PIV studies of Gurka et al., suppression of the dimensional streamwise velocity fluctuating velocity was also reported. Gurka et al. used two-point correlations functions to carry out an autocorrelation of the streamwise velocity fluctuations so as to investigate the spatial characteristics of DRS solution flow. Autocorrelation of the streamwise velocity fluctuations in axial direction $R_{uu}(x)$ shows that surfactant additives do not have any significant effect of the longitudinal (axial direction) length scale. However, the transversal (spanwise) correlation $R_{uu}(z)$ shows that surfactant additives significantly increased the length scales (i.e., increase the distance between low- and high-speed zones) in the flow. The decorrelation of the velocity components has been associated with the occurrence of DR by surfactant additives and the significant decrease in the Reynolds stresses. Tamano et al. carried out separate PIV studies of boundary layer flow of cationic and nonionic DRS over flat plate, respectively. Their plot of free-stream-velocity-normalized streamwise velocity fluctuation shows that streamwise velocity fluctuation of water was generally slightly higher than that of DRS solution (Figure 39A, B). The report on cationic surfactant, however, showed two peaks of fluctuating streamwise velocity of DRS solution. This led Tamano et al. to propose a bilayered-structure model for DRS turbulent boundary layer flow (Figure 39C). Near the wall, where shear stress is significant, the flow assumes the SIS and is viscoelastic. Whereas, in the region of the flow further from the wall where there is potential and turbulent flow mixing, the flow assumes a non-SIS and is nonviscoelastic. A second peak of the streamwise velocity fluctuation may sometimes be visible.

Regardless of whether or not the fluctuating wall-normal velocity is presented in dimensional of nondimensional form, PIV investigations have generally reported a reduced fluctuating wall-normal velocity for DRS solution compared to that of the solvent (Newtonian fluid) for all test Re in the turbulent flow regime. The difference in the fluctuating wall-normal velocity of DRS solution and that of the solvent is more obvious when the data is presented in the dimensional form or when bulk velocity is used for scaling rather than friction velocity. This is because of the difference is the friction velocity of DRS solution and that of the solvent (with the former being smaller). Results of the PIV measurements of fluctuating wall-normal velocity of Li et al. in channel flow is depicted in Figure 40. The fluctuating wall-normal velocity is suppressed in DRS solution and the level of suppression appears to be increase with increase in DR (highest in C2 with DR of 60% and lowest in C5 with DR of 0%). Again, curves C5 and W5 do not coincide. For the flow of viscoelastic solution it has been shown that the contributions to friction factor are: laminar contribution, turbulent contribution, and
It has been suggested that even when the solution (C5) has lost its drag-reducing ability completely, additional contribution to wall friction may still exist (viscoelastic effect). Therefore, the viscoelastic characteristics of the cationic surfactant may persist in the fluid in this regime, hence the suppression of fluctuating wall-normal velocity in that regime. Li et al.\textsuperscript{60} also reported suppressed turbulence intensities and wall-normal vorticity due to DRS, however this effect was reported primarily in the buffer layer. This led to the conjecture that turbulence suppression in the buffer layer contributes the most to DR in wall bounded flows.

Furthermore, Li et al.\textsuperscript{42} used data of power spectral velocity fluctuations to study the characteristics of DRS solution. As described by Doorn et al.,\textsuperscript{123} PIV allows for direct wave number spectra measurement using the Taylor's hypothesis. Flow regime C1 and C3 both have similar degree of DR but are in different regimes: in regime II turbulence production
is predominant is a layer away from the wall, while in regime III it is nearer to the wall in a similar way to water flow (see spectra plots of Li et al\textsuperscript{42}). This suggest that in regime III, the DRS solution behavior in the proximity of the wall is quite similar to water, just as in indicated by profiles of $u'/U_b$ for flows $C3$ and $C4$ (Figure 38B). In regime IV, $C5$ showed similar wave number characteristics with water flow, but the contribution of the central flow region of $C5$ to turbulence production is still not as significant compared to water flow, suggesting that the central region of the flow of $C5$ has not regained Newtonian flow characteristics.

In the boundary layer flow studies of Tamano et al.,\textsuperscript{111,119} cationic and nonionic surfactant additives suppressed the fluctuating wall-normal velocity and shifted the peak of the fluctuating wall-normal velocity further from the wall. The fluctuating wall-normal velocity decreased from the peak to the midsection for both water and DRS solution.

PIV investigations of the effect if DRSs on Reynolds stress tensor have also been done by several researchers and the results are similar to those of polymer solution. Adding DRS to Newtonian fluid flows have been reported to reduce Reynolds stress tensor across the entire flow crosssection. For wall-bounded flows of nonionic surfactant solution Gurka et al\textsuperscript{121} and Li et al\textsuperscript{51} reported a substantial decrease in the Reynolds stress tensor of DRS compared to that of water. Gurka et al\textsuperscript{121} also highlighted the significant difference in the skewness factor for water and DRS, which as stated earlier, was associated with the decorrelation of the velocity components. According to Gurka et al\textsuperscript{121} in addition to the decorrelation effect of the surfactant additives, DRS reduces kinetic energy production and momentum transfer. This led them to conclude that reduction of turbulent $K.E.$ production in DRS solution is due to the combination of reduced Reynolds stresses, decrease in rate-of-strain and decorrelation effects. Figure 41 shows $u_2^2$ normalized Reynolds stress tensor profiles of Li et al\textsuperscript{42} obtained by PIV technique in channel flow. The figure shows that Reynolds stress tensor is significantly reduced throughout the channel crosssection and this depression appears to increase with increase in DR. The depression in Reynolds stress is more significant in $C1$ (regime II) than in $C3$ (regime III) despite the closeness in the level DR in both cases. This once again point to the difference in characteristics of both fluids and the Re dependence of the flow characteristics of cationic DRS solution. Figure 41C shows a suppression of Reynolds stress tensor in DRS solution that has lost its drag-reducing ability. Explanation for the difference shown between water and DRS has been provided in previous sections. Suppression of Reynolds stresses was also recorded by Tamano et al.,\textsuperscript{111,119} in the PIV studies of DRS flows of cationic and nonionic DRS respectively. In general, the degree of suppression of Reynolds stresses was more than those of wall-normal and streamwise velocity fluctuations. This has been associated with the decorrelation (decoupling) of the axial and wall-normal fluctuating velocities corresponding to the reduction in the intense coherent motion close to the wall.\textsuperscript{91,121} In Newtonian fluid flow, the axial and wall-normal fluctuating velocity typically show negative correlation in a shear layer and a good approximation is given by the mixing length hypothesis in such case. Given the high extensional viscosities of viscoelastic DRAs, Kawaguchi et al\textsuperscript{91} suggested that there would inhibition of random movements of fluid particles and fluid mixing. The random fluid particle movements are thereby repressed in the drag-reduced

**FIGURE 41** Fluctuating Reynolds stress tensor for water and DRS solution: regime (A) II, (B) III, and (C) IV. Source: Reproduced from Li et al\textsuperscript{42} with permission from [Physicsof Fluids]
state and the mixing length theory does not apply. In laminar flow of Newtonian fluids, the shear stress resulting from
the strain inhibits arbitrary motion of fluid element. However, for viscoelastic turbulent flows, a force emanating from
fluid elastic property suppresses random movement as well as mixing of the fluid element. If high extensional viscosity
is assumed, the vortex stretching is inhibited and the rate of production of turbulence energy is suppressed. Also, fluid
structures motion will have to overcome the stretching resistance and further departure from the mixing length theory
occurs. As fluid elements resist shear-induced stretching deformation, it simultaneously stores energy. After fluid trans-
lation to another region, the elastic fluid element is restored and releases the energy and increase fluctuating velocity.
This difference is mechanism of turbulence production have been stated as the reason for the decorrelation between the
fluctuating velocities and the consequently the discrepancy between large suppression of Reynolds stress tensor and the
small suppression of the fluctuating velocities.

5.2.3 | PIV studies of turbulence structures for the flow of DRS

The reduction of turbulent drag using surfactant solution is accompanied by alterations in the overall structure of the
flows. These include the reduction in frequency of small eddies, reduced frequency of intermittent large-scale motions,
weakening of near-wall vortices, increase in spacing between low-speed streaks among others. In separate PIV measure-
ments of turbulent velocity vector field carried out by Kawaguchi et al and Li et al fluid penetration from the low
speed zone into the high speed zone was established. This feature, which is characteristic of turbulence energy generation
and turbulence mixing, was reported in water flow but nearly absent in DRS solution. The strong vorticity fluctuations
near the wall disappeared and the probability of “Eddy” and “convergence” accompanying vortex motion is reduced near
the wall. The lack of large-scale-motions close to the wall results in reduced streamwise length scale for surfactant solution
compared to Newtonian fluids such as water. The lower length scale of DRS flow supports the school of thought of
smaller turbulent diffusivity and smaller drag reported in DRS flows.

The angle of inclination of the low-momentum zone under the hairpin vortices close to the wall and the frequency
turbulence bursts, are reduced in drag-reducing flows, which suggest that the DRS inhibits turbulence bursting events.
Li et al linked the inclination of the low-momentum zone to the strength of the burst. Furthermore, the influence of DRS on vortex structures depends on the level of DR as well as the concentration of the additive. The added dependence of vortex structures on concentration was highlighted by an instance of reduced frequency of vortex structures and reduced Reynolds stress tensor without an increase in DR (in fact there was decrease in DR). The effect of concentration on vortex structure was associated with the contribution of elasticity (in addition to viscous and turbulence contributions) to stress. It follows that the occurrence of bursting events and the characteristics of vortex structures in drag-reducing flows are not simply a function of DR but also a function of concentration or viscoelasticity. Li et al also reported a decrease in vorticity with DR and a shift of the maximum vorticity profile towards the wall.

Li et al reported a single streamwise-elongated counter-rotating vortex pair in their PIV measurement and the effect
of DRS was to further elongate the vortex pair. This suggests that the inclination of the vortex tubes or the legs of the
hairpin vortex for DRS flow is generally smaller than that of water. Results of Li et al also showed that the streamwise vortex structures for drag-reducing CTAC solution were less organized compared to those for water. The power spectra plots of Li et al showed that in the flow DRS the main contribution to the power spectra of instantaneous velocity reduced to small wave numbers. Their plots also showed a cutoff of the spectral density function above some threshold wave number over the channel crosssection. This implies that the DRS solution increases the significance of the contributions at small wave numbers characterizing large eddies compared to those characterizing small eddies. This behavior of DRS is similar to that of DRPs described the previous sections. In addition, their contour maps show that DRS also resulted in a shrink in the contour region with high power spectra value towards the wall. This means that the central portion of the flow has less contribution to turbulence production (less contribution to drag) when compared to water flow.

Stereoscopic PIV (2D-3C) technique has been used to capture vortex structure and low-speed streaks close to the
wall for water and surfactant flows through the measurement of velocity fields in the horizontal and vertical planes. Vertical plane data showed reduced streamwise vorticity of the hairpin vortices by DRS additive. While measurement in the horizontal plane shows that a number of wall-normal vortices align with the low speed streaks having opposite signals at adjacent sides of the low-speed streaks for both water and DRS flows. Similar to PIV investigations for DRP flows, there is larger separation between low-speed streaks in DRS compared to Newtonian fluid such as water.
The effect of nonionic DRS additive on turbulence structures in boundary layer flows was investigated by Tamano et al. using PIV and the reported velocity fluctuation for water and DRS is shown in Figures 42 and 43. A sweep event (A) and two vortex cores (B and C) which constituting a packet of hairpin vortex can be seen from Figure 42A. Figure 42B shows the vortex core (D) which appears subsequently and this is usually followed by ejection. This flow behavior recorded for water is in agreement with a self-sustaining mechanism of turbulence production in the near-wall region. In Figure 43B, the fluctuating velocity is suppressed across the turbulent boundary layer and a single vortex core (E) of comparatively larger scale is observed. According to Tamano et al., no distinct sweep and ejection events were recorded. In region (F) Figure 43B, the velocity fluctuation vector field are nearly parallel to the wall and are in the negative direction. This is similar to the increased unidirectional axial fluctuating velocity reported for the flow of DRPs. Also, in their earlier study of cationic DRS similar trend of velocity fluctuation vector field in the region (F) was reported. However, for flow of cationic surfactant a layering pattern was observed in the velocity vector map which was not observed in non-ionic surfactant flow. PIV investigations into the complex interactions between DRS and coherent structures (elliptical and hyperbolic structures) are lacking and should be explored in future PIV studies.

5.2.4 PIV studies of surfactant degradation and mechanism of surfactant DR

Although the action of DRS in reducing turbulent frictional pressure losses are similar to DRP, their drag-reducing capability stems from a different dynamic processes of DRS microstructure. The ability of DRS to act as drag reducers is associated with micelles formation. These micelles alter the structure of turbulent flow close to the wall. In the case of cationic DRS, under appropriate conditions of surfactant/counter-ion ratios, concentrations, chemical structures, and temperature rod-like micelles are formed. At certain shear stress, these micelles assume a network structure, the so-called shear-induced structure. The SIS formed around the critical Reynolds is the most effective state and corresponds to the maximum DR. There is a sudden change in the rheological behavior of cationic surfactants in the shear-induced state. Particularly, there is an abrupt increase in the dynamic viscosity of the DRS (this does not occur with nonionic surfactants). Above the critical Reynolds number, the network structure formed by rod-like micelles begins to breakup resulting in reduced drag-reducing ability and eventually a complete loss of drag-reducing capability. The
network structures of rod-like surfactant micelles differ from the network formed by DRP chains in that they can break up and recombine and also grow by monomer addition.\textsuperscript{126} Hence, the SIS of DRS solution flow is expected to have dual relaxation mechanisms: one linked to the diffusion of polymer-like chains and the other linked to the breaking and rejoining of the chains.\textsuperscript{42,126} It was therefore suggested that the dynamic changes that occur in SIS control the rheological behavior of cationic DRS. Although the micelles formation has also been linked to the drag-reducing capability of nonanionic surfactants they do not necessarily form shear-induced structures.

6 | CONCLUSION

This review focused on the application of PIV technique in the study of wall-bounded and boundary layer flows for both Newtonian and drag-reducing fluids. In this review it was shown that PIV technique made it possible to visualize important flow structures such as large-scale motions, coherent structures, and the shear layer in drag-reducing flows. PIV techniques provide information on turbulence statistics with a comparative accuracy to point measurement techniques like LDA. The following are conjectures drawn from the PIV investigations reviewed:

1. PIV technique is able to capture turbulence structures like wall-normal vortex and low-speed streaks.
2. Two-dimensional velocity vector fields of PIV provide useful information on the motion scales that contribute to turbulence energy production and transport.
3. Turbulence statistics obtained from PIV measurements have revealed that both streamwise velocity fluctuations and turbulence intensities have peak values near the pipe wall where the average velocity gradient is at a maximum. Also, wall-normal fluctuating velocity and Reynolds shear stress have two peaks each at approximately the same distance from the wall and the location of the peaks are located further from the wall. The location of the peaks away from the wall is the result of suppression of wall-normal fluctuations by the impenetrable wall.
4. PIV data of separated two phase gas-liquid flows suggest that the interface acts as a moving wall and dampens wall-normal fluctuations. Where waves are present, the waves produce secondary flows which alter the velocity profile of the flow. In the case of shallow liquid depth, there is reduced average streamwise velocity near the interface and increase in the mean axial velocity near the wall (thereby assuming a characteristic S-shape profile) in comparison with that without wave.
5. The pipe wall and an interface region in liquid-liquid flows significantly influence the turbulence statistics in such flows. In general, higher values of Reynolds stress tensor, root mean square axial, and radial velocities are reported in flow sections with large mean velocity gradient. This suggests there is a connection between turbulence production and shear mean flow.
6. PIV investigations revealed that for single- and two-phase flows in horizontal tubes, the velocity profile of polymer solution, in the turbulent regime, show asymmetric behavior. Both the position and the magnitude of the peak changes with streamwise distance until flow fully develops.
7. PIV studies of drag-reducing flows also showed that DRAs act to dampen both wall-normal and streamwise fluctuating velocity along with the Reynolds stress tensor. The reduction in Reynolds stress tensor is higher than that of both axial and radial fluctuating velocity and this discrepancy has been associated with the decorrelation of the velocity fluctuation. Furthermore, DRAs result in the shift of the peak wall-normal velocity fluctuations away from the wall due to thickening of the buffer layer.
8. Effect of DRAs on flow structure depends not only on the level of DR but also on the concentration and molecular weight. The effect of concentration is associated with the elastic properties of the DRA.
9. Behavior of surfactant DRAs is highly Reynolds number dependent.
10. In general, PIV investigations have revealed that; polymer elasticity weakens coherent structures by the application counter forces to that which maintains these structures; polymer elasticity dampens ejection and sweep events; polymer chains stores energy in both of these processes which involve polymer stretching and subsequently releases the energy in the streamwise direction, directly or indirectly, when it relaxes in the bulk flow; and polymer stretching is maximum and minimum in the buffer region and the center of the conduit and is significant near the wall.
11. DRAs change the average axial velocity profile by an upshift in the log-law region and change in the slope of the profile especially for large DR.
12. The addition of DRP increases the maximum average axial velocity of water and also has significantly changed oil-water flow turbulence statistics. As with single phase flow the most significant influence of the polymer is seen in the reduction in Reynolds stress tensor. Reynolds and wall-normal stress tensors were reduced across the entire pipe crosssection while the streamwise stress diminished at the interface and near the wall but is enhanced in the bulk flow.

7 | RESEARCH GAPS

The application of PIV has several limitations some of which bothers on spatial and temporal resolutions as well as difficulties in making measurements near the interface of multiphase flows and near the wall in pipe flows. These limitations have hindered the application of PIV technique to certain flow scenarios. The review revealed gaps in experimental data that can be filled by PIV or other technique and these include;

1. The significant uncertainties in PIV measurements in regions of high shear gradients and at the interface of two-phase flows warrants that more research effort is focused on improving measurement accuracy. Such effort would necessarily include the development of improved preprocessing and postprocessing algorithms, optimization of tracer application, illumination and background lighting among other things. Furthermore, there is need for improvement of both spatial and temporal resolutions of PIV data acquisition especially where transient characteristics is to be measured.
2. Recent numerical simulation studies have revealed important coherent structures such as hyperbolic structures (besides the elliptical vortices) and there is limited experimental investigation to validate this.
3. Although, significant research has been done on the effect of DRAs on turbulence structures such as vortices and the associated ejection and sweep events, very limited studies have been done on the effect of DRAs on low-speed streaks. Some recent numerical simulation studies have remarked that, in the near-wall region, polymer does not only release energy to the streaks but also to elliptical and hyperbolic structures. Therefore, the traditional view on the mechanism of energy release by polymer when it relaxes requires further investigation. PIV techniques provide an excellent platform for the validation of numerical simulation data.
4. Some very interesting numerical simulation results on the transient characteristics of turbulence, particularly, those of Graham and coworkers requires experimental validation. Some of the questions such experimental study could answer include:

- Does the transient characteristics reported in numerical simulation studies occur in real systems?
- If such transient characteristics do exit in real systems, are they dependent on the geometry of the flow?
- If viscoelasticity plays an important role in transient characteristics such as *hibernating* turbulence and shear layer formation, then to what extent does this depend on Reynolds number or Weissenberg number?
- What is the mechanism of interaction between viscoelastic polymers and dynamic turbulence?
- Considering the difference in mechanism of DR between DRPs and DRSs (as well as fibers), how does the interaction of each DRA with dynamic turbulence characteristics differ?

5. Relationship between turbulence characteristics and $Re$ has not been well investigated and the idea of *universality of turbulence* requires further studies.
6. Limited studies have been carried out on drag-reducing flows near transition. The recent shift from the traditional view off transition as merely a change from linear to nonlinear dynamics has been shown (by numerical simulation) to extend to viscoelastic drag-reducing flows. Numerical simulation studies, such as that of have demonstrated interesting similarities between Newtonian laminar-turbulent transitional flow and drag-reduced viscoelastic flows, however, there are gaps that can be filled by both numerical simulation and experimental studies (such as PIV technique). These include:

- Dimensionless parametrization of the common characteristics of these two types of flow.
- Comparison between both types of flow at similar wall friction (DR).
- Connection between *hibernating* turbulence state and high-DR as well as the *active* turbulence state and low-DR.
7. Comparison of the low-DR and high-DR limits of both flows. Applications of PIV technique for the capture of vortex structures are limited in open literature. Considering the significant effect of DRAs on vortical structures there is need for future PIV investigation to focus on the interaction these additives have with vortices at various Reynolds and Weissenberg numbers.

8. A recent study on DR in bend was carried out by Ayegba et al.127 A number of interesting characteristics of drag-reducing solution flows was reported in bends. These include; lower DR in the bend relative to fully developed flows in horizontal straight pipes; lower DR in the redeveloping straight pipe section downstream of the bend. The lower DR in bends and in the redeveloping flow section relative to fully developed flows was attributed to the effect of flow redistribution resulting from bend forces. Future PIV in the area if DR in and around bends could shed more light into the DR behavior in bends.

CONFLICT OF INTEREST
Authors have no conflict of interest relevant to this article.

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