A review of drag reduction by additives in curved pipes for single-phase liquid and two-phase flows

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Abstract
The effect of drag-reducing agents (DRAs) on fluid flows in straight pipes has been well documented. Key among these is the effect of DRAs on turbulence statistics (Reynolds shear stress, turbulence intensity, streamwise and wall-normal velocity fluctuation among others). These primary effects result in secondary effects such as modification of mean velocity profile and reduction in frictional losses (drag reduction, DR). Interestingly, in curved pipe flows, the characteristic of flow is more complex due to secondary flow, wake effects and under-developed flow characteristics. Therefore, a review of investigations on the effect of DRAs in curved pipe flows is presented in this paper. The paper highlights the difference between DR in straight and curved conduits as well as the interaction between DRAs and flow characteristics of curved pipe flows. Proposed mechanisms of DR, and factors that influence their effectiveness also received attention. It was shown that significant DR can be achieved in curved pipes. A review of various experimental results revealed that DR by additives in curved pipes is generally lower than in straight pipes but with certain similarities. It decreases with increase in curvature ratio and is more pronounced in the transition and turbulent flow regimes. Maximum DR asymptote differed between straight and curved pipes and between polymer and surfactant. Due to the limited studies in the area of DR for gas-liquid flow in curved pipes, no definite conclusion could be drawn on the effect of DRAs on such flows. A number of questions remain such as physical interaction between molecules of DRA and flow features such as secondary flow streamlines and wakes. Hence, some research gaps have been identified with recommendations for areas of future researches.

Keywords
curved pipes, drag-reducing agents, drag reduction, single phase flow, two phase flow
1 | INTRODUCTION

Locations of petroleum wells are sometimes several kilometers from processing plants. There is therefore need to transport single and multi-phase fluids through pipes, including pipe fittings such as bends, to processing plants and for separation. A large percentage of the energy cost in petroleum production and transport results from pressure losses. Most of the pressure losses in pipeline flows are associated with the production of turbulence eddies resulting in non-axial components of flow. Unlike laminar flows where pumping power is directed at providing axial unidirectional fluid flow, turbulent flows are characterized by both axial and radial flows. The implication of this is loss of pumping power or increased drag. A common view is that any process mechanism that results in flow laminarization would also result in drag reduction (DR).

Fluid flow in coiled tubes and bends are associated with secondary flows which superimpose on the mean stream-wise flow. The superimposition results in reduced turbulence intensity (TI) and the delay in the onset of turbulence. In the case of fully developed flows in coils, the suppression of TI increases with curvature ratio of the coil and with increase in curvature ratio the onset of turbulence regime is shifted to higher Reynolds number. Due to the often-short length of bends, flow in bends is often under-developed. This compounds the complexities of the flow and regions of high pressure gradients are encountered within the bend and even after the bend. Where the curvature ratio of the bend in large and fluid flow is at high Reynolds number, flow detachment from the inner wall of the bend as well reverse flow may occur. Also, the resulting wake from flow detachment from the wall contributes significantly to pressure losses both within the bend as well as its downstream section. This is consequent upon high interfacial shear stresses of the wakes which can be very dissipative. Significant pressure losses are also associated with flow redistribution in the redeveloping flow section immediately after bends. These additional pressure losses (relative to developed flows) have been reported even as far as 20 pipe diameters downstream of bends. Ward-Smith et al remarked that, for curvature to diameter ratios less than 3, the wake effect consequent upon flow detachment provides the highest contribution to the pressure gradient, while, contributions from secondary flows and bend length are less. In the converse scenario, the wall friction provides the highest percentage of the total pressure gradient in bends. It should be remarked that, the DR additives are generally associated with frictional pressure losses. On this basis, drag-reducing agents (DRAs) may impose different levels of DR in bends of different ratios of form to frictional drag. It has also been reported that flow redevelopment downstream of bends differ between Newtonian and drag-reducing fluid flows.

DR is a process of reducing pressure losses associated with flows. Additives, called DRAs, are often used for drag reduction. After the pioneering work credited to Tom, several studies have examined the effect of DRAs on liquid flows through straight pipes and channels of various orientations. A few others investigated this effect in curved pipes. Other methods of drag reduction involving pipe modifications such as riblets, dimples, wavering walls, and amenable surfaces are also common.

DR as originally defined by Savins is given by Equation (1).

\[
\text{DR(\%)} = \frac{\left( \frac{dp}{dl} \right)_s - \left( \frac{dp}{dl} \right)_{\text{DRA}}}{\left( \frac{dp}{dl} \right)_s} \times 100\% \tag{1}
\]

where \( \left( \frac{dp}{dl} \right)_s \) and \( \left( \frac{dp}{dl} \right)_{\text{DRA}} \) are frictional pressure gradients for solvent and DRA solution respectively, at equivalent throughput. Where the viscosity and density of solvent and polymer solution are almost the same, Equation (2) gives an equivalent measure of drag reduction.

\[
\text{DR(\%)} = \frac{f_s - f_{\text{DRA}}}{f_s} \times 100\% \tag{2}
\]

where \( f_s \) is the fanning friction factor before the addition of DRA, and \( f_{\text{DRA}} \) is the fanning friction factor after the addition of DRA.

\[
f = \frac{\tau_w}{\frac{1}{2} \rho U^2} \tag{3}
\]
The wall shear stress $\tau_w$ is given by

$$\tau_w = \frac{d\Delta p}{4l}$$

where $d$ is the internal diameter of pipe and $\Delta P$ is the frictional pressure drop over the pipe length $l$.

Equations (1) and (2) are referred to as pressure drop drag reduction and friction factor drag reduction.\(^{24}\)

A measure of drag reduction, in curved and straight pipes, called turbulence reduction drag (TRD) given by Equation (5) is sometimes used.\(^{25}\)

$$\text{TRD(\%)} = \frac{f_T - f_{T_{\text{DRA}}}}{f_T - f_L} \times 100\%$$

where $T$ and $L$ denote turbulent and laminar flow of the solvent, respectively.

The definition given by Equation (5) enables comparison of only the effect of DRA on TI in curved and straight pipes (that is, the level of flow laminarization achieved by the addition of DRA). In general, the difference between Equations (2) and (5), for straight pipes is small. However, the respective difference is large in the case of developed flow in curved pipes (such as coiled tubes) due to reduced TI consequent upon secondary flow effects.\(^{26,27}\)

DRAs also influence turbulent heat transfer.\(^{28-30}\) In certain applications, the effect of DRAs on heat transfer reduction outweighs its effect on drag reduction.\(^{31}\) Besides heat transfer and drag reduction, DRAs affect flow structure, phase-distribution, and flow regime transitions.\(^{32-38}\)

Until date, most of the drag reduction studies have focused on flows through vertical, horizontal, inclined, and undulated pipes. Application of DRAs for flows in curved pipes has received little attention. Moreover, the flow of single and multiphase fluids through curved pipes is a common occurrence in the petroleum and chemical industries. Such a flow are associated with large pressure drop and pressure fluctuations among other characteristics.\(^{5}\) It is important to gain insight into drag reduction in curved pipes to improve the economics of pipeline design and operation. A number of interesting reviews of DR studies carried out in straight pipes have been done.\(^{10,21,39-42}\) These reviews have highlighted the influence of DRA on turbulence statistics (Reynold shear stress, TI, streamwise, and wall-normal velocity fluctuations) and coherent structures (elliptical and hyperbolic strictures) in fully developed flows in straight conduits. These reviews have also discussed various approaches used in the assessment of DRA performance as well as the effect of DRA on mean axial velocity and frictional pressure losses for straight conduit flows. The effect of DRA on complex flows, such as flows in coiled tubes and bends, has been subject of research interest. It is important to provide a review of some important findings in the application of DRA in such flows. Fsadni,\(^{31}\) provided a brief review of pressure drop reduction studies for flow in helical coils. Besides this review, the authors are not aware of any other reviews pertaining to drag reduction in curved pipes. Hence this work is devoted to the review of existing research on single and two-phase drag reduction for flows through curved pipes.

## 2 DRAG REDUCTION IN CURVED PIPES

Virk\(^{43}\) published an extensive review on drag reduction in straight pipes. The paper highlighted some important aspects of drag reduction such as mechanism of polymer drag reduction, turbulence structure, and velocity profile. The work also pioneered the concepts of maximum drag reduction (MDR) and drag reduction envelop. The Virk’s envelop for polymer drag reduction in straight pipes is shown in Figure 1 on the Prandtl-Karman coordinates. Equations (6)-(8) give the equations for laminar flow, turbulent flow, and maximum drag reduction asymptote (MDRA). The maximum drag reduction law holds irrespective of polymer specie used, its concentration, or molecular weight.\(^{44}\)

$$\frac{1}{\sqrt{f}} = \frac{N_{Re} \sqrt{f}}{16}$$

$$\frac{1}{\sqrt{f}} = 4N_{Re} \sqrt{f} - 0.4$$

$$\frac{1}{\sqrt{f}} = 19N_{Re} \sqrt{f} - 324$$
Between the turbulent flow and the maximum drag reduction curves is a roughly linear polymeric regime characterized by the wall shear stress ($\tau_w$) and the increment in slope ($\delta$). This regime is represented by Equation (9).

$$\frac{1}{\sqrt{f}} = (4.0 + \delta)N_{Re}\sqrt{f} - 0.4 - \delta \left[ \frac{\sqrt{2d}}{v_3} \left( \frac{\tau_w}{\rho} \right)^{\frac{1}{2}} \right]$$

The centrifugal forces associated with flow in curved pipes results in secondary flows which appear in the form of vortices. Centrifugal force causes faster-moving fluids in the middle of the pipe to move to the outer wall while fluids in the outer wall to move to the center resulting in secondary flow. These vortices flow behavior results in flow fluctuations and sometimes higher-pressure gradient in curved pipes compared with that in straight pipes. The higher pressure drops observed for fully developed flows in curved pipes prompted Shah and Zhou to propose a modified Virk’s envelop. They replaced the Prandtl-Karman Law (Newtonian turbulent flow curve in Figure 1) with a Newtonian friction factor correlation for coiled tubing given by Srinivasan. Findings have revealed that MDRA for curved pipes is lower than that of straight pipes, and depends on the curvature ratio of the pipe. Shah and Zhou proposed an expression for MDRA for flow of drag-reducing polymers (DRPs) for fully developed flow in curved pipes as a function of curvature ratio given by Equation (10). Figure 2 shows the MDRAs for coils of various curvatures, as determined by Equation (10).

$$\frac{1}{\sqrt{f}} = AN_{Re}\sqrt{f} + B$$

where:

$$A = \left[ c_1 + c_2 \left( \frac{a}{R} \right)^{0.5} \right]^{-1}, \quad c_1 = 0.053109965, \quad c_2 = 0.29465004$$

and

$$B = \left[ c_3 + c_4 \left( \frac{a}{R} \right)^{0.5} \right]^{-1}, \quad c_3 = 0.0309447, \quad c_4 = 0.245746$$

when $\left( \frac{a}{R} = 0 \right)$, $A = 18.83$ and $B = 32.32$, and Equation (10) reduces approximately to the Virk’s MDRA.

Based on the redefined MDRA for curved pipes, Shah and Zhou described a new drag reduction envelop. This drag reduction envelop is bounded by three lines—the laminar flow line, the MDRA for curved pipe, and the zero-drag reduction line given by the Srinivasan correlation for Newtonian turbulent flow in curved pipes. The laminar flow correlation chosen for their work was that of Liu and Masliyah.
Studies have shown that phenomenological models for MDRA, developed for polymers, are not applicable to surfactants. An interesting characteristic of surfactants is their higher shear viscosity compared to polymer solutions. This makes surfactant solution more shear rate dependent and makes the definition of the Reynolds number all the more difficult. Zakin et al. showed that fanning friction factor curves of most surfactants in straight pipes lie below the Virk MDRA. They proposed an MDRA for surfactant solutions in straight pipes given by:

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

Their work did not account for how viscosity depends on the shear rate in surfactants. 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

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

Surfactant solutions exhibit higher MDRA than polymers. Kamel and Shah therefore extended Zakin et al.’s MDRA for straight pipes to curved pipes and proposed a correlation for MDRA for surfactant in coiled pipes given by Equation (13).

\[
f = \left[-32200.42 \left( \frac{a}{R} \right)^3 + 1830.62 \left( \frac{a}{R} \right)^2 + 0.32 \right] N_{Re}^{[7210.95 \left( \frac{a}{R} \right)^{-3} - 316.97 \left( \frac{a}{R} \right)^{-0.55}]}
\]

where \(N_{Re}^{[\text{Ref}]}\) is the Reynolds number of drag-reducing solution flow given by; \(N_{Re}^{[\text{Ref}]} = \frac{\rho_{DRA} U D}{\mu_{DRA}}\), \(\mu_{DRA}\) is the shear viscosity which is dependent on the shear rate.

They further suggested a modified maximum drag reduction envelop for surfactant in coiled pipes bounded by Liu and Masliyah’s equation for laminar flow, the Srinivasan et al. correlation and Equation (13).

### 2.1 Drag-reducing agents (DRAs)

DRAs include additives such as polymers, surfactant, fibers (insoluble polymers), and micro-bubbles. The use of polymer as a DRA is most common because only small concentrations are needed to produce significant drag reduction. DRAs can either be soluble or insoluble resulting in homogeneous and heterogeneous fluids mixtures, respectively. The benefits of DRAs include reduced operation cost and ease in application. Its application in oil and gas ranges from petroleum product transport to in-situ phase separation.

#### 2.1.1 Polymer DRAs

Polymer DRAs are grouped into synthetic and natural polymers. Examples of synthetic polymers include; polyethylene oxide, polyisobutylene, polyacrylamide (PAM), partially hydrolyzed polyacrylamide (HPAM), and so on. Synthetic...
polymers generally produce high percentage drag reduction. They are, however, mostly non-biodegradable thereby posing environmental challenges. Natural polymers include: carboxymethylcellulose (CMC), guar gum (GG), xanthan gum (XG), Aloe Vera, tragacanth, karaya, locust bean, chitosan, and okra.\textsuperscript{22,55,56} Natural polymers are biodegradable thus making them environmentally friendly.\textsuperscript{57,58} However, this biodegradability reduces their shelf life therefore reduces their effectiveness for long-distance transport. Grafting the artificial polymers into the rigid structures of natural polymers has been suggested as a means of controlling biodegradation.\textsuperscript{22,59-61} Recent advances in polymer technology have seen the rise in high performance biodegradable polymers. Some of the recent synthesis have been centered around improved cross-linking of polymer chains.\textsuperscript{62,63} A common characteristic of DRAs is the increase in efficiency with increase in molecular weight of polymer. A drawback of polymers DRAs is their susceptibility to both chemical and mechanical degradation. High molecular weight ($M_{\text{wt}} > 10^6$) polymers are the most commonly employed DRAs possibly because of their unique rheological properties, which make them effective and economical.\textsuperscript{22,64} Various theories exist seeking to explain the mechanism of polymer drag reduction. These theories include those based on shear thinning, viscoelasticity, vortex stretching, molecular stretching, flow anisotropy, and turbulence suppression.\textsuperscript{65,66}

A number of researchers have tried to explain the mechanism of polymer DR by molecular stretching of polymer molecules. In this model, the shear-hardening characteristic of DRPs is assumed to increase resistance to extensional flow, thereby inhibiting turbulent burst at the near wall region. The Lumley\textsuperscript{67} model, which is based polymeric chain extension, suggests that DR involves increased elongational viscosity. This results in increased thickness of the viscous sub-layer which dampens and suppresses small eddies and turbulent fluctuations. The overall effect is higher turbulence dissipation, reduction of both velocity gradient and shear stress near the wall, and consequently reduction of drag. It has also been suggested that stretching of polymer molecules results in the storage of elastic energy (see Figure 3A) emanating from flow very close to the wall.\textsuperscript{68} Thus, if there is sufficient relaxation time, the elastic energy is transported to the buffer layer and dissipated there by the vortex motion resulting in DR.\textsuperscript{69} Parallels between drag-reducing solution flow and Newtonian laminar-turbulent flow transition were drawn by Pereira.\textsuperscript{70} They tried to provide explanation to the cyclic mechanism responsible for the space-time dynamics (alternating active and hibernating turbulence) of such flows. According to them, one half of the cycle, in Newtonian fluid flow transition regime, involves an increase in perturbations until the active turbulence phase is attained.\textsuperscript{70} The formation of elliptical and hyperbolic structures, during active turbulence, is accompanied by higher velocity gradient (in the turbulent boundary layer). Consequently, there are higher viscous stresses which suppress turbulence by the weakening of the elliptical and hyperbolic structures. Velocity gradient reduces and the hibernating turbulence phase ensues. This phase is characterized by lower viscous stresses with increased potential for higher levels of perturbation.\textsuperscript{70} The analogy between drag-reducing solution flow and Newtonian laminar-turbulent transitional flow led them to suggest that viscous effects (Lumley’s theory) were predominant over elastic effects in drag-reducing flows. Contrary to Pereira,\textsuperscript{70} some investigators have suggested a greater influence of polymer elasticity with their description of elastic-inertia turbulence.\textsuperscript{71-73}

Transient and dynamic characteristics of drag-reducing solution flows have been explored in recent times to provide a description of the drag reduction phenomenon. One of such transient characteristics of drag-reducing solution flows...
flows is the shear layer (domain of high 2D vorticity and negative shear strain) reported by Zadrazil et al. This domain separates the flow into low and high momentum regions. Instantaneous velocity field data obtained from particle image velocimetry (PIV) showed gradual increase of instantaneous velocity for Newtonian fluid flow from the wall to the center of the pipe. The Addition of polymer separates the flow field into low and high momentum regions, evidenced by a sharp velocity gradient at the interface created by the shear layer. The extent of this transient domain was also reported to increase with molecular weight and concentration of the DRP. It however reported to decrease with flow rate. Qualitative analogies were drawn between shear layer thickness and the qualitative effects of DRPs leading to the suggestion that this transient domain was somehow linked to the mechanism of DR. Transient characteristics of drag-reducing solution and Newtonian fluid flows were also reported by Graham and co-workers. They characterized the turbulence regime into hibernating and active turbulence regimes. The hibernating turbulence regime is synonymous to maximum drag reduction and is characterized by negligible Reynolds shear stresses and significantly weak coherent structures. This transient behavior was linked to the weak dependence of maximum drag reduction on polymer properties such as size, geometry, and thermal stability. The longer duration of the hibernating turbulence regime led to them to suggest that the addition of DRPs results in the unmasking of the hibernating turbulence.

A number of proposed DRP drag reduction mechanisms are based on polymer's spring-like behavior. A bead-spring model was used by Armstrong and Jhon to describe the mechanism of DR. The polymer molecule is assumed to be a chain of identical beads linked by an arbitrary spring potential. Here the effect of the stochastic velocity field on the polymer molecule is associated with a renormalization of the connector potential and the dumb-bell probability density is derived for the arbitrary connector potential. At certain degree of turbulence, the second moment of the probability density becomes infinite. The renormalization of the connection potential between the beads reduces the connection force, thus making the beads extend (or polymer molecules expand). A mechanism analogous to the dumb-bell model wherein stretched polymer molecules are simplified as springs with masses at their ends was also proposed by Sher. The theory assumes that there is a balance between centrifugal stretching force and centripetal restoring force acting on rotating polymer chains. The rotational flow kinetic energy is converted to polymer elastic energy and subsequently becomes damped by the surrounding viscous fluids when the polymer relaxes.

A common view is that, turbulence suppression by DRPs (resulting in flow laminarization) is the main reason for its efficiency as a DRA. The complex rheological properties of DRPs such as viscosity and elasticity play important role in the process. The non-axial component of turbulent flows results in wasteful turbulent eddy dissipation and the impnication is increased drag. The ability of DRP to induce flow laminarization translates to reduction of wasteful energy dissipation and consequently DR. In effect, the action of DRPs in flow laminarization is to reduce radial velocity fluctuations and Reynolds stresses.

The anisotropic behavior of DRP solutions, where shear rate, structure, and viscosity of the solution are directionally dependent, have been used to explain polymer DR. Here the effect of DRPs is to alter the turbulence structure and reduce drag. Models based on the finite elastic non-linear extensibility-Peterkin (FENE-P) have also been used to quantify polymer DR. Here pre-averaging approximation is applied to a suspension of non-interacting finitely extensive non-linear elastic dumb-bells, thus accounting for the finite extensibility of the molecule.

A few numerical simulation studies have been carried out to shed more light on DR mechanism. In the Brownian dynamic simulation studies of Terrapon et al it was demonstrated that polymers experience significant straining around the vortices resulting in molecular stretching. As polymer molecules stretch around the vortices, by upward and downward fluid motion, there is extraction of energy from the near-wall vortices. Numerical studies have also been carried out to describe the systematic storage and release of energy to the flow by polymer. Energy storage occurs at the near-wall vortices, while the release of energy occurs at the very-near-wall region. Numerical studies were also used to show that polymer mixing acts as a relaxation mechanism for DR. Direct numerical simulation was used to investigate the roles of shear stress/shear rate anisotropy and elasticity on DR. The hypothesis is that, when polymer stretches, the viscous anisotropic effect produces change in turbulent structures and change in entropy which in turn results in DR. To shed more light on the mechanism of DR and explain certain observed behaviors, various studies have been carried out using laser Doppler velocimetry and PIV. An extensive review of PIV investigations of DR by additives can be found in Ayegba. Further details on the mechanism of polymer drag reduction and polymer degradation can be found elsewhere.

Overall, it appears that more than one of the suggested mechanisms is involved in DR. Notwithstanding the mechanism(s), polymers do stretch in the flow thereby absorbing the energy in the streak. This inhibits turbulent burst formation (Figure 3B) in the buffer region and results in turbulence suppression.
The above reports outlined some efforts to explain the DR mechanism via investigations of flows in straight pipes. Similar to straight pipes, DR by polymer solutions in curved pipes and channels have been linked with the dampening of turbulent intensities. A few suggested mechanisms for polymer drag reduction in the laminar flow regime of curved flow exist. The general understanding is that for DRAs to be effective in the laminar flow regime of curved pipe flows, there must be an interaction between the DRAs and secondary flow stream lines. A few early studies investigated the effect of DRAs on secondary flows but the conclusions are inconsistent and mostly speculative. Frictional losses as well as secondary flow losses contribute to pressure losses in hydrodynamically developed flows in coils. In the case of under-developed flows in and after bends, additional form-drag exists due to flow redistribution. It is speculated here that, DRP particle dynamics in curved pipe flows could have important influence on pressure drop profile of drag-reduced flows. Effort to describe the pressure gradient profile along bends and in the downstream tangent of bends of various bend angles was done by Ito. It was shown that there is a gradual increase in pressure gradient (expressed in terms of head loss) from the inlet to the outlet of bends. In addition, the head loss immediately downstream on the bend was shown to be significantly higher than the mean pressure gradient in the bends themselves. The evolution of pressure gradient and centrifugal forces along curved pipe flow has the potential of influencing DRP molecule distribution and ultimately the drag reduction at various locations along the bend as well as its downstream tangent. A preliminary investigation by the authors into polymer DR in U-bend showed reduced levels of DR across the bend and the downstream tangent relative to DR for fully developed flows in straight horizontal straight pipes. Furthermore, the effect of DRPs at various locations in and around U-bends is a subject of investigation by the authors using a dedicated flow loop at the University of California Berkeley.

2.1.2 | Surfactant DRAs

Surfactants are surface-active chemical agents of relatively low molecular weight, which alter the surface tension of the liquid in which it dissolves. They assume various structures in solution such as spherical micelles, rod-like micelles, crystals, emulsions, and vesicles depending on the concentration, temperature, salinity, and so on. The classes of surfactants are ionic (examples: anionic, cationic, and zwitterionic) and non-ionic surfactants. When compared to polymer they have higher resistance to mechanical degradation and are thermodynamically stable. This is due their ability to self-repair after degradation. The efficiency of surfactants in reducing drag depends on its concentration, temperature, geometry of flow channel, size of micelles, and bond strength. Some early researchers linked the mechanism of drag reduction by surfactants to the viscoelastic rheology of the solution. However, drag reduction has since been observed in non-viscoelastic surfactants. The ability of surfactants to act as drag reducers is associated with the formation of thread-like micelles. These micelles change the structure of turbulent flow at the near wall region. It has been suggested that surfactants drag reduction is achieved when micelles, under shear stress, line up in the direction of flow, and build a huge network structure (the so-called shear-induced state for cationic surfactants). This leads to a damping of radial turbulence and subsequently reducing pressure loss. Different surfactants show different response or characteristics under the influence of shear. For example, the viscosity of Habon G decreased under prolonged shearing or mixing while that of the mixture Ethoquad T 13/sodium salicylate (NaSal) increased after prolonged shearing in a rotational viscometer. The effective velocity range for which various surfactants produce drag reduction depends on the concentration and age of the surfactants. The effectiveness of surfactants as DRAs is negatively influenced by disturbances in the flow, though sensitivity of surfactants to disturbances differs. This is important in bend-flow applications where there are high disturbances resulting from the bend. As reported by Gasljevic and Matthys, additional drag results from the flow of surfactant solutions in the region of high flow disturbance after the bend.

Cationic surfactants are by far the most commonly used drag-reducing surfactants (DRS). Cationic surfactants combined with suitable counter-ions are effective drag reducers. The applicability of anionic surfactants in aqueous or hydrocarbon solutions depends on their molecular weight. In general, low-molecular weight surfactants are used as DRAs. Very low-molecular weight (<10 carbon atoms in chain) anionic surfactants are too soluble to have substantial surface effect and thus results in small drag reduction. The surface-active portion of zwitterionic surfactants carry opposing charges on it as well as a subgroup derived from imidazoline. Zwitterionic surfactants are more environmentally friendly than the cationic ones. However, at the recommended (low) concentration, they are very sensitive to upstream disturbances (as is common in bends) in the flow which may impede their drag-reducing capabilities. Non-ionic surfactants are known to be chemically, mechanically, and thermally stable in comparison with ionic surfactants. In addition,
non-ionic surfactants do not precipitate in the presence of calcium ions.\textsuperscript{52} Non-ionic surfactants are only applicable over a limited range of temperature and concentrations and may be susceptible to chemical degradation.\textsuperscript{22} Glycolic acid ethoxylate, Arquad 16-50 cetyltrimethylammonium chloride (CTAC), Ethoquad O12, Soya-$N\textsubscript{(CH}_3\textsubscript{3}Cl$, and sodium oleate are some examples of commonly used surfactants.\textsuperscript{22} Van der Plas\textsuperscript{106} recently defined some essential characteristics required by viscoelastic surfactants for them to be effective DRAs in petroleum applications. In general, micelle formation and rheological properties of surfactants are essential to understanding the mechanism for drag reduction of surfactant solutions. Also, due to the high shear stresses observed in curved pipes, surfactants are more suitable as DRAs for flow through bends than polymers.\textsuperscript{80} One draw back to the application of surfactants especially in commercial fluid transport is their corrosion tendencies. In general, surfactants are corrosive to steel pipes. For example, the effective range of application of anionic surfactants is within the acid range and this limits their application in steel pipes due to their corrosiveness.\textsuperscript{39} To ensure their commercial application, it is necessary to add corrosion inhibitors.\textsuperscript{107-110}

### 2.1.3 Micro-bubbles DRAs

The application of air in micro-bubbles drag reduction is environmentally friendly and cheaper compared to polymers and surfactants.\textsuperscript{111,112} Micro-bubbles have diameters less than 10 $\mu$m and exhibit behaviors different from those of larger size bubbles. These differences are seen in their chemical and physical characteristics such as the tendency to remain suspended in the liquid phase over longer periods of time.\textsuperscript{112} The first work published on the application of micro-bubbles as DRAs was by McCormick.\textsuperscript{113} The mechanism of drag reduction by micro-bubbles is not yet well understood. Similar to other drag reduction techniques, the purpose of micro-bubble injection is to alter the structure of the boundary layer. It had been suggested that micro-bubbles reduce drag by altering both laminar and turbulent boundary-layer characteristics.\textsuperscript{113} It has been reported that, injecting air bubbles results in an increase in kinematic viscosity and decrease in the turbulent Reynolds number in the buffer layer.\textsuperscript{114} This results in thickening of the viscous sub-layer and decrease in the velocity gradient at the wall. Hassan and Ortiz-Villafuerte\textsuperscript{111} used PIV to study the effect of injecting low void fraction micro-bubbles into the boundary layer of a channel flow. Some of their results showed some similarities with drag reduction behavior by polymers or surfactants as well as reports of some earlier investigations using micro-bubbles.\textsuperscript{114,115} These similarities include thickening of the buffer layer as well as upward shift of the log-law region. They remarked that the micro-bubble layer formed at the top of the channel was not responsible for the drag reduction recorded. This micro-bubble layer served to reduce the slip between the micro-bubbles and the liquid. The major contribution to drag reduction is the accumulation of micro-bubbles in a critical zone within the buffer layer. The interaction of micro-bubbles with turbulence in the buffer layer was associated to the observed DR. In general, injection of micro-bubbles reduces turbulent energies with the shear in the boundary layer remaining unchanged.\textsuperscript{116} There appears to be some agreement on the mechanism of micro-bubble drag reduction especially as it relates to thickening of the viscous sub-layer and turbulence suppression.

### 3 EFFECT OF POLYMER AND SURFACTANT DRAG-REDUCING AGENTS ON SINGLE PHASE PRESSURE GRADIENT

Several reports suggest that the effectiveness of DRAs is higher in straight pipes than in curved pipes.\textsuperscript{18,19,31} The reduced drag reduction in curved pipes, compared with straight pipe has been attributed to secondary flow resulting from the centrifugal forces.\textsuperscript{31} The lower drag reduction in curved pipes is the result of the differences between the extended laminar and extended turbulent flow friction factor curves which are much larger for straight pipes. This is based on the understanding that, for fully developed Newtonian fluid flow, the TI is lower in curved pipe and the straight pipe.

### 3.1 Polymer and surfactant DR in coiled pipes

A number of interesting reports on the application of polymers and surfactants as DRAs for flow through coils exist in open literature. In general, the effectiveness of polymers and surfactants in reducing pressure loss is dependent on pipe geometry, flow rate as well as type, concentration, and molecular weight of the DRAs. It also depends on temperature, presence of dissolved salts, and phase distribution before and after adding the DRA.\textsuperscript{105,117}
DR by surfactant DRAs in coiled pipes have generally been reported in the turbulent flow regime. While majority of investigations reported no DR in the laminar flow regime, a few others (eg, Gajšjčević and Matthys\(^5\)) reported increased drag in the laminar flow regime. The effect of surfactant DRAs on pressure drop/friction factor as reported by Aly et al\(^{31}\) is shown in Figure 4. They investigated the effect of oleylidihydroxyethylamineoxide (ODEAO) surfactant on single phase water flow in straight and coiled pipes. DR was observed in the turbulent flow regime as indicated by the reduction in friction factor with the addition of surfactant. They linked this to turbulence suppression by well-ordered network of rod-like micelles.

A few early reports on the effect of polymer DRAs for flow in curved conduits indicate a reduction in friction loss in the laminar and transition flow regime.\(^{92,118,119}\) Their results were, however presented in terms of fluid flux (not flow resistance). They all reported increased flow rate and reduced friction loss in the laminar flow regime. It should be stated that the percentage reduction in friction loss, in the laminar flow regime, reported by some early researchers were generally very small. The reports of limited drag reduction may be explained by the interaction of DRP with secondary flows in the laminar flow regime in curved pipes. In more recent investigations, using advanced instrumentation to study the effects of polymer DRAs on flow in curved conduits, DR was generally recorded in the turbulent flow regime.\(^7,19,46\)

### 3.1.1 Effect of concentration on drag reduction in coiled pipes

Reports on the effect of concentration of DRP on drag reduction for hydrodynamically developed flows in coiled pipes are quite conflicting. Some early investigations on the effect of DRP concentration on DR (eg, Kelkar and Mashelkar\(^{120}\)—12.5 mm internal diameter curved pipe/polyacrylamide polymer solution and Rao\(^{121}\)—9.35 mm internal diameter coil/Carbocol) reported decrease in friction factor (increase in DR) with increase in concentration. More recently, it was shown that the effect of DRP concentration on DR depends on the pipe diameter.\(^{8,45}\) For larger diameter pipes, higher concentrations resulted in lower drag reduction and even enhanced the drag at lower flow rates (see fig. 4 of Shah\(^{45}\)). In addition, higher concentration for the larger pipes delayed the onset of drag reduction. This becomes obvious when the plots are done on the Prandtl-Karman Coordinates (see fig. 7 of Shah\(^{45}\)). For smaller pipe diameter, Shah\(^{45}\) reported that higher concentration of polymer resulted in higher drag reduction.

Other even more recent studies did not investigate the coupled effect of concentration and pipe geometry, and the reports on the effect of DRP concentration on DR are rather inconsistent. For example, Zhou et al\(^6\) and Shah and Zhou\(^{46}\) reported higher DR when low concentration polymer was used in coiled pipes. However, reports of Shah et al,\(^7\) Gallego and Shah,\(^{122}\) and Kamel\(^{19}\) showed that DR in coiled pipes increased with concentration of DRAs until a peak value where further increase in concentration increased drag. Shah et al\(^7\) used 2-Acrylamido-2-methylpropane sulfonic acid (AMPS)-copolymer for their study as opposed to Xanthan used by Shah and Zhou\(^{8,45}\) and reported an optimum concentration of 0.07% by volume polymer. This concentration was employed in subsequent works by Gallego and Shah\(^{122}\) and Kamel.\(^{19}\) The optimum concentration recorded by Gallego and Shah\(^{122}\) for Nalco ASP-820 and Nalco ASP-700 were 0.05% and 0.03% by volume, respectively. However, the drag reduction recorded for these concentrations were very close to that of 0.07%.

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**FIGURE 4** Friction factor vs Reynolds number for water and ODEAO surfactant solution in both straight and coiled pipes. *Source: Reproduced from Reference 31 by permission from the American Society of Mechanical Engineers*
Reports on the effect of concentration on DR for surfactant solution flow in curved conduits are scanty. It has been reported that below a certain surfactant concentration in the turbulent regime, no drag reduction was observed. However, beyond this concentration, the percentage drag reduction increased with increase in concentration until a value of concentration beyond which no further drag reduction was achieved (Figure 4). The reason given for this (where further increase in concentration results in no further drag reduction) is the saturation of the network structure of the rod-like micelles. Therefore, further increase in concentration was ineffective in producing additional drag reduction. Plots of Inaba et al (f_C/f_SL vs N_{De}^*) shows a negative drag reduction for higher surfactant concentration at low Dean number N_{De}^*. However, at high Dean number it appeared that higher concentration of surfactant results in higher drag reduction. For both polymer and surfactant solution flows in coiled pipes at fairly high Reynolds numbers, most investigations reported an increase in DR with increase in concentration up to an optimum concentration beyond which further increase in concentration produces no further increase in DR.

3.1.2 Effect of flow rate on the drag reduction in coiled pipes

Similar to flow in straight pipes, drag reduction using polymer or surfactant DRAs in coiled pipes increases with increase in Reynolds number or flow rate (Figure 7A,B). In both straight and coiled pipes, the increase in drag reduction with flow rate is limited by critical shear stress above which polymer and surfactant DRAs degrade either permanently or temporarily. The difference in effectiveness (as defined by Equation (2)) of DRA in coiled and straight pipes reduces with increase in Reynolds number (Figure 5). Beyond the critical shear stress, drag reduction decreases with increase in flow rate (see Figure 7A,B). Similar to observations in straight pipes, Gasljevic and Matthys reported that there is no significant drag reduction in laminar flow regime in coiled pipes.

3.1.3 Effect of coil curvature ratio on drag reduction

The curvature ratio plays an important role in determining the friction losses in coils. In general, when polymer DRA is used, an increase in curvature results in a delay in the onset of drag reduction (Figure 6A,B). This is linked to the delay of turbulence with increase in curvature. Shah and Zhou proposed a correlation for determining the Reynolds number at the onset of drag reduction for polymer DRAs given by;

\[ N_{Re}^* = c_1 - \frac{c_2}{\left( \frac{a}{R} \right)^{0.5}}, \quad c_1 = 13172, \quad c_2 = 835.33 \]  

\[ (14) \]
The effectiveness of polymer DRAs generally reduces with increase in curvature (Figure 7A,B).\textsuperscript{7,27,46} In the case of surfactants DRAs, there is increase in friction factor with increase in curvature ratio and this is linked to increase in the intensity of secondary flows.\textsuperscript{9,31} For a special case of very low Reynolds number $N_{Re} < 25$, Robertson and Muller\textsuperscript{123} reported that extremely small drag reduction occurred and it increases with the curvature of the pipe. Their results require further investigation to be validated.

### 3.1.4 Effect of pipe diameter on drag reduction in coiled pipes

The effect of diameter on the effectiveness of DRAs in curves remain unclear. For the case of polymer DRA, the effect of curvature on effectiveness of DRAs is said to be more pronounced in small diameter pipes than in larger ones.\textsuperscript{16} Though further investigation is required, existing data show that the effectiveness of DRPs in small diameter pipes is higher than in larger ones. Coil diameter has been reported to influence the onset of drag reduction. However, for larger diameter coiled pipes, the onset of drag reduction tends to a higher generalized Reynolds number.\textsuperscript{8,45} Investigation on the effect of
pipe diameter on DR by surfactant DRAs is lacking and studies in this area could throw more light on the mechanism of surfactant DR.

3.1.5 | **Effect of temperature on drag reduction in coiled pipes**

Limited studies have been carried out to demonstrate the effect of temperature on the effectiveness of both polymer and surfactant DRAs. Reports show that the effect of temperature is more pronounced in straight pipes than in curved pipes of equivalent length.\(^{19,122}\) Conflicting reports exist on the effect of temperature on effectiveness of DRPs. While Kamel\(^{19}\) reported that DR was unaffected by temperature in coiled pipe flow, Gallego and Shah\(^{122}\) stated that DR decreased with temperature. Data from the limited studies available for flow of surfactant solution, in both straight and coiled pipes, show that, the range and maximum values of drag reduction increased with temperature.\(^{31,103}\) This is linked to the increase in critical wall shear stress associated with increase in temperature. These tests were, however, conducted over a limited range of temperatures (5°C-20°C) for both straight and coiled pipes. More research is required to establish the effect of a wider range of temperature for all drag-reducing agents.

3.1.6 | **Effect of pipe roughness on drag reduction in coiled pipes**

Pipe roughness is expected to have appreciable effect on DR since it is likely to affect both velocity fluctuations and degradation of polymer and surfactant DRAs. It has been reported that the mechanism that sustains turbulence in smooth and rough pipes are quite different.\(^{124}\) Due to the limited studies in this area, the effect of pipe roughness on DR it remains unclear. In the case of straight pipe flow of DRPs, Karami and Mowla\(^{125}\) reported increased DR with increase in pipe roughness, while in a rectangular open channel Petrie et al\(^{126}\) observed a decrease in DR with pipe roughness. This discrepancy is not entirely surprising. The increase in percentage DR with pipe roughness reported by Karami and Mowla\(^{125}\) could be explained by increased velocity fluctuation and turbulent mixing with increase in pipe roughness. In smooth pipe flows increase in Reynolds number is often associated with increase in velocity fluctuation and turbulent intensities. It has been reported that, below critical wall shear, percentage DR increases with Reynolds number.\(^{6,8}\) Therefore, one would expect an increase in percentage DR with increase in velocity fluctuation and turbulent mixing associated with increased pipe roughness. On the other hand, increased pipe roughness could also increase the rate of polymer degradation within the channel. The implication of this would be reduced percentage DR with increase in pipe roughness, especially for high Reynolds number flows. Since increased turbulent intensities/velocity fluctuation and increased DRA degradation could result from flow over rough surfaces, the dominant of the two would most likely determine whether there is increased or reduced DR with roughness. Gallego and Shah\(^{122}\) reported that, for the flow of DRPs, the effect of pipe roughness was more pronounced in curved pipes than in straight pipes. Their plots showed that pipe roughness results in decrease in DR in coiled pipes. This might be associated with increased shear in curved pipe flow when compared to straight pipe flow which in turn results in degradation of polymer chains.

3.1.7 | **Effect of polymer and surfactant DRAs on pressure drop for single phase flows in bends**

Flow through bends exhibits a more complex geometry than flow in coiled pipes. This is because of entry and separation effects coupled with the idealized flow similar to that in coiled pipes. The disturbance generated at the bends, increases the downstream flow redevelopment length. The redevelopment for surfactant solutions, for example, has been reported to be slower than that of water (more so at high Reynolds number).\(^{5}\) The slower redevelopment for flow of surfactants compared to water introduces added drag which reduces the overall DR.\(^{5}\) This additional drag effect is linked to flow redistribution. It has been reported that, for flow of surfactant solutions through threaded elbows there is significant drag reduction within the bend but not in the redeveloping section downstream of the threaded elbow.\(^{5}\) The report indicates that, although there is drag reduction in the bend, the overall effect of flow redevelopment is overbearing on the drag reduction. One may deduce from the work of Gasljevic and Matthys\(^{5}\) that, drag effects in the elbow are linked to the influence of the surfactant on flow separation and reattachment. There are limited studies on
the influence of DRPs on flows in bends. Although the action of both DRP and DRS on fluid flows share significant number of similarities, the mechanisms of DR differ. Also, the concentration of DRP required for significant level of drag reduction is relatively small. This may translate to difference in flow development behavior between DRP and DRS and by extension difference in the influence of both classes of DRAs on bend-effects such as wakes. Ayegba et al.\(^3\) investigated the influence of DRP on single-phase water flow in U-bend of internal diameter 20 mm and bend radius of 150 mm. They reported lower DR in the bend and the under-developed flow section downstream of the bend relative to hydrodynamically developed straight pipe flow. They remarked that, the DRP was more effective in reducing frictional drag and less effective in reducing losses resulting from secondary flows in the bend as well as losses resulting from form drag downstream of the bend (Figure 8A). Their results also showed very limited influence of bend orientation (horizontal or downward flow in bend) (Figure 8B). Several questions remain among which are the effect of bend curvature, the effect of polymer molecular weight, as well as the action of DRPs on various levels of flow development among others.

### 3.1.8 Effect of DRAs concentration on pressure drop in bends

There are limited reports in open literature on the effect of DR concentration on DR in bends. Munekata et al.\(^{127}\) investigated the flow of surfactant solution, cetyl trimethylammonium bromide (CTAB) in 90° square-cross-section bend where reduced drag reduction as well as delayed onset of drag reduction with increase in concentration was reported. Only two concentrations were tested and so no conclusion could be drawn. Their plots showed reduced critical Reynolds number (or flow velocity) with decrease in concentration. DR over a combined section consisting of U-bend and the under-developed flow section downstream of the bend was reported to increase with polymer concentration until an optimum concentration beyond which further increase in concentration produced no further increase in DR.\(^3\) The difference in the results of Munekata\(^{127}\) and that of Ayegba\(^3\) could be linked to the fact that lower concentration of DRP was used (0-40 ppm) compared to surfactant (100 and 300 ppm). In particular, the rheological properties of the solution such as density and shear viscosity are significantly affected by DR concentration. This difference in the rheological properties is expected to have significant impact on form drag (consequent upon flow redistribution). Notwithstanding the limited literature in this area, DR concentration is expected to impact DR efficiency since concentration can influence flow redevelopment and the overall ability of the DRA to suppress turbulence.\(^5\)

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**FIGURE 8** Flow of water and 10 ppm HPAM solution in horizontal straight pipe and in U-bend: (A) P-K plots (B) DR vs Reynolds number. fs, fch, and fcd are friction factors for straight pipe, U-bend in horizontal configuration, and U-bend in downward flow configuration respectively. DRch and DRcd are calculated drag reduction for horizontal and downward bend configurations, respectively. Source: Reproduced from Reference 3 licensed under CC-BY
3.1.9  |  Effect of curvature on effectiveness of DRAs in bends

Bend angles and curvatures are known to influence centrifugal forces in the bends and consequently affect fluid redistribution in and around the bend. While in coils, increased curvature delays the onset of turbulence and suppresses turbulence, in the case of bends, increased curvature may result in increased flow fluctuations, even under laminar flow conditions. There are contracting reports from the limited studies that have been carried out to investigate the effect of curvature ratio hence, its effect remains unclear. For low Reynolds number flows, Jones and Davies\textsuperscript{128} reported that the effect of curvature on drag reduction is negligible. Nonetheless, the observed drag was higher than that which occurred in straight pipes. Yokoyama and Tomita\textsuperscript{96,129} studied the flow of polyethylene-oxide in a 360° bend of varying curvature ratios. They recorded a decrease in drag reduction with increase in curvature ratio. The drag reduction recorded was predominant at high Reynolds numbers. Only three curvatures were tested and so the effect of curvatures on the effectiveness of DRAs in 360° bends was inconclusive. In the knowledge of the Authors, the effect of curvature ratio for flow in 45°, 90°, and 180° bends had not been reported in open literature. Another area of interest is in determining the effect of pipe diameter on drag reduction in elbows. This is because, the effect of flow separation is expected to reduce with increase in pipe diameter.

3.2  |  Effect of micro-bubble injection on pressure drop for single phase liquid flow

Application of micro-bubbles for DR in curved pipe flows have received little scholarly attention and the effect of micro-bubbles on pressure losses as well as the mechanism of micro-bubble DR remain unclear. It was highlighted earlier that, the action of micro-bubbles on turbulent flows is similar, in a number of ways, to that of polymers and surfactant DRAs. To this end, it is expected that micro-bubbles will result in significant DR in curved pipe flows. The application of micro-bubbles for drag reduction in helical coils was first carried out by Shatat et al\textsuperscript{112} and Shatat et al\textsuperscript{130} using hydrocyclone effect to generate micro-bubbles. Their investigation involved three helical coils of curvature ratios 0.025, 0.05, and 0.1. They reported that, though there was significant drag reduction in helical coils by injection of micro-bubbles, this drag reduction was less than that in straight pipes under similar conditions of flow. The reduced drag reduction in helical coils was linked to centrifugal forces (resulting in suppressed turbulence) associated with the flow. Though the theories for micro-bubble drag reduction in helical coils are in agreement with existing micro-bubble DR theories for other geometries, further research is needed to establish these theories. The effect of various parameters such as pipe geometry, micro-bubble fraction, flow rate, and micro-bubble size remain unclear due to the limited research in this area. Based on the limited data available, only a brief outline of the effect of these parameters is presented in this review.

3.2.1  |  Effect of curvature ratio on micro-bubble drag reduction in curved pipes

Figure 9A gives an illustration of the effect of curvature on effectiveness of micro-bubble drag reduction in helical coils. It can be observed that increase in curvature resulted in decrease in drag reduction as well as a shift of both the onset of drag reduction and maximum drag reduction to higher values of Reynolds number. The figure also shows higher drag reduction in straight pipes compared to helical coils. Though there is limited data on the effect of curvature, two important hydrodynamics properties may play important roles: first, unlike flows of polymer and surfactant solutions in curved pipes, gravity/centrifugal forces may result in significant phase separation (micro-bubble and liquid phases) for the case of micro-bubble DR. In the case, the concentration distribution of micro-bubbles (particularly in the buffer region where it is most effective) becomes inhomogeneous and this has the potential of reducing DR efficiency; second, the curvature effects in coils is expected to suppress turbulence and thus it should be expected that the percentage DR is affected by the degree of curvature. Further study is, however, required to fully investigate the effect of curvature ratio on drag reduction in curves.

3.2.2  |  Effect of micro-bubble fraction on drag reduction in curved pipes

The effect of micro-bubble fraction is illustrated in Figure 9B. It can be seen that the effect of bubble fraction on the onset of drag reduction is insignificant. However, the bubble fraction has a profound effect on the percentage drag reduction
FIGURE 9 Drag reduction vs Reynolds number for flow of water in helical coils with the injection of micro-bubbles. \( \alpha \) is the fraction of air in the coil. (A) change in curvature ratio (B) change in air fraction. Source: Reproduced from Reference 112 by permission from the Japan Society of Mechanical Engineers

and the range of Reynolds numbers over which drag reduction occurs. In general, the percentage drag reduction increased with increase in bubble fraction. Again, additional data are needed in order to understand the effect of micro-bubble fraction on drag reduction since very scanty reports are available.

3.2.3 Effect of flow rate on micro-bubble drag reduction in curved pipes

Similar to flow of polymer and surfactant solutions in curved pipes, where DR is reported predominantly in the turbulent flow regime, the limited reports on the application of micro-bubbles in curved pipe DR also report DR in the turbulent flow regime. Since the degree of turbulence increases with increase in flow rate, it is expected that flow rate will affect the efficiency of micro-bubble DR. It can be seen from Figure 9A,B that drag reduction occurs above a critical Reynolds number and increases with Reynolds number until a maximum drag reduction is achieved. Further increase in Reynolds number results in decreased drag reduction. At very high Reynolds numbers, there is increased centrifugal forces resulting in phase separation (with higher bubble concentration at the inner wall where the wall shear stress is lower).

3.2.4 Effect of micro-bubble size on drag reduction in curved conduits

In the knowledge of the Authors, no published research is available that investigates the effect of micro-bubble size on DR in curved pipes. There is therefore need for more research to enhance understanding of any possible effect of micro-bubble size on DR. In the application of micro-bubbles as DRAs for straight channel flow, conflicting reports exist on its effect on DR. It suffices to say, however, that bubble behavior is size dependent, thus DR is expected to be influenced by micro-bubble size. In general, small sized bubbles will be better retained in the liquid under the action of centrifugal forces. Hence, it would be expected that the smaller the size of the bubbles the more effective it’ll be as a DRA.

3.3 Effect of polymer and surfactant DRAs on fluid flux in curved pipes

A number of early researchers chose to present their results in terms of flow rates rather than drag. The limited studies in this area have focused on the application of polymer DRAs in curved pipe flows. There appears to be an agreement among the limited reports that addition of DRPs results in increased flow rate particularly at low and moderate Dean numbers.
Barnes and Walters\textsuperscript{92} reported that, for fully developed turbulent flows in curved pipes, there is decrease in flow rate after adding polymer. It was suggested that the suppression of turbulence may have an adverse effect on the flow rate at high Reynolds numbers. Given that a number of recent studies have reported DR in the turbulent flow regime, it is possible that the polymer used in that study has degraded at the turbulent flow conditions studied. They also reported an increase in flow rate with increase in polymer concentration and a negligible influence of pipe curvature on the effectiveness of the DRPs in the laminar and transition flow regimes. Though further research is required to understand the effect of fluid characteristics and pipe geometry on the flow rate of DRAs, the limited research available suggest that flow rates would increase in the region of DR.

3.4  |  Secondary flow in bends and coiled pipes

The secondary flow observed for the flow of Newtonian fluids in bends and coiled pipes result from centrifugal forces associated with such flow. The secondary flow of spiral form superimposes on the axial primary flow and there is also reduction in flow rate as a result of higher dissipation resulting from secondary flow compared to primary flow. The maximum axial velocity in bends and coiled pipes is shifted to the outer side of the curve. As Dean number increases the secondary flow become more confined to a thin area near the pipe wall\textsuperscript{27,133}

3.4.1  |  Effect of DRAs on secondary flow for fully developed single phase flows in curved pipes

It has been suggested that DRAs would have an effect on secondary flows.\textsuperscript{5} At high flow rates, the secondary flow field can be categorized into two regions. These are the shear free mid-region and the offside boundary layer region.\textsuperscript{103} The non-Newtonian characteristic of fluid changes the thickness of the shedding layer. For pseudo-plastic fluids the shedding layer becomes thicker, whereas for dilatant fluid flow it is thinner than that of Newtonian fluids. This thickening or thinning effect may, to a small or large extent, alter the secondary flow. Figure 10A shows the paths of fluid particles projected on the cross section of the pipe. The extremes of $m = 1$ and $m = 0$ represent viscoelastic and Newtonian viscous liquids respectively. It is seen from the figure that, the effect of elasticity (measured roughly by $m$) on the projected streamlines is small. However, the neutral point for the viscoelastic liquid is slightly nearer to the outer edge of the pipe compared to that for the Newtonian liquid.

The elasticity of the liquid has a profound effect on the pitch of the spirals in which the liquid particles move along the central plane (Figure 10B). Figure 10B shows that a decrease in $m$ leads to a major increase in the curvature of the streamlines in the central plane. The main effect of elasticity on the flow of viscoelastic liquids through a curved pipe is to decrease the curvature of the streamlines in the central plane and to increase the fluid flux through the pipe.\textsuperscript{92,134}

\textbf{Figure 10}  \hspace{1cm} (A) Particle paths projected on the cross-section of flow for $m = 1$ (full line) and $m = 0$ (dash line). $N$ and $N'$ represent neutral points for $m = 1$ and $m = 0$ respectively. (B) Paths of particles in the central plane for varying $m$. Source: Reproduced from Reference 134 by permission from Cambridge University Press
For a third-order fluid (see Coleman and Noll\textsuperscript{135}), Jones\textsuperscript{118} presented correlation (Equation (15)) for the streamline function, which describes the secondary flow in the cross-section of curved pipes.

\[
\psi = \frac{2La_1}{\rho a} \left[ \left( \frac{1}{144} + \frac{a'_3}{48} \right) r_1 - \left( \frac{1}{64} + \frac{a'_3}{24} \right) r_1^3 + \left( \frac{1}{96} + \frac{a'_3}{48} \right) r_1^5 - \frac{r_1^7}{576} \right] \cos \alpha
\]  

Equation (15) indicates that, for third-order fluids, the non-Newtonian effect on secondary flow streamline could be associated mainly to the elastic behavior ($a_3$) of the fluid.

It has also been suggested that an analogy existed between the counter-rotating secondary flow vortex, superimposed on the primary flow in curved pipes, and the vortex pair at the near wall region of turbulent shear flow in straight pipes.\textsuperscript{94} Since drag reduction is predominant in the near wall region where the flow is primarily a shear flow, it is suggested that any mechanism that results in this phenomenon would also affect the secondary flow in curved pipes, at least in the laminar flow regime. It should be stated here that this assumption relies on the notion that secondary flow, like turbulent flow, is dissipative. Though a few other studies\textsuperscript{121,136,137} made brief mention of the effects of DRAs on secondary flows, there is insufficient data from which concrete conclusions can be drawn.

### 3.4.2 Effect of DRAs on secondary flow in under-developed bend flow

There are very few studies on the effect of DRAs on secondary flows in bends and though the limited reports agree that such effects exist, there is no clarity on whether DRAs suppress or enhance secondary flows. In the study carried out by Jones and Davies\textsuperscript{128} using very dilute polyacrylamide and Kezan solution, the onset of non-Newtonian effects was around Dean number of 300. This is the region where secondary flow with a Newtonian fluid is sufficiently strong enough to cause appreciable deviation from \textit{Poiseuille flow}. Munekata et al\textsuperscript{127} in their study of viscoelastic fluid flow in square-section elbow bends suggested that centrifugal effects are suppressed by viscoelastic effect of the fluid flow. They reported that secondary flow for Newtonian fluids increases gradually downstream while for viscoelastic fluids it decreases slightly resulting in DR. Their result was not corroborated by any other research findings, and further study is therefore required.

### 3.5 Flow transition and critical Reynolds number in bends and curves of circular cross-section

Studies show that, flow regime transition in curved pipes occurs at much higher Reynolds number than in straight pipes. There is also delayed onset of turbulence with increase in curvature. Taylor\textsuperscript{138} in one of the early researches in this area showed that streamline motion persisted to Reynolds number of about 6000 in curved pipe of $a'/R = 1/18$. The mechanism by which turbulence is produced in curved flow varies with the location in the curves.\textsuperscript{139} Turbulence near the inner wall results from gradual superposition of higher order frequencies on the fundamental frequency. On the other hand, turbulence, near the outer wall, results from high frequency bursts near the outer wall. The sinusoidal oscillations near the inner wall always precede the turbulent bursts.\textsuperscript{27} The transition region for flow of Newtonian fluids in straight pipes is associated with violent bursts which is not the case in curved pipes. Also, the pressure fluctuation for fully developed turbulent flow in curved pipes is relatively damped.

#### 3.5.1 Effect of DRAs on flow transition and critical Reynolds number

The transition from laminar to turbulent flow regime in curved pipes is gradual and sometimes difficult to identify. This transition is even more gradual in the case of non-Newtonian drag-reducing fluid flow in curved pipes.\textsuperscript{8,45,140} A delayed and gradual transition from laminar to turbulent regime occurs for flow of DRAs through curved pipes.\textsuperscript{31} Two factors could be responsible for this: turbulence suppression in curved flow geometry, and effect of DRA on flow transition. Effect of DRAs on flow transition in curves and bends depends on the curvature of the bend and concentration of DRA. Figure 4 shows that the critical Reynolds number decreases with curvature and increases with concentration of surfactant.
Transition to turbulent flow occurred when the wall shear of the DRA exceeded the critical wall shear stress under strong mechanical load at high Reynolds numbers.

The critical Reynolds numbers also depend on the temperature especially in the turbulent regime. In separate experiments conducted by Inaba et al. and Aly et al. using surfactants in the temperature range of 5°C-20°C, it was observed that critical modified Reynolds number $N'_{Re, crit}$ increases with increase in temperature. This is associated with the critical wall shear stress at the wall which increases with temperature.

### 3.6 Friction factor correlations for single phase flow in curved pipes

Several theoretical and empirical models are available for predicting friction factor of non-Newtonian fluids through curved pipes. In majority of the correlations, friction factors are simple functions of the Dean number and curvature ratio, $a/R$, of the pipe. In general, at low Dean number the friction factor can be defined as a sole function of Dean number, $N_{Dn}$. At higher Dean numbers, the frictional characteristic of flow not only depends on $N_{Dn}$, but also on $a/R$. Most of these correlations appear in the form of ratios of friction factors in curved pipes to that in straight pipes at similar conditions. On the bases of DR mechanism based on action of fluid viscoelasticity on turbulence, quantification of DR is sometimes related to the Deborah number ($N_{De}$) which is defined as:

$$N_{De} = \frac{\text{characteristic fluid time}}{\text{characteristic flow time}}$$  (16)

The characteristic flow time is derived according to the chosen mechanism of DR. Where it is assumed that the main effect of DR is to make the energy dissipation conservative (frequency of energy-dissipating eddies is higher than the inverse of fluid time), the characteristic flow time is defined as the inverse of energy-dissipating eddies ($\omega$).

$$w = U^2/\rho = \left\{ \begin{array}{ll}
& \left( \frac{U}{a} \right) N_{Re}^{0.8} \\
& (a/D)^{0.1} \left( \frac{U}{a} \right) N_{Re}^{0.8}
\end{array} \right. \text{ straight pipe}
\left\{ \begin{array}{ll}
& \left( \frac{U}{a} \right) N_{Re}^{0.8} \\
& (a/D)^{0.1} \left( \frac{U}{a} \right) N_{Re}^{0.8}
\end{array} \right. \text{ coiled pipe}
$$

$$N_{De} = \left( \frac{U^2}{\rho} \right) T = wT$$

where $U$ is the mean axial velocity, $a$ is the tube diameter, $D$ is the coil diameter, $\nu$ is the kinematic viscosity, and $T$ characteristic fluid time.

### 3.7 Fluid flux correlations for single phase flow of non-Newtonian fluids in curved pipes

Several theoretical and semi-theoretical solutions to the governing equations of flow in curved pipes have resulted in series equations for fluid flux. Most of the theoretical correlations proposed for fluid flux in curved pipes are functions of material constants ($\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_5$, $\beta_1$, and $\beta_2$). The normal stress difference for flow in curved pipes involve $\alpha_2$ and $\alpha_3$ only and the term ($\alpha_5 + \beta_1$) represents the departure from a constant viscosity. For straight pipe flow the flux is determined by the viscosity constant $\alpha_1$, $\alpha_5$, and $\beta_1$ and is independent of normal stress terms $\alpha_2$ and $\alpha_3$. The material constants are also expressed as, $\alpha_2' = \frac{a_2}{(\rho \omega)^1}$, $\alpha_3' = \frac{a_3}{(\rho \omega)^1}$, $\alpha_5' = \frac{a_5}{(\rho \omega)^1}$, and $\beta_1' = \frac{\beta_1}{(\rho \omega)^1}$. Others presented their correlations for flow rates as functions of Weissenberg number, $N_{We}$, Reynolds number, $N_{Re}$, and ratio of polymeric to shear viscosity, $\mu_p/\mu$.

In the friction factor correlation of Robertson, the Reynolds number and Weissenberg number are given by Equations (19) and (20) respectively.

$$N_{Re} = \frac{\rho W_o R_o}{\mu}$$

$$N_{We} = \frac{\lambda W_o}{R_o}$$

$$W_o = \frac{Gr_o}{4\mu}$$

(21)
where $\lambda$ is the fluid relaxation, $W_o$ is the maximum axial velocity for flow in straight pipe, $\mu_p$ is the polymeric viscosity, $\mu$ is the total shear viscosity, $\rho$ is the constant fluid density, and $r_o$ is the radius of the pipe. More details on the choice of dimensionless number for the modeling of viscoelastic fluid flow can be found in Robertson.\(^{123}\)

### 3.8 Two phase flow in curved pipes

Limited reports are available in open literature on the effect of DRAs on gas-liquid flow in curved conduits. In the knowledge of the authors, no report is available in the public domain that investigates the effect of DRAs on liquid-liquid flows in curved pipes. Unlike the flow of gas-liquids in curved pipes, two-phase liquid-liquid flows in curves and bends have received little attention till date. Research has shown that liquid-liquid properties such as density, viscosity, and interfacial tension have profound effects of pressure drop and flow pattern characteristics.\(^{16,147-150}\) It has also been established that flow patterns and fluid characteristics such as interfacial tension play important role in determining the effectiveness of drag-reducing agents.\(^{152,153}\)

#### 3.8.1 Effect of DRAs on gas-liquid flows in curved pipes

Though there is limited literature on the flow on gas-non-Newtonian fluids in curved pipes, a reasonable body of knowledge exist for the case of Gas-Newtonian fluid flows in curved pipes. A few reports on the flow of air-CMC solution in helical coils have shown that the CMC solution has a significant influence on both in-situ volume fraction and pressure drop.\(^{154}\) Pressure drop reduction was reported by Mujawar and Rao\(^{154}\) when the drag coefficient approach\(^{155}\) was used for analysis but not when the Lockhart and Martinelli\(^{156}\) approach was used. This highlights the limitations to the applicability of these correlations for predicting gas-non-Newtonian liquid flows. Some more recent reports on air-sodium salt of carboxymethylcellulose (SCMC) systems have shown that polymer concentration, pipe curvature, pipe diameter, and to a lesser extent helical coil pitch does influence frictional pressure losses, phase distribution, and liquid holdup of gas-liquid flows in helical coils.\(^{157-159}\) Although the objective of these studies was not to determine DR, useful information on DR can be derived from them. It is important to state here that SCMC solutions can behave as pseudo-plastic, dilatant or thixotropic fluids depending on the concentration and temperature of the polymer solution.\(^{160}\) In general, however, it behaves as a shear thinning (pseudo-plastic) fluid at low concentrations (<1 wt%). This behavior probably explains the results of Biswas and Das\(^{157}\) where an increase in frictional pressure loss with increase in fluid viscosity (increase in concentration) was reported. The implication of the result is that DR (if any) occurs at low polymer concentration. In a separate report that focuses on mass transfer characteristics of air-SCMC solution in helical coils, it was reported that mass transfer ($k_t$) was higher for Newtonian water flow than for SCMC solution and it decreases with SCMC concentration.\(^{159}\) Since mass transfer is proportional to frictional force,\(^{161,162}\) it may be inferred that the frictional force in water was higher than that of SCMC at the test concentration of <3 kg/m² used in that study. The effective viscosity for shear thinning liquids is higher when it flows as a single-phase liquid in coils than when it flows together with gas.\(^{162}\) This is due to the higher shear rates for two-phase gas liquid flows compared to the simple shearing flow of single-phase liquid flow. The implication of this is higher drag reduction than single phase flow of polymer solution due to reduced effective viscosity. It may be deduced that for shear thickening liquids lower drag reduction would be obtainable in two-phase flow compared to single phase flow (though no research is available to confirm this postulation).

Besides the effect of DRAs on pressure drop and velocity profiles in gas-liquid flows, the addition of DRAs has been reported to have significant impact on phase distribution by inducing phase separation. The effect of DRAs on phase distribution of gas-liquid flows in straight conduits is well documented and can be found in review papers of Al-Sarkhi\(^{36}\) and Abubakar.\(^{21}\) In general, adding DRAs to gas-liquid flows results in delayed transition from stratified to slug flow; changes in flow pattern from slug and annular to stratified flow; reduced liquid entrainment in the gas-core of annular flow regime; dampening of interfacial waves; and changes in liquid holdup.\(^{21,35,162-167}\) One interesting effect of DRAs on gas-liquid flows in the slug flow regime is the reduction in flow instabilities and fluctuations which are characteristic of slug flow.\(^{21,35,165,166}\) Al-Sarkhi\(^{36}\) attributed this to less liquid circulation in the slug flow regime due to the addition of DRA. The elimination of slug flow regime by the addition of DRAs to gas-liquid flows has been given as the reason for the lower corrosion rate when DRA is added to such flow.\(^{165,168-170}\) Abubakar\(^{21}\) remarked that, the changes in flow pattern from annular to stratified flow could be the result of the elimination of disturbance waves and reduction in liquid entrainment.
by the addition of DRA. Although, similar effect of DRAs on phase distribution can be expected in fully developed flows in curved conduits (such as long-length coiled pipes), very limited work has been done on the effect of DRAs on phase distribution in curved conduits. It should be remarked that the centrifugal forces in curved pipes also imposes significant phase separation on two-phase flows and this centrifugal effect on phase distribution is likely to surpass that resulting from the addition of DRA. Thandlam et al\textsuperscript{158} studied flow pattern transition of gas-liquid flow in helical coiled tube. They reported that stratified flow (ST) regime of air-SCMC solution occupied a larger region of the flow pattern map compared to air-water flow. The implication of this changes of other flow patterns to stratified flow pattern by the addition of DRA. Although, at the time of this report, investigations into the effect of DRAs on gas-liquid flows in bend could not be found, it is speculated here that any such effect would be more complex. This speculation is based on the complex flow behavior exhibited by bend flows due to the under-developed nature of the flow and its downstream tangent. Clearly further research is needed to investigate the effect of DRAs on gas-liquids flows in curved pipes.

The application of DRA for drag reduction in pipeline transport of rich gas has also attracted some research interest. The reason for this is because, rich gas in its dense phase exhibit some similar properties of liquid.\textsuperscript{171,172} Research in this area have been mostly limited to commercial application in long distance transport of rich gas and at the time of this report investigation into the effect of rich DRAs on drag reduction of rich gas in curved conduits could not be found in open literature.

\section*{4 KNOWLEDGE GAP}

The review revealed key findings that go a long way in answering questions regarding the effects of DRPs, surfactants, and micro-bubbles for flows in curved pipes. However, certain research gaps were identified particularly in the area of two-phase liquid-liquid drag reduction in curved pipe flows.

\subsection*{4.1 Single phase flow in curved pipes}

Several studies have been carried out to investigate the non-Newtonian effects of DRAs in single phase liquid flow in curved pipes. However, some research gaps remain. Some of the areas where further works are needed are outlined below:

\begin{itemize}
  \item [i.] Further studies are required to investigate the effect of DRAs on secondary flows. Understanding of the mechanism of interaction of polymer and surfactant macromolecules with secondary flow streamlines could provide answers to the reported trends in the laminar flow regime.
  \item [ii.] In the case of under-developed flow in bends, the effect of DRAs on flow separation and reattachment is not yet understood. The reduced drag reduction in bends (compared to developed coiled pipe flow) has been linked to flow separation and reattachment. Therefore, insight into the effect of DRAs on flow separation and reattachment could provide answers to this observation.
  \item [iii.] The use of non-intrusive measurement techniques for the capture of coherent structures in curved pipe flows are limited in open literature. Considering the significant effect of DRAs on coherent structures, there is need for future studies to focus on the interaction of these additives with coherent structures.
  \item [iv.] Most of the existing researches on drag reduction in curved pipes are centered on coils. Limited studies have been carried out to investigate the effect of DRAs for flows in bends. In particular, research is needed to investigate the effect of bend angles on drag reduction.
  \item [v.] Detailed study of the effect of pipe diameter on the effectiveness of polymer, surfactant, and micro-bubble drag reduction is required.
  \item [vi.] Recent reports in straight pipe flows have revealed important effects of DRA on hibernating turbulence\textsuperscript{76} and shear layer formation.\textsuperscript{74} These findings have not been reported for curved pipe flows. Numerical studies and non-intrusive measurements of flows in curved pipes could shed light on these characteristics of drag-reducing flow.
  \item [vii.] Recent studies in straight pipe flow has faulted the description of transition as simply a change from linear to non-linear dynamics. It was shown in this review that transition behavior in curved pipe shows marked difference from those of straight pipes. Pereira\textsuperscript{70} recently reported striking similarities between laminar to turbulent flow transition in Newtonian fluid flow and drag-reducing solution flows in straight pipes. Extension of this study to curved pipe provides better understating on the onset of DR in curved pipe flows among other thin
viii. The effect of micro-bubble size on drag reduction for curved pipe flows is another area where research is required. The exiting studies are limited to straight channel flow and reports on the effect of bubble size on drag reduction are conflicting.

ix. Adequate understanding of mechanism of polymer and surfactant drag reduction in curved pipes could provide a means of quantitatively linking polymer and surfactant properties to the reported drag reduction.

x. The maximum drag reduction for polymer and surfactant DRAs in curved pipes is an area that needs to be explored further. There is the need to further investigate the effects of pipe geometry such as diameter and curvature on DRAs in curved pipes.

xi. The synergistic effect of polymer-surfactant combination may also be explored.

xii. The effects of temperature, dissolved salts, and silt on drag reduction by additives in pipe bends and curves need to be further explored. Reports on these are either scanty or conflicting.

xiii. Research into the effect of DRAs on velocity profile distribution in curved pipes is not available in open literature. Studies in this area could provide more explanation to this behavior observed in straight pipe flow.

4.2 Two-phase flows in curved pipes

Studies into the effects of DRAs on liquid-liquid flows in curved pipes are lacking and those pertaining to gas-liquid flow are scanty. Experience from single phase flow shows that straight pipe data cannot be extended to account for observations in curved pipes. Some of the areas where there are need for further research include the following:

i. Effects of DRAs on phase distribution, pressure drop among others for two-phase liquid-liquid flows through curved pipes is yet to receive proper scholarly attention.

ii. The effect of pipe orientation on pressure drop, phase distribution, and effectiveness of DRAs for two-phase flows in curved pipes needs to be investigated.

iii. There is limited study that investigates the effects of temperature, dissolved salts, and silt on drag reduction for liquid-liquid flows in curved pipes. Research in this area could provide practical solutions for field scale operations.

iv. Researches in the area of drag reduction in two-phase flows in bends are lacking. The few existing literatures have focused on coiled pipe flows. Insight into the effect of DRA on phase distribution in pipe bends could go long way in improving process management and safety.

5 CONCLUSION

This review focused on the application of DRAs to fluid flows in curved conduits. The review highlighted some important characteristics of drag-reducing flows in curved conduits which include:

i. In general, significantly lower DR occurs in curved pipe flows compared to straight pipe of equivalent length. Also, DR for developed flows in curved pipes (such as coiled tubes) are generally higher than those in under-developed flows (such as short bends). This is due to higher form drag resulting from flow redistribution in bends relative to coiled tubes.

ii. DR decreases with the curvature of the curved conduit. In the case of developed flows in coiled pipes, this is primarily due to decreased TI of Newtonian fluid flow with increase in curvature resulting from the superimposition of secondary flows on the mean axial flow. In the case of bends, this is primarily due to increased flow redistribution with increase in bend curvature.

iii. Similar to straight pipe flows, drag reduction by additives is predominantly in the turbulent flow regime, although a few studies reported DR in the laminar flow regime in curved pipes. Beyond certain critical Reynolds numbers, in the turbulent regime, drag reduction by additives reduced with increase in Reynolds number but prior to this, the reverse is the case. This has been attributed to uneven distribution of air bubbles or degradation of polymer or surfactant as the case may be.

iv. The reviewed literatures showed that the effectiveness of polymer and surfactant DRAs increased with concentration until a threshold concentration is attained. Likewise, the effectiveness of micro-bubble as DRA in curved channel flow generally increased with air fraction.
v. Also highlighted in this review is the difference in MDRA and drag reduction envelope between curved and straight pipes and between polymers and surfactants.

vi. The limited research on the application of DRA to two-phase flows in curved conduits reported significant DR. The effect of gas on the rheological properties of the liquid (into which DRA is dissolved) in addition to phase separation makes the analysis of such flows complex.

With the prospect of reduced pumping cost, improved operational flexibility, and transport safety, research is expected to continue in this area in the future. Extension of hydrodynamic and drag reduction studies to three-phase gas-liquid-liquid flows is also essential owing to the occurrence of this flow in petroleum installations.

**PEER REVIEW INFORMATION**

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**CONFLICT OF INTEREST**

The authors declare no potential conflict of interest.

**NOMENCLATURE**

- **R**: coil radius or radius of curvature of curve
- **a**: pipe diameter
- **a/R**: curvature ratio
- **NDn**: Dean number
- **NRe**: Reynolds number
- **NRe'**: modified Reynolds number
- **Nwe**: Weissenberg number
- **NRe_crit**: critical Reynolds number for flow transition from laminar to turbulent flow
- **H**: coil pitch
- **L**: original definition of Dean number
- **f**: friction factor
- **K**: consistency factor of power law model
- **Kp**: consistency factor from pipe viscometer, lbfsnft²
- **n**: behavioral index (exponent of power law fluids)
- **S**: slip ratio
- **P**: static pressure head
- **T**: fluid relaxation time
- **β**: inlet water fraction
- **Cc**: dimensionless concentration defined as the ratio of surfactant concentration to the lower critical concentration in a straight pipe of Cnonbreakingspace=nonbreakingspace250thinspaceppm for ODEAO surfactant at which the rod-like micelles cannot be formed and there is no drag reduction effect
- **Tc**: dimensionless temperature, defined as the ratio of actual surfactant solution to the lower critical absolute temperature of 275thinspaceK where there is no drag reduction effect
- **∅**: is the angle of curvature measured from the inlet of the curved tube
- **m = 1/2αs**: a measure of the elasticity of the fluidr1=ra
- **Ψ**: secondary flow stream function
- **h_r**: pipe roughness projections

**SUBSCRIPTS**

- s: solvent
- p: polymer
- w: water
AUTHOR CONTRIBUTIONS

Paul Ayegba: Data curation; resources; writing-original draft. Lawrence Edomwonyi-Otu: Conceptualization; formal analysis; project administration; resources; supervision; writing-original draft; writing-review and editing. Nurudeen Yusuf: Project administration; supervision; validation; writing-review and editing. Abdulkareem Abubakar: Conceptualization; project administration; supervision; validation; writing-review and editing.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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