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A Review of Drag Reduction in a Turbulent Flow using Polymers

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***Abstract*— On dissolving small amount of high molecular weight polymers in water results in significant drop in pressure across the pipe. Drag reduction rate increases significantly with increase in the flow rate of polymer solution. The specific energy required to maintain turbulent flow of the polymer solution can be significantly less than that compared to solvent alone. This aim of this review is to compile all the published work on drag reduction by Drag Reducing Polymers. Although this phenomenon was first discovered in 1949, but mechanism responsible for drag reduction still remains contradictory. Many researchers have given this individual perceptions from their respective experimental study and numerical analysis. So there is an absolute need to understand this mechanism due to its wide range of practical applications and feasibility.**

Keywords*— *Drag Reduction; Polymer; Turbulent Flow.

I. INTRODUCTION

Injecting small amount of polymer solution in the single- phase water flow in the pipe significantly reduces the pressure drop across the pipe. This effect was first discovered by toms in 1949 also known as “Tom’s effect”. Though the polymers are injected in the pipe flow on a smaller scale, it influences the macro-scales of the flow that determines the drag to the great extent.

For the past couple of years, numerous numerical and experimental studies has been carried out on polymer induced drag reduction in turbulent flow in a pipe. It was Virk in the year 1975 found that there is no drag reduction at low Reynolds number (laminar flow) and there is a considerable amount of drag reduction in the turbulent regime. He presented experimental evidence that drag reduction is limited to an asymptotic value known as maximum drag reduction (MDR) asymptote. Hanratty in 1999 characterized two distinct regimes low drag reduction (LDR) and high drag reduction (HDR) in which LDR exhibits almost similar statistical trends to Newtonian fluid. At drag reduction above 40%, flow enters the HDR regime in which Reynolds shear stresses are very less or negligible. Lumley in 1969 described the changes in the turbulence structure is due to the stretching of randomly coiled polymers because of strong turbulent flow leads to increases flow rate i.e., drag reduction.

In recent studies many numerical simulations were performed to relate turbulence and polymer stresses. Many explanations were proposed for the mechanism of polymer induced drag reduction through such computations. Most of these studies were relied on time and space averaged statistics. Min in 2003 analyzed their simulation on the basis of elastic energy observing remarkable transport of energy from sublayer to buffer layer and logarithmic region. Sureshkumar in 2006 presented the results of direct numerical simulation (DNS) of polymer solution where polymer chains are modelled as finitely extensible non-linear elastic (FENE-P) dumbbells.

II. STUDY OF DRAG REDUCTION USING DRAG REDUCING ADDITIVES

Ptasinski [1] performed the Laser Doppler Velocimetry (LDV) experiments in polymer induced turbulent pipe flow. In this experimental study Superfloc A110 (hydrolyzed polyacrylamide) was used as polymer additive, and conditions were close to MDR or Virk’s asymptote. Amount of drag reduction was observed in terms of change in friction factor as a function of wall Reynolds number. Wall Reynolds number is used following the fact that for non-Newtonian fluids the viscosity does not have a constant value. It is based on an introduction of wall viscosity related to wall shear stress.

All the LDV experiments were performed at Re=10000, showing high rate of drag reduction. The results obtained are compared with the results obtained with water and also with the very dilute solution exhibiting very small amount of drag reduction. The polymers contributes significantly to the total stress. An increase in the slope of logarithmic profile and thickening of buffer layer is found with respect to the mean velocity profile. It is also found that for streamwise velocity fluctuations, root mean square increases for low polymer concentrations but returns to the values comparable to those of water at high concentrations. Reynolds stress and correlation coefficient of streamwise and normal components drastically reduces over the entire pipe diameter. Reynolds stress are non-zero at maximum drag reduction (MDR). The reason for decrease in the Reynolds stress is large polymetric stress which can be around 60% of the total stress. The kinetic energy of turbulent flow shows a possible negative polymetric dissipation of turbulent energy.

Virk [2] has done the physical interpretation of polymer induced drag reduction in the turbulent pipe flow. The turbulence-polymer interactions that are responsible for the drag reduction commences near the plane of peak turbulent energy production, suggesting that randomly coiled polymer molecules influences the turbulent bursting process. In the region near the onset of drag reduction, the duration of a turbulent burst is of the order of relaxation time of the macro-molecule, and just after the onset, the extent of drag reduction is related to the turbulent strain energy of dilute polymer solution. Therefore, these observations suggests that the polymer chain extension is involved in the drag reduction mechanism. The radius of gyration of randomly-coiled macromolecule is smaller than 10^{-3} times the turbulent burst length scale. The radial and axial flow fields are decoupled near the region of interaction, as experienced by a striking reduction in the u-v *c*orrelation coefficient, relative to Newtonian. The decoupling of polymer induced turbulent flow fields seems to retard about the radial transport of axial momentum and turbulent kinetic energy. The drag reduction observed is possibly a consequence of the rearrangements, with an increase in maximum kinetic energy that the inner flows that maintains the overall cross-sectional turbulent energy balance. The data for maximum drag reduction (MDR) is plotted in friction factor (f) versus Reynolds number (Re) graph shown in Fig. 1.

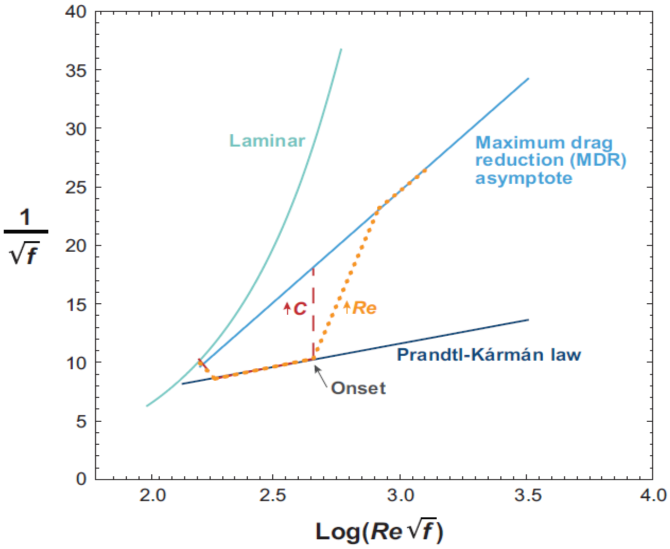

Fig. 1: Representation of the data for maximum drag reduction in the friction factor versus Reynolds number plot [2].

Li et al. [3] performed direct numerical simulation of drag reduction by polymers in the turbulent channel flow. FENE-P and Oldroyd-B models were applied to evaluate the polymetric chain dynamics. In this study it is shown that for high percentage of drag reduction, polymer chain extensibility and high Weissenberg number is required. These results are used to develop a scaling describing the interplay between maximum polymer chain extensibility and relaxation time, and also the extent of drag reduction rate as a function of Reynolds number. In addition to this the turbulence statistics were also analyzed and the correlations between polymer body forces and velocity fluctuations were obtained with particular emphasis on high drag reduction (HDR) and maximum drag reduction (MDR) regimes. The results shows that there is a positive relation between the polymer body force in the near wall region and stream wise velocity. It also indicates that stretching polymer chains extracts energy from the flow, reducing the turbulent fluctuations. The results suggests that there is an intricate balance between average rotation speed of axial vortices near the wall and elastic forces, which is the measure of Reynolds stress production.

Warholic et al. [4] has studied the effects of concentration and mixing of polymers (DPR’s) on turbulence. The Reynolds shear stresses are approximately negligible across the entire cross section of the channel for the flows close to maximum drag reduction (MDR). By considering the energy balance, the turbulence at MDR is produced by the fluctuating polymetric stresses. The velocity profile obtained under MDR does not have the parabolic profile observed for the Newtonian laminar flow.

It is observed that for the maximum drag reduction, the near wall vortices sustaining the turbulence in a Newtonian fluid are destroyed. Hence, the velocity field is somewhat different from the classical turbulence, produced by the interaction between the polymer additives and fluctuating flow field.

From this study it is discovered that the rate of drag reduction mainly depends upon how the polymers are added, and this effect was observed for the polymer concentrations as low as 0.25 ppm. This result is interpreted as the effectiveness of the drag reducing polymers (DRP’s) depends on the presence of aggregates in the aqueous solution. These aggregates needs to be break up irreversibly to be consistent with experimental measurements. This interpretation gives a theory to explain polymer degradation and the effect of chemical composition of the solution. The polymer aggregates appears intermittently, so it is difficult to understand the effect on velocity field at such small concentrations. It also illustrates that the near wall vortices regenerates themselves by certain process which is followed by several generations. From the change in local turbulence due to the destruction of the vortices while interacting with the polymer aggregates much stronger impact can be expected.

Dubief et al. [5] performed numerical simulations on polymer solution in a turbulent flow using the FENE-P model to characterize the effect of polymers on turbulent structures. The polymers stores and releases energy to the flow in a systematic manner. The energy is stored in the near wall vortices was anticipated for a long time, but quite unexpectedly the coherent energy were observed in the near wall region. The fluctuating polymetric work is shown to re-energize the reducing stream wise velocity fluctuations in the high velocity streaks just above the viscous sublayer.

The drag reduction and turbulence intensifying properties of polymers are related to the coherent structures. Polymer influences the near wall vortices and enhances the kinetic energy of near wall streaks. The net balance of these two opposite actions leads to drag reduced turbulent flow. Hence, the study on polymer work characterizes when the polymers are more likely to release the energy into the near wall streaks. This phenomenon is related to the region where kinetic energy decreases in absence of polymers. The release of energy from the polymers in this region counteracts the viscous effects which occurs after the polymers resides in the streaks but not when they are transported from buffer region to the streaks through downwash flows by the vortices. The damping of turbulence takes place in the flows generated by the vortices, since upwash and downwash flows occurs around the vortices with the preference of upwash events because of pre-stretching of the polymer chains by high shear close to the wall.

Toonder et al. [6] has examined the role of elasticity and stress anisotropy in the mechanism of polymer induced drag reduction in a turbulent pipe flow using direct numerical simulation (DNS) and laser doppler velocimetry (LDV). In this study they considered two models to illustrate the effect of polymers in the turbulent flow. The first model is based on the theory of elongated particles in the Newtonian fluid that models the viscous anisotropic stresses due to the polymer chain stretching. Second model is the extension of previous one with an elastic component that can be described by anisotropic maxwell model. They observed thickening of buffer layer in the drag reduced flow and corresponding offset in the logarithmic region. The peak value of axial rms profile increases and shifts away from the wall but in other directions as its value decreases. No proper evidence for Reynolds stress deficit is found in DNS. The changes due to the viscous anisotropic model is mainly due to the presence of normal stress in the axial direction. The turbulence in the axial direction is distributed from smaller to larger scales. The radial velocity fluctuations are damped over the entire wavenumber spectra near the wall. It is also shown, the stretching characteristics are altered by the viscous anisotropic model, positive and negative deformations are suppressed. The negative stretching is suppressed much strongly as compared to positive stretching.

Another DNS was performed using the anisotropic model to test de Gennes hypothesis, it was interpreted that the extension of viscous anisotropic stress with an elastic component. Their results confirms the hypothesis of Lumley (1969) that stretching of polymer chains are responsible for drag reduction but not with the increasing viscosity proposed by him. On the basis of their results they proposed that in the mechanism of polymer induced drag reduction viscous anisotropic stresses play an important role.

Graham [7] studied the polymer induced drag reduction phenomenon also known as the “Toms effect”. The rate of strain near the wall is much larger than the polymer relaxation rate, polymer chain stretches in the near-wall streaks and do not relax until they enter the quasi stream wise vortices until they suppress them. It is these stream wise vortices in the buffer layer that drive convective momentum transport; suppressing them leads to drag reduction. The strength of these vortices decreases which leads to redistribution of Reynolds stresses, resulting in changes in the velocity fluctuations of the buffer layer. It seems likely that a related mechanism is involved in the log layer, as also the mean shear flow tilts and stretches the vortices into the mean flow direction. As the strain rates are lower here, the polymers are not highly stretched and their influence is weaker than the buffer region.

Kim et al. [8] examined the effects of polymer stresses in the fully developed turbulent structures using DNS. They used two point spatial correlations and linear stochastic estimation for finding the patterns of vorticity, polymer torque, velocity, and polymer force in the conditional eddies. Both low drag reduction (LDR) and high drag reduction (HDR) regimes are investigated and compared with the results of Newtonian fluid and for computation the conditional averaged near wall eddies, linear stochastic estimation were employed. It is shown that the near wall turbulent structure are depleted and prolongate in streamwise direction due to the polymetric stresses. In this study the averaged conditionally fields are responsible for the events concerned with huge contribution to the polymetric work are also examined. This study explains vortex retardation by the polymetric forces in the fully developed turbulent flow by relating the 3-D structure of eddies to the structure of polymetric forces. In more detail, the torque due to the polymer stress opposes the vortex rotation are responsible for their weakening. The simulations also shows that the total number of vortices in the drag reduction flows are also reduced and also some part of reduction in Reynolds stress. Hence these results offers an explanation of possible mechanism of polymer induced drag reduction in the outer region of wall turbulence and also in the buffer region.

Petrie et al. [9] performed experimental study on the effect of surface roughness on polymer drag reduction in a flat plat turbulent boundary layer at zero pressure gradient. In this study they considered both slot injected polymer and homogenous polymer ocean cases in wide range of flow conditions as well as surface roughness. In this study, they measured skin friction drag reduction and found 60 % of drag reduction for both homogenous and injected cases with rough surfaces. To achieve higher percentage of drag reduction, higher polymer concentration is required for the homogenous case if the roughness is more. The percentage of drag reduction decreases to very low values quickly with the increase in surface roughness when the freestream velocity is increased. It is observed that the percentage of drag reduction is more on the rough surface with polymer injection as compared to the smooth surface. From their experimentation it is observed that in some conditions with polymer injection the skin friction drag on the rough surface is less than the drag force on smooth surface under comparable conditions.

Omrani et al. [10] performed experimental study on the effect of Coriolis force in polymer induced drag reduction in a turbulent pipe flow. In this they used a smooth pipe of 25 mm diameter on a horizontal table rotating about the vertical axis. This rotation is made dimensionless to form Rotation number (Ro) with friction velocity and pipe diameter. The pressure drop is measured between the two different Reynolds numbers 15000 and 30000 for a range of bulk rotation number between 0 to 0.6 from which average friction factor f is calculated. The friction factor (f) changes with the rotation number for the single phase flow, these results match qualitatively with the square duct flow. It is found that the effect of rotation and polymer seems to be super positional in the regime of drag reduction with polymers and remains unaltered by the rotation. It is now inferred that large scale secondary flow caused by the rotation doesn't influence the near wall phenomenon causing polymer induced drag reduction.

Ali et al. [11] performed experimental investigation of polymer induced drag reduction in flowing crude oil, which could increase the pumping capacity of crude oil over long distances. In their study two types of crude oil namely, Karkok crude oil and Basrah crude oil are used.

Three types polymers with high molecular weight namely poly isobutylene PIB150K, PIB90K and poly isoprene (PIP) are used, the polymers are injected through pumping system at different concentrations rounded between (10-50) parts per million (ppm) with temperatures range of 30˚C to 50˚C. They performed several experiments to determine the best concentration of polymer which satisfies the lowest drag force on crude oil flow rate.

From the experimental results they have concluded that best concentration for PIB150K for maximum drag reduction is 30ppm when added to Kurkuk crude oil at 35ºC reducing the draf force by 22.23% for velocity of 1.85m/s. Same concentration when added to Basrah oil at 45ºC reduces the drag force by 20.3% at 45ºCfor velocity of 6.65m/s. The friction factor gradually decreases when the polymer concentration increases. The performance of the polymer is better for light crude oil than heavy crude oil.

III. CONCLUSION

This review paper contains different research works performed to understand the phenomenon of polymer induced drag reduction for the past many years. It can be concluded that there is still no unifying interpretation for the phenomenon of drag reduction. Therefore, it still remains a wide area for research to understand this process at fundamental level.

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