RESEARCH ARTICLE OPEN ACCESS

Studies on Drag Reduction for Flow through Circular Conduits with Coaxially Placed Single Disc Turbulence Promoter

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ABSTRACT
The Paper Reports on Studies on effect of drag reduction study were conducted in flow through circular conduits with coaxially placed single disc turbulence promoter using with polyacrylamide (PAA) as additive was chosen as the system of the study. The study covered range of parameters like effect of disc diameter, flow rate, polyacrylamide concentration. The percentage drag reduction varied between 87 to 97% as the coaxial disc diameter increases from 0.03 m to 0.04 m. The percentage drag reduction of 89 to 93% is observed as the polyacrylamide concentration is varied from 50 to 200ppm. A model was developed for mass transfer data. The developed model is presented here under.

$$\frac{1}{\sqrt{f}} = 1.15\log\left(\mathrm{Re}\sqrt{f}\right) - 0.45$$

***Keywords*:** circular conduits, disc diameter, flow rate, polyacrylamide concentration, mass transfer, modeling.

I. INTRODUCTION

Energy conservation is a norm in modern industry, to stand in competition and for sustained economic advantage. This is particularly important in process industries where large numbers of fluid streams are transported through pipes. Large quantities of power are being expended. Energy can be conserved by the addition of small quantities of additive by which drag or friction can be reduced as high as 80%. Certain operations like cooling towers, petroleum transport lines, recirculation chambers, heat exchangers could be operated with drag reducing aid without much loss on intended operations. The other important area is debottle necking or capacity enhancement can be made with the addition of additive without shut down for maintenance.

Drag reduction is accomplished by the addition of following type chemicals, (a) Long chain polymer (b) Surfactants (c) Natural gums (d) Fibers.

Among them long chain polymer molecules have been chosen for the present study. The polymer selected is Polyacrylamide (PAA). Addition of Polyacrylamide (PAA) reduces the wall shear there by reducing friction factors up to 80% reported by **Virk [1].** Earliest study in the drag reduction is reported by **Toms [2].** Since then extensive research work has been continuing in this area. Extensive studies were conducted and confirmed by **Lumley [3]**, **Hoyt [4], Landahl [5]** provided greater breadth on the topic.

The mechanism of drag reduction involves dynamical interaction between polymer and turbulence. Sufficient experimental evidence has been provided in literature. (1) Laminar pipe flow of dilute polymer solution shows no significant differences in skin friction compared with laminar pipe flow of Newtonian fluids. (2) At a particular Reynolds number drag reduction depends upon number of monomers present in the chain of a linear polymer.

The basic mechanism in drag reduction for polymers molecule in a turbulent flow is stretching of a polymer in a shear flow. The onset of a drag reduction occurs when the ratio of polymer time scale to the flow time scale near wall turbulence defined by weissenberg number $We_t = \frac{T_z \rho \mu^2{}_t}{\mu_s}$

T_z is the average time taken for a stretched polymer to return to a coiled configuration. μ_s is the viscosity of the solution, ρ is the density of solution, μ_t is wall friction velocity.

The mechanism of drag reduction is presented by Lumley. A large increase in effective viscosity just outside the viscous sub layer will reduce the turbulent fluctuations inrease the buffer layer thickness and reduce the wall friction. The other mechanism is effective viscosity of a solution is a function of polymer concentration and the maximum expandability for a given polymer solvent pair.

In view of above facts, drag reduction is highly useful in annular pipe flow with additives like polyethyleneoxide, polyisobutylene, Polyacrylamide etc. Several other molecules have been used in various studies. But, in the recent advances the indicate use of concentrically placed disc in an annular conduit providing good heat and mass transfer rates. Hence it is proposed to study drag reduction with concentrically placed single disc in an annular flow. It is proposed to test the effectiveness of the disc promoter and the wall shear and form drag reduction. The range of variables in the present study and the several drag reducing polymers that have been reported in literature are maintained in tables 1 and 2 respectively.

Table.1 Range of variables

S. No	Variable	Maximum	Minimum
1.	Friction factor, f	0.305222	0.000819
2.	Reynolds number, Re	15546.97	208.8358
3.	Velocity, m/s	0.2884	0.022
4.	Polyacrylamide concentration, ppm	200	50
5.	Disc diameter, m	0.04	0.03

Table.2 Common Drag Reducing Polymers

Water Soluble	Hydrocarbon Soluble
Polyacrylamide (PAA)	Polyisobutylene (PIB)
Polyethylene oxide (PEO)	Polyethylene oxide (PEO)
Guar gum (GGM)	Polymethylmethacrylate (PMMA)
Xanthan gum (XG)	Polydimethylsiloxane (PDMS)
Sodiumcarboxymethylcellulose (CMC)	Polycisisoprene (PCIP)
Hydroxyethyle cellulose (HEC)	Polystyrene (PS)

The present work is proposed to study the following effects

a) Drag reduction with Reynolds number
b) Effect of disc diameter
c) Effect of Polyacrylamide concentration
d) Effectiveness of drag reduction in form drag

The study yielded the following information. Drag is reducing marginally with increase in Reynolds number. Polyacrylamide is an effective drag reducing agent. Drag reduction is increasing with decrease in disc diameter. Polyacrylamide concentration has marginal effect on drag reduction.

The following correlation is reported for the present system of study.

$$\frac{1}{\sqrt{f}} = 1.15\log(\mathrm{Re}\sqrt{f}) - 0.45$$

II. EXPERIMENTATION DETAILS

A photograph and schematic diagram of experimental set up are shown in Fig. 1 respectively. It essentially consisted of a storage tank (TS), centrifugal pump (P), rotameter (R), entrance calming section (E1), test section (T) and exit calming section (E2). The storage tank is cylindrical copper vessel of 100 liter capacity with a drain pipe and a gate valve (V1) for periodical cleaning. The tank is connected to the pump with a 0.025m diameter copper pipe on the suction line of the centrifugal pump. The suction line is also provided with a gate valve (V2).The discharge line from the pump splits into two. One served as a bypass line and controlled by valve (V3). The other connects the pump to the entrance calming section (E1) through a rotameter. The rotameter is connected to a valve (V4) for adjusting the flow at the desired value. The rotameter has a range of 0 to $166\text{x}10^{-5}\text{m}^3/\text{s}$. The entrance calming is made of circular copper pipe is 0.05 m ID and a length of 2m (40D).It is provided with a flange and is closed at the bottom with a gland nut (G).The up-stream side of the entrance calming section is filled with capillary tubes to damp the flow fluctuations and to facilitate steady flow of the electrolyte through the test section.

The test section was made of a graduated Perspex tube of 0.44m length. Two pressure taps (P1, P2) were provided at both the ends of the test section so as to connect it to the manometer. Carbon tetrachloride is served as manometric fluid. Exit calming section is also of the same diameter copper tube of 0.5 m, and it is provided with a flange on the upstream side for assembling the test section. It has gland nuts (G1, G2) at the top and bottom ends to hold the central pipe. The entrance calming section, test section and the exit calming section were joined together by means of flanges (F) and gland nuts(G1, G2).

The turbulence promoter was made by fixing a circular disc on a pipe which was fixed coaxially in the circular conduit. The variables of the study are flow rate, the diameter of the annular pipe, the diameter of the disc and the concentration of polyacrylamide.

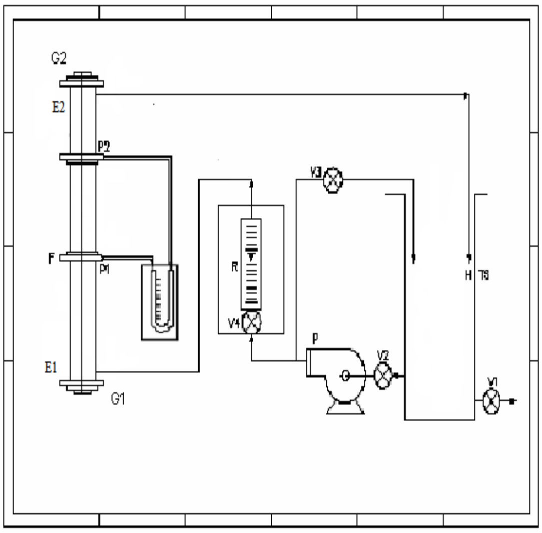

Fig. 1: Schematic Diagram of Experimental Setup

EXPERIMENTAL PROCEDURE

Pressure drop data were obtained with coaxially placed disc promoter in forced convection flow of water and also for the case of addition of polyacrylamide to water as drag reducing agent. Pressure drop measurements were obtained across the test section using a U-tube manometer with carbon tetrachloride as the manometric fluid.

At each flow rate pressure drop was measured across the test section with insert promoter. The measurements were obtained for water and also after the addition of polyacrylamide to water. Prior to the assembly of the main unit the disc diameter and the diameter of the annular pipe were measured using a Vernier calipers and a micrometer screw gauges. The rotameter was calibrated prior to the commencement of the experimental work.

The turbulence promoter was fixed in the circular column, with the help of the gland nuts G1 and G2. About 60 liters of water was taken in the tank and was pumped through the test section. After the flow rate was stabilized the difference in the manometer reading and the temperature were noted. The flow rate was changed and the experiment was repeated. The experiment was repeated foe varying flow rates, difference in disc diameters and diameter of the annular pipe.

For the studies on drag reduction polyacrylamide was added to water and the above experiment was repeated covering the parameters mentioned. The same experiment was repeated for different concentrations of the polyacrylamide in water. These measured data were used to calculate the drag reduction, friction factor (f) and the velocity (V) that is used for the correlation development. The ranges of variables are covered in table 3.

Table. 3. Range of variables

S.No	Variable	Minimum	Maximum
1.	Disc diameter, m	0.03	0.04
2.	Flow rate, m^3/sec	10	80
3.	Polyacrylamide concentration , ppm	25	200

III. RESULTS AND DISCUSSIONS

Addition of small amount of chemical additive reduce drag drastically, the reduction is upto 50%. Several works have been reported in literature. The earlier works on the subject was made by **Toms [2], Lumley [3], Landahl [5]** reported effectiveness of drag reducing agent. **Hoyt [4]** demonstrated the effect of fibers in drag reduction. The other mechanisms that reduce drag are coarse dust particle in air, magnetic field and flexible walls. The drag reduction in turbulent flow is effective with linear polymer of high molecular weight such as polyethylene has been subject of interest for the last four decades. The other drag reducing agents are polyacrylamide, xantha gum, guar gum, sodiumcarboxymethylcellulose (CMC), hydroxyethyl cellulose, polyisobutylene, polymethylmethacrylate, polyisobutylene etc.

The various chemicals employed for drag reduction are presented from table 4. From the earlier studies reported if is observed that polyacrylamide has not been subjected for the study of drag reduction in annular conduits with coaxially placed disc as turbulent promoters. Therefore, polyacrylamide additive is proposed to conduct experiments at varying concentrations of polyacrylamide (PAA) in water solution. Experiments are conducted in the vertical column of 5 cm diameter is presented. Drag reduction has been measured through the pressure drop method. The drag reduction is computed and presented in terms of effective friction factor. The drag may be due to shear of the fluid near the wall and between the layers of fluid and also due to form drag. All the study mentioned above reduce the drag, shear. The relative proportion is unclear but the cumulative effect can be measured by the means of manometer as drop in pressure. The pressure drop is measured by U-tube manometer. The measured pressure difference is used for the computation of effective friction factor by the following equation

$$f = \frac{\Delta P g_c D}{2LV^2\rho} = \frac{\tau_\omega}{\frac{1}{2}\rho \upsilon^2}$$

The superficial velocity is computed by the following,

$$V = \frac{q}{\pi \frac{D^2}{4}}$$

The Reynolds number calculated by the following equation, $\mathrm{Re} = \frac{D_e \upsilon \rho}{\mu}$

The data is analyzed in terms of friction factor versus Reynolds number.

Theories of Drag Reduction

Effects of Polymer Concentration

For low concentrations the drag reduction is found to be directly proportional to the concentration, for high concentrations the reduction reaches to a maximum designated as the maximum drag reduction asymptote. To observe the effect of polymer concentration an experimental study was carried out in the same pipe for solutions of the same polymer with different concentrations. Friction factor versus Reynolds number plots at different polymer concentrations occur in a region confined between an upper limit Prandtl-Karman law and maximum drag reduction curve. It is seen that the effect of polymer additive on drag reduction increases with increasing polymer concentration.

Effects of Pipe Diameter:

Pipe diameter is another important parameter in drag reduction. **Virk [1]** reported that the onset of drag reduction shifts toward higher polymer concentrations with increasing pipe diameter. The drag reduction of a polymer solution becomes more pronounced as pipe diameter is reduced. It has been speculated that dependence of the drag reduction characteristics on pipe diameter is due to the changing length scale ratio of the polymer chains to turbulence. As diameter increases, larger eddies are observed which suppresses the drag reduction ability of the polymer.

Comparison of Polymeric and Surfactant Additives:

Cationic, anionic, and zwitterionic surfactants are used as drag reducer reducing additives in the turbulent flow and the studies on these have grown in recent years. The drag reducer additives are generally used in recirculation turbulent flow system, therefore investigations focus on the additives which do not degrade or repair themselves after degradation.

The differences in the flow behaviors of polymeric and cationic surfactants were studied by **Myska and Zakin [38]**. According to this study, polymer solutions degrade irreversibly when sheared and lose their drag reduction behavior. Cationic surfactants degrade under high shear, but the structures are repairable and they regain their drag reducing ability when shear is reduced. Dilute polymer solutions become drag reducing when the critical shear rate exceeded. Surfactant solutions generally show a gradual departure from the laminar flow curve and drag reducing until a critical shear rate is reached. Friction factors significantly below those predicted by the maximum drag reduction asymptote for high polymers can be reached in cationic surfactant and aluminum disoap systems. Turbulent mean velocity profiles for cationic surfactants can be significantly steeper than the limit predicted by the elastic sub layer model for the high polymers.

Despite their higher level drag reductions than polymers, use of surfactants has been quite limited. The main drawback of surfactants is due to their negative impact environment compared to polymers.

Turbulent Pipe Flow Characteristics:

Let us consider a fully developed turbulent flow through a straight pipe with diameter D. The mean shear stress at the wall, τ_ω, for Newtonian and non-Newtonian fluids and for all regimes is given by $\tau_\omega = \frac{D\Delta P}{4\Delta x}$, Where $\frac{\Delta P}{\Delta x}$ is the constant pressure gradient. The wall shear stress is usually expressed in terms of the Fanning friction factor *f* given by $f = \frac{\tau_\omega}{\frac{1}{2}\rho U_b^2}$, Where U_b the mean velocity in the pipe and ρ the density of the fluid. For instance, the expressions for *f* for laminar and fully developed turbulent pipe flow of a Newtonian fluid are $f = \frac{16}{\mathrm{Re}}$ and

$$\frac{1}{\sqrt{f}} = 4\log \mathrm{Re}\sqrt{f} - 0.4,$$

$$\mathrm{Re} = \frac{\rho U_b D}{\eta}.$$

Reynolds number (Re) based on the constant viscosity η of the fluid.

For polymeric liquids the viscosity is in general shear-rate dependent, so that the usual definition of the Reynolds number cannot be used. In this study, a method proposed by **Pinho and Whitelaw [39] and Draad et al. [40]** is used for the Reynolds number calculation. In this approach the Reynolds number is based on the viscosity at the pipe wall (η_ω) as obtained from $\eta_\omega = \frac{\tau_\omega}{\gamma_\omega}$, where $\eta_\omega = \eta(\gamma_\omega)$ and γ_ω is the local shear rate at the wall. At maximum drag reduction of non-shear-thinning fluids the friction law approaches an empirical asymptote, called the maximum drag reduction asymptote given by

$$\frac{1}{\sqrt{f}} = 19 \log \mathrm{Re} \sqrt{f} - 32.4$$

For shear-thinning fluids, the friction factor versus the wall Reynolds number collapses the data near Virk asymptote. This does not happen when Reynolds number is based on the viscosity of water. Therefore the wall Reynolds number Re*w* is used in the above equation. The amount of drag reduction is defined as the reduction of pressure-drop due to the addition of the polymers,

$$DR\% = \frac{\Delta P_0 - \Delta P}{\Delta P_0} .100 = \frac{f_0 - f}{f_0} .100$$

Present experimental program is planned to study the effect of Polyacrylamide (PAA) on friction factor and also under varying diameter disk. In the present study, annular conduits with co-axial disc have been chosen. Concentration of Polyacrylamide (PAA) and disc diameters are selected as parameters of the study. The ranges of variables covered in the study are present in the table 5.

Table. 4: Different chemicals and their concentration ranges used by the earlier studies

S.No	Chemical	Author	PPM
1.	Polyethylene oxide	Ralph C. Little [6]	300,360,450,560,780,1500,2500
2.	Polyacrylamide (PAA)	George A.McConaghy et al [36]	50 – 325
3.	Polyethylene oxide, PAA, CMC	G.H.Sedahmed et al [37]	10,50,100,200
4.	Polyethylene oxide	R. Smith, M.F Edwards [41]	500-3000

Table. 5: Range of variables

S.No	Variable	Maximum	Minimum
1	Velocity	0.28845	0.022
2	Reynolds number, Re	11345.7	208.8358
3	Polyacrylamide concentrations PPM	200	50
4	Disc Diameter	0.04	0.03

Effect of Disc Diameter on Friction Factor:

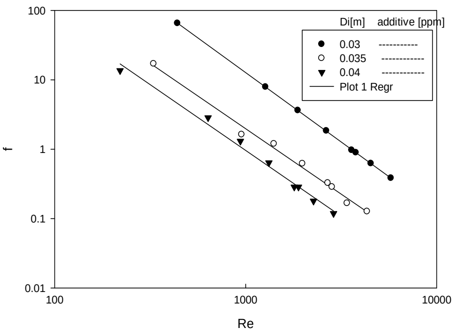

Fig. 2 Variation of friction factor with reynolds number in water

A graph is drawn as f versus Re with disc diameter as a parameter for pre solvent with no additive. The graph reveals the following information. Effective friction factor values are decreasing with increase in Reynolds number. As the disc diameter increases f values are decreasing. The exponent Re is found as -1.9979.

Effect of disc diameter and additive on friction factor

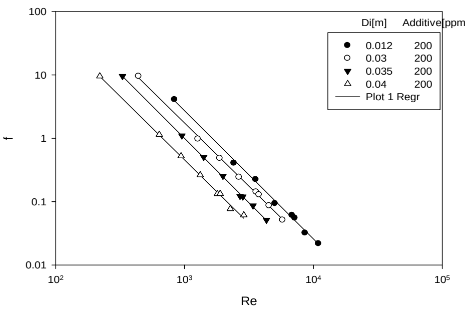

Fig .3 Variation of friction factor versus Reynolds number

Fig. 3 demonstrates the effect of disc diameter with polyacrylamide as additive and its concentration is maintained at 200 ppm. The following observations are made. Friction factor values are decreasing with increase in Re. Increases in disc diameter offered lower friction factors in contrary to the pure solvent it is due to the addition of additive but exact mechanism is not clearly understood. Slopes of the lines are found derease wit increase in additive. Slope is -2.0437.

Effect of additive concentration on friction factor:

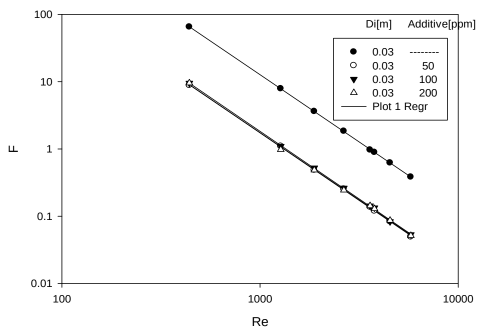

fig .4 Variation of friction factor with Reynolds number

The Fig. 4 is drawn as friction factor versus Reynolds number for varying concentration of polyacrylamide. The figure reveals the following information. Friction factor values are decreasing with increase in Reynolds number. Presence of additive in the fluid has showed a decrease in friction factor but the effects of polyacrylamide consistently has marginal. It indicates a lower concentration of polyacrylamide is sufficient to gain the advantage of drag reduction. For the study below 50 ppm and above 200 ppm additive concentrations may yield some more useful information.

Effect of disc diameter on DR Percent:

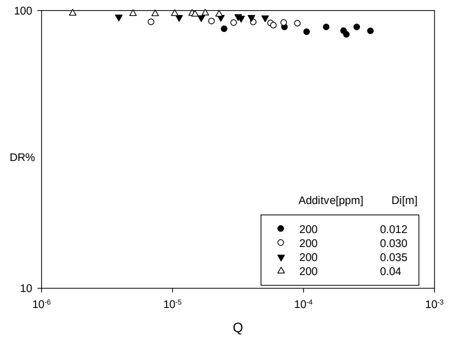

Fig 5 Variation of DR Percent with Flow rate

Fig. 5 is a graph drawn for DR percent Vs flow rate with the additive of 200 ppm polyacrylamide and water. The DR percent is decreasing with the increase in flow rate and it is also observed that the varying disc diameter has marginal effect on DR percent.

Effects of Additive on percentage drag reduction:

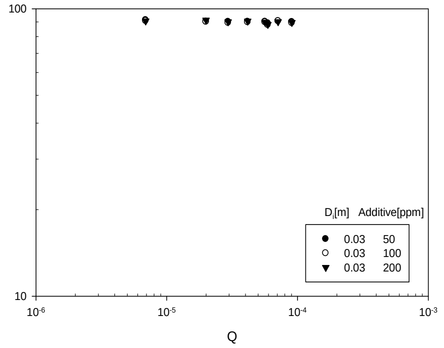

Fig .6 Variation of drag reduction versus flow rate- effect of additive

The Fig. 6 demonstrates the effect of additive concentration on percentage drag reduction. The efficiency of polyacrylamide in drag reduction is about 89 percent to 93 percent. But the effect of polyacrylamide concentrations has not shown any significant effect. The effect of disc diameter and additive concentrations are shown in Fig 5 and 6 respectively. Disc diameter has marginal influence while additive concentration has no significant impact on drag reduction.

Effect of disc diameter on drag reduction:

Present study aims at the reduction of pumping power with additive. The additive used is polyacrylamide (PAA). Its efficiency is observed by drag reduction. A graph is drawn Fig. 7 between drag reduction versus Reynolds number with coaxially with disc diameter as parameter. The graph reveals the following information. The drag reduction is 97% for 0.04m disc diameter and 87% for the disc diameter of 0.012m. This shows that the drag reduction is increasing with the increase in the disc diameter.

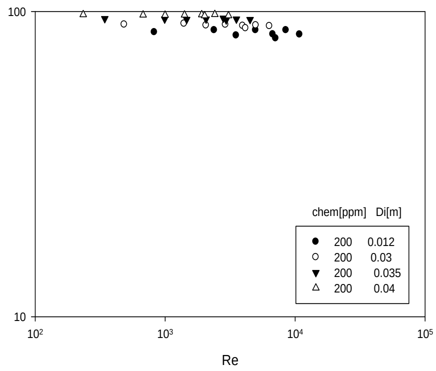

Fig 7 Variation of drag reduction with Reynolds number

Effect of polymer concentration on Drag reduction:

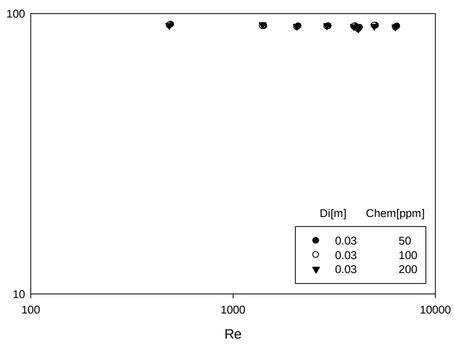

Fig 8. Variation of percentage DR with Reynolds number

A graph is drawn in Fig. 8 for drag reduction versus Reynolds number with additive concentrations as parameter. The graph reveals the following information. There is no significant effect of polymer concentrations on the percentage drag reduction efficiency. But the drag reduction is significantly high even at concentration of 50 ppm. Efficiency percentage has shown marginal effect by the increase in the concentration. Marginal variation is observed with Reynolds number.

Effect of polymer on friction factor:

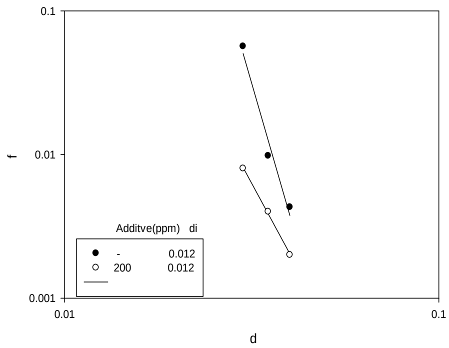

Fig 9 Friction factor versus diameter of the disc

Plots are drawn in Fig. 9 for friction factor versus Reynolds number data with and without additive which explains the effect of polymer on friction factor.

The above two plots in Fig. 9 shows the effect of polymer concentrations on friction factor. The friction factor is decreasing gradually due to polymer addition.

IV. DEVELOPMENT OF CORRELATIONS

Flow of dilute polymer solution through circular conduit with coaxially placed single disc on a pipe as promoter generates a variety of flow fields. Pressure loss for the system comprises of skin friction at walls of annular conduit together with form drag on front and rear side of the disc. Additional form drag due to turbulence throughout the column also contributes to the pressure loss. An attempt is made to develop a correlation in terms of friction factor and Reynolds number along with the geometric parameters of the study namely diameter of the central pipe, diameter of the disc and additive concentration. The development of momentum transfer correlations for the present situation could be carried out on the basis of empirical correlation of data. Conventional f – Re type correlations have been attempted and the following format of equation is used.

$$f = C\,\mathrm{Re}^{m}(\Phi_1)^{n_1}(\Phi_2)^{n_2}(\Phi_3)^{n_3} \qquad 1$$

Where $\Phi_1, \Phi_2,\ \Phi_3$ are the geometric parameters.

$\Phi_1 = d_i/D$,

$\Phi_2 = d_d/D$, $\Phi_3 = C_A/C_S$,

Where di = Diameter of the conduit, d_d = Diameter of the disc, C_A= Concentration of the Additive, C_S = Concentration of Saturated Chemical, D= Diameter of column.

Regression analysis of the data in accordance with the above format of equation yielded the correlation with high deviations.

In view of these large deviations, an alternative approach has been attempted by the use of the wall similarity concept proposed by **Nikuradse, J [42] and Deissler R. G and Webb, R, L et al [43], Dippery and Saborsky [44], Rajendra Prasad, P [45]., VNR [46].,** and several others., The similar concept assumes velocity distribution is expected to experience the effect of viscosity at the surface. When an object is placed across the flow in a circular conduit, drag is generated and the drag enhances turbulence. Thus generated turbulence exerts attractive force at the wall and makes the boundary layers thinner. The flow is divided into two regions namely inner region and outer region. The inner region constituted with boundary layer whose thickness is δ at y^+, where δ is small. The velocity distribution depends on y^+, τ_0, μ. For inner region the velocity profile in terms of dimensionless velocity is given by

$$u^+ = y^+ \qquad 2$$

$where \quad u^+ = u/u^*$, $y^+ = yu^*/\nu$ For the outer wall region where the dependency of velocity distribution on molecular viscosity ceases to exist, the velocity distribution would follow the relationship

$$u^+ = \frac{1}{k}\ln y^+ + C_1 \qquad 3$$

By the application of boundary conditions u=0 at $y=y_0$, where y_0 is the thickness of laminar sub layer that depends on the turbulence generated , equ. 4 reduces to

$$u^+ = \frac{1}{k}\ln(y/y_0) \qquad 4$$

The turbulence in the core and at the wall is significantly affected by the geometric parameters of the promoters employed in addition to the fluid velocity. In the present case, diameter of the disc (D_d), diameters of the annular pipe (D_i) are major characteristic geometric parameters. These are expected to affect significantly the thickness of the laminar sub layer. In the present study the parameter (D_d), was chosen while computing u^+ therefore,

$$y_0 \;\alpha\; D_d \qquad 5$$

Equ.4 could be modified as

$$\frac{u_{\max} - u}{u^*} = \frac{1}{k}\ln(y/D_d) \qquad 6$$

Combination of equation 5 and 6 gives the velocity distribution equation for the turbulent dominated part of the wall region

$$u^{+} = 2.5\ln[y/D_d] + R(h^{+}) \qquad 7$$

The above equation presents modified velocity profile for the case of outer turbulent region in the presence of promoters. Assuming that equation5.7 holds good for the entire cross section of the circular conduit, the friction factor for the turbulent flow with entry region coil inside the annular conduit can be given by integration of equation5.7. The generated roughness function R (h+) is given by the following equation

$$R(h^{+}) = 2.5\ln[2(D_d)/d_e] + \sqrt{2/f} + 3.75 \qquad 8$$

Where R(h+) is roughness momentum transfer function, This type of analysis is followed by the earlier workers **P.Rajendra prasad [45], V.Nageswara rao [46],** and successfully analyzed their data. To present the data in terms of Prandtl Von karaman coordinate the following rearrangement is made which yields the following equation.

$$\sqrt{2/f} = R(h^{+}) - 2.5\ln[2(D_d)/d_e] - 3.75 \qquad 9$$

$$\sqrt{1/f} = R(h^{+}) - 2.5\ln[2(D_d)/d_e] - 3.75 \qquad 10$$

The resulting format of equation for correlating the momentum transfer data with entry region coaxially placed discs as promoter in annular conduits can now be written as

Where, $\mathrm{Re}_m{}^{+} = \log \mathrm{Re}\sqrt{f}$, Here, C_1 is proportionality constant and b_1 is an exponent

$\mathrm{Re}_m{}^{+}$ is roughness Reynolds number defined by the following equations for entry region of coaxially placed discs with annular conduits in homogeneous flow. The analysis could also be useful for fluidized beds with modification of particle Reynolds number defined in following text.

Homogeneous flow:

Data on homogeneous flow is analyzed in terms of Rh+ vs $\mathrm{Re}_m{}^{+s}$

$$R(h^{+}) = 2.5\ln[2(D_d)/d_e] + \sqrt{2/f} + 3.75 ...... \qquad 11$$

$$\mathrm{Re}_m{}^{+} = \mathrm{Re}\sqrt{f/2} \qquad .... \qquad 12$$

Where D_d is disc diameter, d_e is diameter of the conduit and f is friction factor.

On regression analysis and by omitting geometric parameters of the promoter yielded the following equations.

$$\frac{1}{\sqrt{f}} = C_4[\mathrm{Re}_m{}^{+}]^{n1} \qquad 13$$

On regression analysis the following equation is resulted. However a graph is drawn in line with Prandtl Karman coordinates resulting with smaller deviation hence the following equation is presented for more generality.

$$\frac{1}{\sqrt{f}} = 1.15\log(\mathrm{Re}\sqrt{f}) - 0.45 \qquad 14$$

Correlation plot for the above equation is shown as Fig. 10.

The regression coefficient is found to be 2.333.

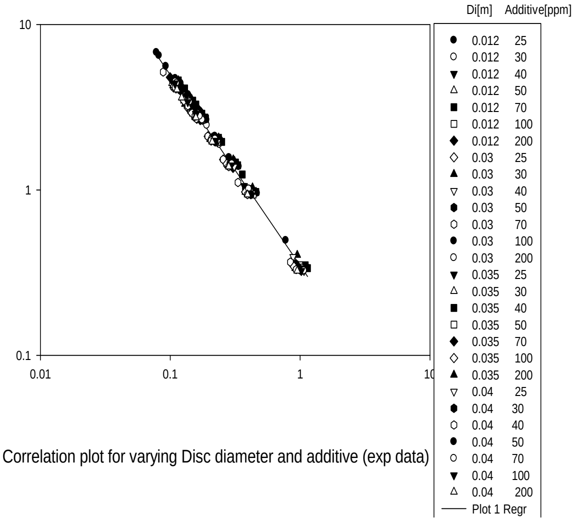

Fig 10 Correlation plot for varying Disc diameter and additive (exp data)

CORRELATION VARYING DISCS IN WATER:

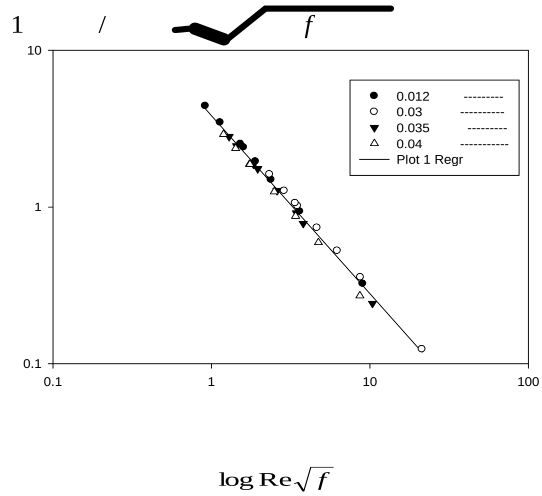

Fig. 11 Correlation plot for varying disc diameter in water.

For comparison data without any additive (solvent water in pure form) was also obtained for the present system of promoter and presented in the following graph as Fig. 11.

COMPARSION VARYING PPMS:

The data of Virk, Choi, and Prandtl are plotted along present with experimental data and shown as Fig. 12. The graph reveals present model is predicting the data of Choi, Virk and Prandtl well. Hence present model is more general and can used without losing accuracy.

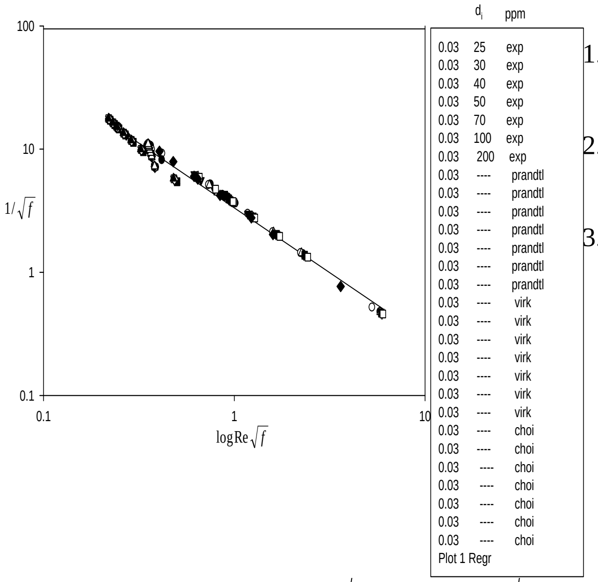

Fig. 12 Comparison: Plot of 1/√f versus logRe√f for the present study and the other investigations

CORRELATION FOR PERCENTAGE DRAG REDUCTION:

A graph is drawn as percentage DR% versus Re and shown in the Fig. 13. On linear regression the following correlation is resulted with regression coefficient mention along with it. The equation is useful for predicting drag reduction at any Reynolds number, Re.

$$DR = 2.2086\,\mathrm{Re}^{-0.0803}$$
$$r^2 = 0.237$$

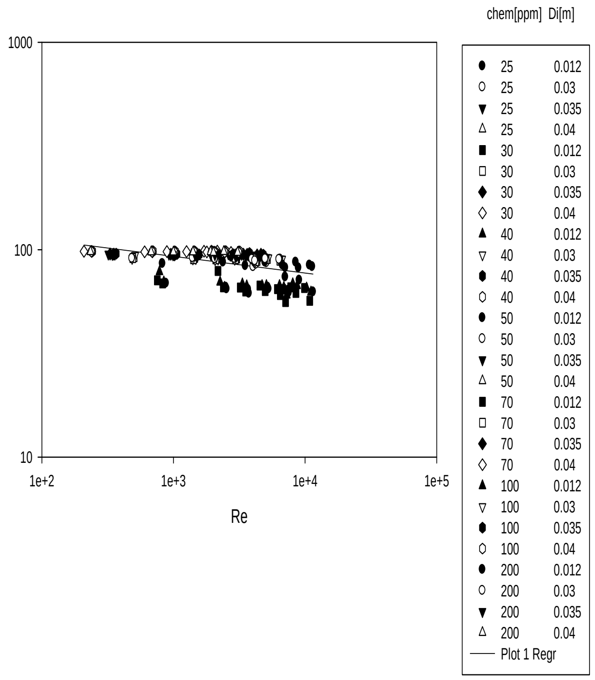

Fig. 13 Correlation of percentage drag reduction

V. CONCLUSIONS

The following conclusions are drawn from the present study

1. The percentage drag reduction varied between 87 to 97% as the coaxial disc diameter increases from 0.03 m to 0.04 m.
2. The percentage drag reduction of 89 to 93% is observed as the polyacrylamide concentration is varied from 50 to 200ppm.
3. The model developed for the present study is

$$\frac{1}{\sqrt{f}} = 1.15\log\left(\mathrm{Re}\sqrt{f}\right) - 0.45$$

The present experimental data have been compared with Prandtl Karman, Virk and Choi and had revealed that present model is more general and can predict friction in annular pipe flow. The correlation for drag reduction and Reynolds number is presented here under DR=2.2 $Re^{-0.0803}$.

NOMENCLATURE

L	Length of Test section, m
D	Diameter of conduit, m
d_i	Diameter of the annular pipe, m
D_{eq}	Equivalent diameter, m
V	Velocity of the fluid (m/s)
ρ	Density of fluid, Kg/m^3
μ	Viscosity of fluid, Kg/m-.sec
f	Friction factor, $\Delta p.gc.d/2L.\rho.V^2$
Re	Reynolds number, DVρ / μ
ΔP	Pressure drop, N/m^2
g_c	Gravitational constant,
T	Temperature of fluid,
Q	Volumetric flow rate, m^3/sec
E1	Entrance calming section
E2	Exit calming section
T	Test section
V_1, V_2	Gate valve
P_1, P_2	Pressure taps
F	Flange
G	Gland nut
TS	Storage tank
P	Centrifugal pump
R	Rotameter
u^+	Dimensionless velocity, u/u^*
y^+	Dimensionless radial distance from the wall, $y\,u^*/\nu$
E	Energy consumed using annular pipe in the conduit, N/m^2
E_o	Energy consumed for empty conduit, N/m^2
u^*	Friction velocity
τ_w	Shear stress at wall, N/m^2
U_b	Mean velocity
η_w	Viscosity at the pipe wall
γ_w	Local shear rate at the wall
y_0	Thickness of laminar sub layer
$R(h^+)^{11}$	Roughness momentum transfer function
C_A	Polymer concentration
C_{AS}	Solubility of PAA
DR%	Drag Reduction Percentage

DRA Drag Reducing Agent
MW Molecular weight
PAA Polyacrylamide
CMC Sodium Carboxy-methylcellulose
PEO Polyethylene oxide
PIB Poly-isobutylene
PPM Parts per million

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