POLYMER ADSORPTION IN POROUS MEDIA FLOWS

by

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ABSTRACT

Studies were conducted on the apparent solution viscosities and polymer adsorption and transport in the flow of dilute aqueous solutions of two polyacrylamide polymers (ionic and nonionic) in beds packed with stainless steel spheres. Apparent viscosities were measured for various polymer concentrations using the Cannon-Fenske viscometer and were evaluated for three diameters of the spherical packing. The apparent solution viscosities were found to be higher for the smaller diameter spheres. For the two polymers studied, the ionic polymer yielded the greater apparent viscosity at the same polymer concentration.

Polymer adsorption zone thicknesses were evaluated as a function of polymer concentration, packing size and the parameter τ_{R_h}. The adsorption layer thickness was found to be of the order of 0.001 cm. and to increase with polymer concentration and to approach a limiting value, with increasing τ_{R_h} and packing size.

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The author wishes to thank Dow Chemical Limited, Michigan for providing polyacrylamide required for this work.

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NOMENCLATURE

D_c	Diameter of Column
D_p	Sphere diameter
k_i	Impermeability factor, the Kozeny-Carman constant
L	Length of packed bed
$\bar{M}_w$	Molecular weight of polymer
p'	Potential drop
Q	Flow rate
$\sqrt{\overline{r^2}}$	Root-mean-square end to end distance of a Polymer macromolecule
R_h	Hydraulic radius
R_p	Sphere radius
ΔR_p	Increase in sphere radius due to adsorption
$\langle u \rangle$	Average velocity; $\langle \bar{u} \rangle = \frac{\langle u \rangle \eta}{R_h \tau R_h}$
u_s	Superficial velocity
u_s'	Superficial velocity dificiency
u_w	Average velocity dificiency; $\bar{u}_w = \frac{u_w \eta}{R_h \tau R_h}$
Δ	Adsorption layer thickness; $\bar{\Delta} = \Delta / R_p$
ε	Porosity of packed bed
ε_{ad}	Porosity in packed bed with polymer adsorption
V_p	Volume of particle
η_s	Viscosity coefficient defined by eq. (3.5)

η Viscosity of solution in mainstream

τ_{R_h} Shear stress difined by $R_h \ (P_O - P_L) \ / L$

Chapter I

INTRODUCTION

The recovery of reservoir oil from an oil well is normally conducted in two stages. The primary stage operating under autogenous pressure, yields only 10 to 20% of the available oil. To recover a further quantity of the residual oil, water flooding may be used. In secondary recovery of oil water is pumped under pressure into injection wells to force the oil to the producing well. When the mobility of the water is greater than that of oil, "viscous fingering" occurs, giving premature breakthrough of the water front. This results in loss of potentially recoverable oil from the less permeable zones, not penetrated by the water flood.

Various water soluble polymers have been used to reduce the mobility of the aqueous phase. The polymer bearing aqueous phase maintains a more regular front for a more effective sweep. This results in the recovery of a larger proportion of available oil. The process is referred to as polymer flooding.

It is recognized that when a polymer solution flows in a porous medium, a portion of the polymer is adsorbed[1-5]. Although the exact role of polymer adsorption in polymer flooding is not understood, some consequences are evident. First, it results in loss of polymer which may need to be replenished. Second, it reduces the permeability of the stratum which may result in partial or complete plugging. Third, the cost of polymer injection to maintain the required solution concentration level is increased

with polymer adsorption. The increased pressure required to achieve the flow may fracture the oil-bearing stratum. When this occurs, the polymer solution is lost in the fisures so formed and the oil cannot be recovered. Adsorbed material tends to plug the stratum, which is generally undesirable, except possibly in dealing with fractures.

It has been reported that the size of the polymer molecules in aqueous solution approaches the dimensions of the smaller pores in a porous stratum[3,6]. Polymer adsorption (retention) values have been reported for various conditions [6,7,8], but any correlation is difficult because of the different conditions of measurement. The effect of polymer concentration and particle size in porous media has not been systematically studied.

The purpose of this study was to gain insight into these questions and to provide adsorption data for a simplified porous structure. Three columns of packed stainless steel spheres were used in the experiments. Pusher-500, a partially hydrolyzed polyacrylamide, used industrially in enhanced oil recovery was chosen for investigation, as well as the nonionic polyacrylamide, with which comparison was made. Very dilute solutions of the polymers were used.

Chapter II

LITERATURE SURVEY

In secondary oil recovery by water flooding, the viscosity of the displacing fluid (water) is generally less than that of the oil, causing chanelling of the displacing fluid through the oil zone. This channelling, referred to as viscous fingering, causes the displacement front to spread and the process becomes uneconomical. Enhanced oil recovery could be achieved by improving the water-oil mobility ratio, which ensures a more uniform flow pattern, resulting in increased areal sweep efficiency. Mobility may be controlled by reducing the oil viscosity by application of heat, gas resaturation and miscible drives or by increasing the viscosity of the water phase. The use of such materials as glycerine, sugar or glycols for viscosity improvement is out of question economically. Consideration was then given to the use of more efficient synthetic water-soluble polymers as viscosity improvers. The large size of the polymer macromolecules makes it possible to effect a significant increase in the viscosity of the water phase even at low polymer concentrations.

Pye [9] observed an unusual phenomenon in the flow of aqueous polymer solutions in porous media. He found that the solution viscosities deduced from measurements conducted with a formation sample depart very markedly from viscometer determined values. This unusual departure from the expected behaviour, attributed to a resistance property of the polymer, was observed for only a few selected water soluble polymers, which include the extensive family

of acrylamide polymers and copolymers. The mechanism responsible for the observed resistance was not established although it appeared to bear a complex relationship to several factors.

Sadowski [2,10] referred to a phenomenon of adsorption and "gelling" of polymer molecules at the surface of a porous medium. This was observed in experiments in which the pressure drop across the packed bed was held constant. It was indicated that a simple layer of adsorbed polymer on the particle surfaces would not significantly change the bed structure. No attempt was made at a quantitative correlation of the adsorption affecting his constant pressure drop data.

Mungan, Smith and Thompson [7] investigated the adsorption of polymers as well as the transport and rheological characteristics and oil recovery enhancement in an effort to assess their effectiveness in waterflooding. Adsorption data for WSR-301 was obtained but the extent of adsorption in porous media flow was not estimated. Static adsorption experiments with silica powder were employed to get AP-30 adsorption data. It was established that the molecular weight distribution was unaltered during the experiments i.e. no scission of the polymer molecules occured during the experiments.

Rowland and Eirich [11] reported the thickness of films of polymethyl methacrylate, polyvinyl acetate and polystyrene adsorbed on pyrex glass. Film thicknesses reported were of the order of magnitute of the free coil diameters in solution and were directly proportional to the intrinsic viscosity of the polymer. It was concluded that polymers adsorb from solution in monolayers of

compressed or interpenterating coils.

Dauben and Menzie [12] investigated the physical parameters involved in the slow flow of high molecular weight polymer solutions in porous media. The interacting effects of polymer and porous media properties on the flow were considered. Experiments were conducted with the polyethylene oxides. The porous matrix consisted of a flow cell packed with glass beads. A higher than expected flow resistance was observed. This behaviour was observed to be a function of flow rate, pore size, polymer molecular weight and concentration. A theoretical explanation for the behavior was presented.

Kozicki et al. [1,13,14] showed that polymer adsorption leads to a negative effective velocity at the wall and demonstrated the applicability of their analysis to flow data involving aqueous polymer solutions. They also proposed a model to explain polymer adsorption and the transition to the separation phenomenon observed in tubes of different diameters under varying shear. It was postulated that polymer molecules adsorbed onto the tube wall give rise to a less mobile, more viscous layer in the vicinity of the solid surface which results in a decreased flow rate. As the shear stress is increased, these polymer molecules tend to uncoil and become elongated leading to the manisfestation of an effective velocity of slip at the wall in turbulent flow.

Harrington and Zimm [15] observed that the passage of several high molecular weight polymers in dilute solution flow through sintered glass disks results in an anomalous plugging of the disks, which is difficult to explain in terms of simple monolayer adsorption of the

polymer upon glass. They suggested that polymer adsorption on to the glass takes place and the observed unusual rheological behavior is associated with this adsorption.

Burcik [16] reported the reduction of water mobility by solutions of partially hydrolyzed polyacrylamide is brought by an increase in viscosity and also by a decrease in effective permeability to water. This decrease in water permeability is due to retention of the polymer within the pore channels, It was shown that solutions of partially hydrolyzed polyacrylamides may contain gel like complexes of a size comparable with that of the pores in a porous mediam. It was suggested these are largely responsible for the observed reduction in mobility and are formed by a crosslinking of some of the polymer molecules.

Gogarty [3] showed that mobility control occurs from a reduced permeability caused by polymer adsorption, mechanical entrapment at the smaller openings between pores and an effective viscosity determined by the average shear rate in the core. Thus rheological behaviour is as important in mobility control as permeability.

Mungan [8] studied the apparent solution viscosities, temperature stability, adsorption and transport in porous media of two partly hydrolyzed polyarcrylamide polymers. It was reported that polymer solution viscosities are higher at low shear rates. The higher molecular weight polymer produced greater viscosities at a given concentration and shear rate. Polymer adsorption was reported for batch type experiments. Adsorption was found to range from a low of 30 to a high of 880 µg/g.

Smith [6] studied the effect of polymer molecular weight, rock and fluid properties, flow rate and temperature for a partially hydrolyzed polyacrylamide solution. The results indicated that the adsorption of polymer varies from one type of mineral surface to another; calcium carbonate appeared to have a much greater affinity for polymer than silica. Polymer adsorption increased with salt concentration. The polymer effectiveness in reducing mobility was greatest at the lowest salinity and also for the polymers with the highest average molecular weight.

Jennings et al. [4] carried out a study of the factors influencing mobility control by polymer solutions and suggested different polymers produced decreased mobility in porous media by different mechanisms. These involve polymer matrix interactions and solution rheology. He was unable to correlate mobility decrease with the polymer adsorption. He suggested mobility control by polymer solution flow at normal field rates can occur by virtue of (a) a high viscosity at the flooding shear rate and (b) a polymer medium interaction, which is a consequence of the structure and large size of the macromolecules.

Arunachalam and Fulford [17] reported experimental evidence supporting an adsorptional mechanism for the pipe flow of dilute solutions of a polyoxy ethylene in water in the form of adsorption measurements. They observed increased polymer concentration at the pipe wall.

Hand and Williams [17] studied the adsorbed entangled layer formation at flow boundries from dilute polymer solutions by observing the kinetics of a wall layer depletion for different

polymers in a measurement of the time dependent solvent rate. The build up of a wall layer during the flow, by infrared adsorption measurements, was monitored.

Hirasaki and Pope [19] reported that the phenomena involved in the displacement of oil by polymer solutions are non-Newtonian effects, permeability reduction and polymer adsorption. Models have been developed to represent these effects as a function of polymer, brine and rock properties. The rheological behavior of the flow of polymer solution through porous media could be Newtonian at low flow rates. Permeability reduction is modeled as an adsorbed layer of polymer molecular coils that reduces the effective size of the pores. The polymer adsorption model assumes that polymer is adsorbed on the surface of a porous medium as a monolayer of molecular coils.

Szabo [20] carried out single phase flow and oil recovery tests in unconsolidated sands and in Berea sandstone core using C^{14} tagged partially hydrolyzed polyacrylamide solutions in which he compared polymer retention data with the data obtained from static adsorption tests. He showed that polymer retention by mechanical entrapment had a dominant role in determining the total polymer retention in short sand packs. The mechanical entrapment was less in the large-surface area Berea cores. Absolute polymer retention values showed an almost linear dependency on polymer concentration.

Entov and Polishchuk [21] investigated the use of solutions of polymers for displacement of petroleum from a porous medium. They showed that interaction between the polymer and the pore walls

play a significant rôle. Its sorption causes an interesting flow pattern in the porous medium. The mechanism of partially reversible polymer adsorption and partially irreversible polymer adsorption are explained. The effect of these phenomena on the displacement of petroleum was discussed.

Thomas [22] reported that polyacrylamide and polysaccharides reduce the permeability of straight glass capillary arrays by forming an adsorbed layer of polymer on the capillary wall that reduces the effective size of the capillary. The effective thickness of the polymer layer on the glass surface was about 0.2 to 0.3 micron in 1200-ppm brine. It was concluded that the reduction of water mobility by polymers in a porous medium, over and above the effect of increasing the viscosity, results from an adsorbed layer of polymer on the pore walls, and from mechanical entrapment in pore constriction and small pores.

Dominguez and Willhite [23] studied the polymer retention and flow characteristics of a solution of partially hydrolyzed polyacrylamide in a porous teflon core, in which adsorption was considered to be negligible. They showed that high molecular weight, partially hydrolyzed polyacrylamide are retained during flow through porous media by the combined mechanism of adsorption and mechanical entrapment.

Hanna [24] studied the flow of a dilute aqueous solution of Polyox (WSR-301 and coagulant) a high molecular weight polymer in beds of packed spheres of stainless steel and Jaytron plastic. He reported the adsorption layer thickness for slow flow rate and

correlated the drag reduction with the polymer adsorption.

Son[25] investigated the adsorption and flow behavior of Polyox (coagulant and WSR-301) in the vicinity of the tube wall during uniform laminar flow. The thickness of the adsorption layer in laminar flow was reported and correlated with drag reduction in turbulent flow by a mathematical equation with polymer macromolecular size and tube diameter. It was suggested that the polymer adsorption could be a basis for the turbulent drag reduction.

Chapter III

THEORETICAL BACKGROUND

In steady, laminar flow of a dilute polymer solution through a tube the shear stress τ_R is determined by the relationship [1]

$$\tau_R = \frac{4\eta\ (\langle u \rangle + |u_w|)}{R} \qquad (3.1)$$

The viscosity η may be assumed to be independent of shear stress on shear rate, $\langle u \rangle$ is the average velocity and u_w is the average velocity deficiency attributable to polymer adsorption onto the wall of conduit.

The analogous equation for porous media flow is the following:

$$\frac{(\langle u \rangle - u_w)}{R_h} = \tau_{R_h/k_i}\ \eta \qquad (3.2)$$

$$\text{or} \quad 1/k_i = \eta\ (\langle u \rangle - u_w)\ /\tau_{R_h} R_h \qquad (3.3)$$

where k_i, the Kozeny-Carman constant (impermeability factor), is a function of the bed geometry.

By making equation (3.3) dimensionless we get:

$$1/k_i = \langle \bar{u} \rangle - \bar{u}_w \qquad (3.4)$$

equation (3.2) can be rewritten:

$$\tau_{R_h} = \eta_s \frac{2\langle u \rangle}{R_h} \qquad ..(3.5)$$

where $\eta_s = \frac{k_i}{2}\left(1-\frac{\bar{u}_w}{\langle \bar{u} \rangle}\right)$

and $1 = \frac{2\eta_s}{\eta} \langle \bar{u} \rangle \qquad ..(3.6)$

by combination of equation (3.3) and (3.6) we get:

$$1/k_i = \frac{1}{2}\ \eta\ /\eta_s - \bar{u}_w \qquad ..(3.7)$$

Equation (3.7) provides a simple method for evaluating $\bar{u}_w$ from experimental values of η, η_s, k_i.

Relation between adsorption layer thickness and dimensionless average velocity deficiency.

The average velocity in packed bed flow without polymer adsorption is:

$$\langle u \rangle = \frac{\tau_{R_h}}{k_i}\frac{R_h}{\eta} \qquad ..(3.8)$$

where $\langle u \rangle = \frac{u_s}{\varepsilon}$ and $\tau_{R_h} = (P_o - P_L)\ R_h/L$

from this superficial velocity becomes:

$$u_s = \frac{P_o - P_L}{k_i \eta L} R_h^2 \varepsilon \qquad ..(3.9)$$

Similarly, the superficial velocity in the presence of polymer adsorption can be represented by:

$$u_{s,\,ad} = \frac{P_o - P_L}{k_i \eta L} R_{h,ad}^2 \varepsilon_{ad} \qquad ..(3.10)$$

Hence the superficial velocity deficiency due to adsorption of polymer is given by:

$$u_s' = u_{s,\,ad} - u_s$$

$$= \frac{P_o - P_L}{k_i \eta L} [R_{h,ad}^2 \varepsilon_{ad} - R_h^2 \varepsilon] \qquad ..(3.11)$$

and the void velocity deficiency by :

$$u_w = u_s' / \varepsilon$$

equation (3.11) is rearranged to:

$$u_w = \frac{P_o - P_L}{k_i \eta L} [R_{h,ad}^2 \frac{\varepsilon_{ad}}{\varepsilon} - R_h^2] \qquad ..(3.12)$$

by dividing equation (3.12) by R_h^2 and substituting:

$$\tau_{R_h} = R_h \frac{P_o - P_L}{L} \quad \text{we get:}$$

$$u_w = \frac{R_h \tau_{R_h}}{\eta k_i} \left[\frac{\varepsilon_{ad}}{\varepsilon} \frac{R_{h,ad}^2}{R_h^2} - 1\right] \qquad ..(3.13)$$

or $$\bar{u}_w = \frac{\eta u_w}{R_h \tau_{R_h}}$$

$$= {}^1/k_i \left[\frac{\varepsilon_{ad}}{\varepsilon} \frac{R_{h,ad}^2}{R_h^2} - 1\right] \qquad ..(3.14)$$

or $$\eta / \eta_s = \frac{2}{k_i} \frac{\varepsilon_{ad}}{\varepsilon} \frac{R_{h,ad}^2}{R_h^2} \qquad ..(3.15)$$

by substituting $R_h = \varepsilon R_p/3\,(1-\varepsilon)$ in equation (3.15) we get:

$$\eta / \eta_s = {}^2/k_i \left[\left(\frac{\varepsilon_{ad}}{\varepsilon}\right)^3 \left(\frac{R_{p,ad}}{R_p}\right)^2 \left(\frac{1-\varepsilon}{1-\varepsilon_{ad}}\right)^2\right] \qquad ..(3.16)$$

Assuming the radius of each particle is increased by ΔR_p and the new radius is $R_{p,ad}$:

$$R_{p,ad} = R_p + \Delta R_p \qquad ..(3.17)$$

we can write:

$$\left(\frac{R_{p,ad}}{R_p}\right)^2 = \left(\frac{R_p + \Delta R_p}{R_p}\right)^2$$

or $$\Delta^2 = (1 + \bar{\Delta})^2 \qquad \ldots (3.18)$$

The effective porosity of the bed with polymer adsorption is given by:

$$\varepsilon_{ad} = 1 - \left(\frac{\text{Volume of particles with adsorbed polymer}}{\text{Total volume of bed}}\right)$$

$$= 1 - \left(\frac{\text{Volume of particles}}{\text{Total volume of bed}}\right) \left[1 + \frac{\Delta V_p}{\Delta R_p} \frac{\Delta R_p}{Vp}\right]$$

now $$\frac{\Delta V_p}{\Delta R_p} = \frac{d\ V_p}{d\ R_p} = 4\pi R_p^2$$

volume of particle with adsorption = $V_p + \Delta V_p$

$$V_{p,ad} = V_p + \Delta V_p$$

$$= V_p \left(1 + \frac{\Delta V_p}{V_p}\right)$$

$$V_{p,ad} = {}^4/_3\ \pi R_{p,ad}^3$$

$$= {}^{4}/_{3}\,\pi R^{3}\,(1+\bar{\Delta})^{3}$$

$$\varepsilon_{ad} = 1 - (1-\varepsilon)\left(1 + \frac{4\pi R_p^2\,\Delta R_p}{\frac{4}{3}\pi R_p^3}\right) \qquad ..(3.19)$$

$$\frac{}{\varepsilon} = 1 - (1-\varepsilon)(1+3\bar{\Delta})$$

$$1 - \varepsilon_{ad} = (1-\varepsilon)\,(1+3\bar{\Delta})$$

or $$\varepsilon_{ad} = \varepsilon - 3\bar{\Delta}\,(1-\varepsilon) \qquad ..(3.20)$$

similiarly:

$$\left(\frac{1-\varepsilon}{1-\varepsilon_{ad}}\right)^2 = \frac{(1-\varepsilon)^2}{(1-\varepsilon)^2\,(1+3\bar{\Delta})^2} \qquad ..(3.21)$$

$$= \frac{1}{(1+3\bar{\Delta})^2}$$

by substitution:

$$\left(\frac{\varepsilon_{ad}}{\varepsilon}\right)^3 = \left(\frac{\varepsilon - 3\bar{\Delta}(1-\varepsilon)}{\varepsilon}\right)^3$$

$$= \left(1 - \frac{3(1-\varepsilon)\bar{\Delta}}{\varepsilon}\right)^3 \qquad ..(3.22)$$

by substititing equations (3.18), (3.19), (3.20), (3.21) and (3.22) in equation (3.16) we get:

$$\eta / \eta_s = \frac{2}{k_i} \frac{\left(1 - \frac{3(1-\varepsilon)\bar{\Delta}}{\varepsilon}\right)^3 (1 + \bar{\Delta})^2}{(1 + 3\bar{\Delta})^2} \qquad ..(3.23)$$

$\bar{\Delta}$ is evaluated numerically with help of experimental values of η , η_s and k_i.

Chapter IV

EXPERIMENTAL DETAILS

Polymers:

Two polymers, a nonionic polyacrylamide (supplied by Polysciences Inc. Pennsylvania) and Pusher - 500 a partially hydrolyzed polyacrylamide (supplied by Dow Chemicals, Michigan) were used in this investigation.

Solution Preparation:

The polymer solutions were prepared by preparation of a concentrate (approximately 0.1%) which was diluted to the desired concentrations, as needed. Initially, the weighed dry polymer was sprinkled uniformly onto the shoulder of a well developed vortex provided with a mechanically driven stirrer. Distilled water was used in preparations. The rate of addition of polymer was such so as to be dispersed over a period of 50 to 60 seconds. When all of the polymer was added, the stirrer speed was adjusted to keep the solid particles from settling to the bottom. The solution was stirred gently for approximately 3 hours. The concentrated solutions were stored at laboratory temperature in brown bottles for three to four weeks (without loss of effectiveness) and diluted to the test concentration, as required.

Characteristics of the Polymer Solutions:

Viscosities of the test solutions were measured by means of

the Cannon-Fenske Routine Viscometer (Viscometer No. 50, supplied by Cannon Instrument Co. Pennsylvania) at 21° C. The molecular weight of the polymers was calculated using the Scholtan's equation [26,27] and the root mean square end to end distance for the polymer macromolecules was calculated using the Flory-Fox equation [28]. Experimental data are reported in Appendix 1.

Polyacrylamide $\bar{M}_w = 5.23 \times 10^6$

$\sqrt{\bar{r}^2} = 3552.8$ Å

Pusher 500 $\bar{M}_w = 5.75 \times 10^6$

$\sqrt{\bar{r}^2} = 6320.4$ Å

Flow Experiments:

A schematic diagram of the packed bed and accessory piping is shown in figure 4.1. The column housing the bed pack was constructed of perspex. The diameter of each column was such that the ratio of column to sphere diameter was constant at 16.71.

Each column was randomly packed with stainless steel (sp.gr. 7.62) spheres supplied by General Bearing Ltd. The porosity of each bed was adjusted to 0.38.

The pressure taps were connected 5 cm below the top and above the bottom of the bed to give direct pressure measurements without correction for entrance / end effects, etc.

The fluid was received from the 25 litre tank and pumped by a

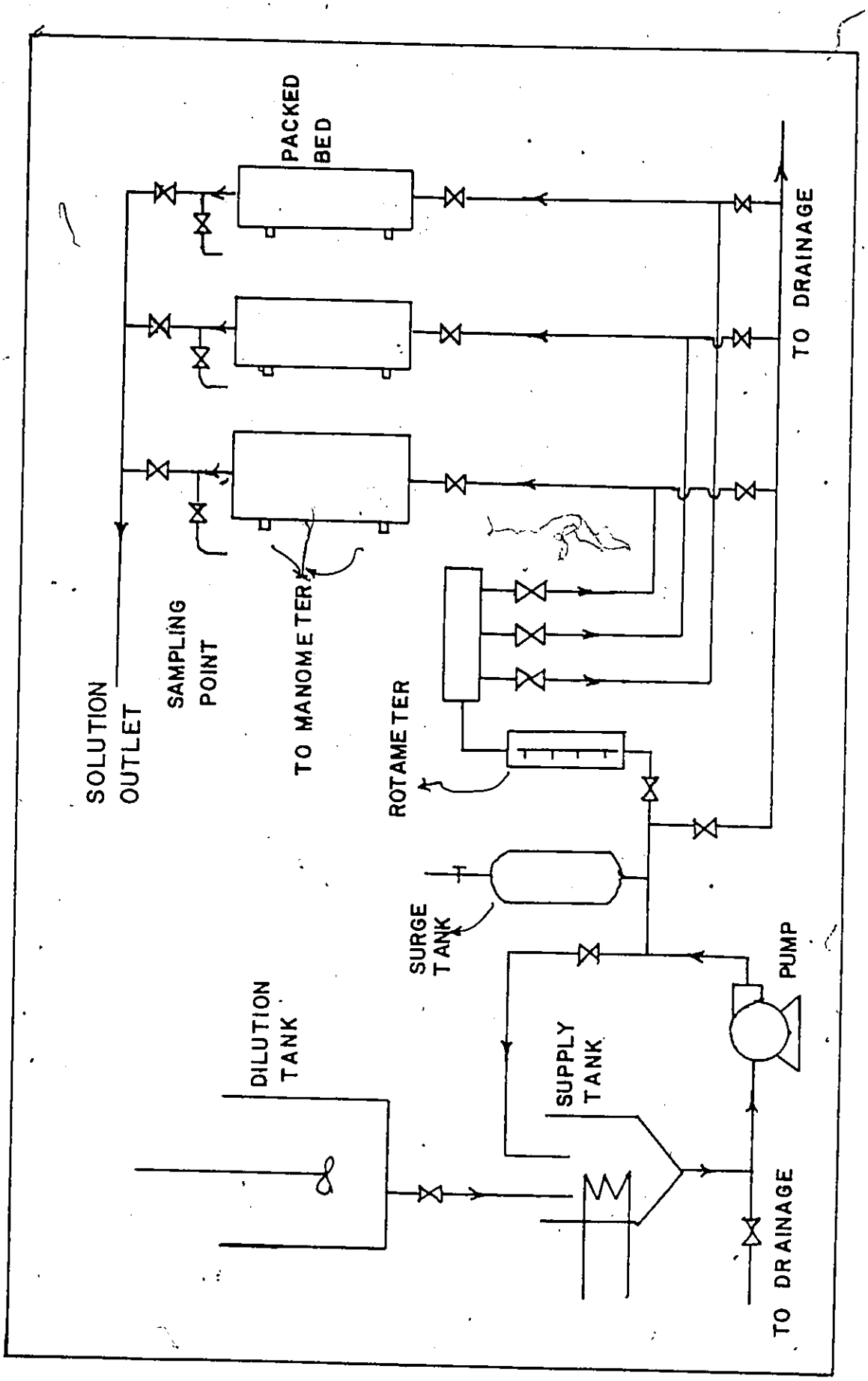


FIG. 4-1 SCHEMATIC DIAGRAM OF THE EQUIPMENT.

gear pump (Model: 507, supplied by Brown & Sharpe). The flow rate through the bed could be varied through a motor speed control mechanism and a bypass line. A surge tank was connected to the line to absorb dampness, slight fluctuations transmitted from the pump. The storage tank was equipped with a thermostat to maintain the temperature of the effluent solution at 21°C. The storage tank, piping and column were insulated to prevent heat exchange with the surroundings.

The flow rate was obtained by measurement of the volume of collected effluent in a measured time. Packed beds were cleaned by circulating distilled water for 4 hours after each run of a particular polymer solution concentration. It was ensured that there was no more polymer in the system by measurement of the viscosity of the distilled water used.

Physical Dimensions of Packed Bed

Diameter of Spheres D_p cm	Diameter of Column D_c cm	R_h cm	ε	L cm
0.1592	2.55	0.015239	0.38	29.7
0.2388	3.99	0.022918	0.38	37.4
0.3999	6.69	0.038382	0.38	37.4

Pressure Drop Measurement

The pressure drop across the column was measured with a differential Meriam oil (supplied by the Meriam Instruments. Specific gravity 1.19) in glass manometer. Fluid levels in the glass manometers were measured by means of a Cathetometer (supplied by the Precision Tool Instrument Co.) with an accuracy of 0.001 cm.

Evaluation of k_i

The Kozeny-Carman constant k_i was evaluated numerically by least square fitting of equation (3.9) individually to flow data obtained for the three beds by circulating distilled water. k_i was substantially the same for each of the three beds i.e. 5.00, 5.05 and 5.02 for the beds with sphere diameters of 0.1592, 0.2388 and 0.3999 cm respectively. Extensive studies of viscous flow involving packing of different sizes and covering a porosity range 0.34 - 0.45 have been made and values of k_i have been found between 4.5 and 5.1. Experimental data are reported in Appendix 2.

Chapter V

EXPERIMENTAL RESULTS AND DISCUSSION

The pressure drop measurements were collected as a function of flow rate for the flow of six dilute aqueous solutions of nonionic polyacrylamide (PAM) and Pusher - 500, a partially hydrolyzed polyacrylamide, in three beds packed with stainless-steel bearings of diameter 0.1592, 0.2388 and 0.3999 cm, respectively. The experimental data are presented in Appendix 3.

Flow Behaviour

Figures (5.1) and (5.2) show typical flow data for solutions of nonionic polyacrylamide and Pusher - 500, respectively. The plots of the data in the form of "shear stress" $\tau_{R_h} = \eta k_i$ ($\langle u \rangle - u_w$) $/R_h$ vs. $2\langle u \rangle/R_h$ are representative of the behaviour observed over the range of measurements. The non-linearity of the τ_{R_h} vs. $2\langle u \rangle/R_h$ curves indicates that the apparent viscosity coefficient defined in eq. (3.5) is a function of shear stress and particle diameter for a particular polymer concentration. This flow behaviour in porous media appears to be in part due to kinetic energy losses created by interaction of the polymer macromolecules and the walls of the porous media flow channels. These figures clearly indicate the wall effects.

In figure (5.3) and (5.4), we see the effect of the flow medium on the evaluation of the solution apparent viscosity. Here solution apparent viscosities evaluated for beds packed with spheres

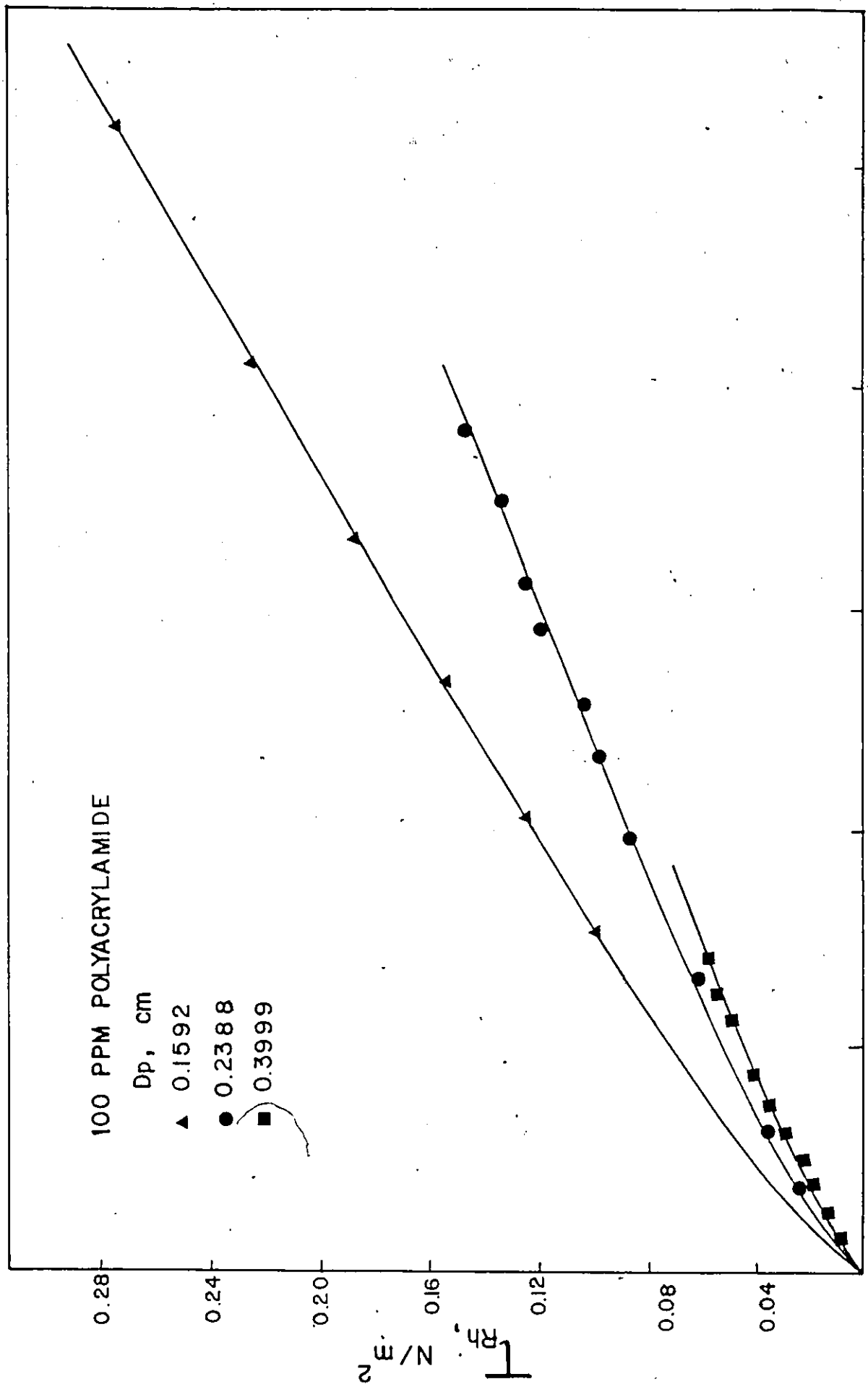


FIG. 5-1 PLOT OF τ_{Rh} VS. 2(u)/Rh.

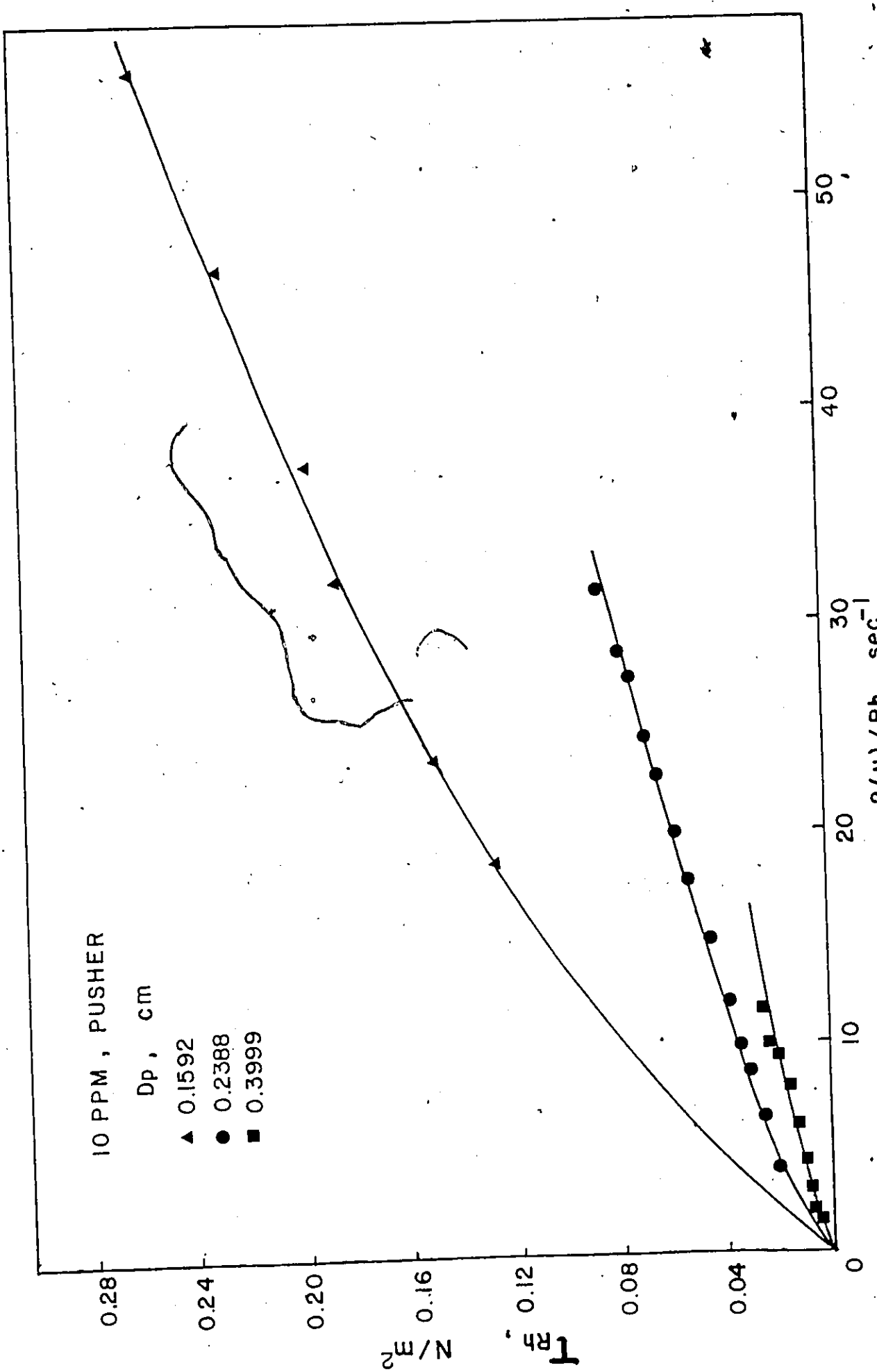


FIG.5-2 PLOT OF τ_{Rh} vs. 2(u)/Rh

are higher than corresponding viscosities measured using the Cannon-Fenske viscometer. The apparent solution viscosities are also higher for the smaller diameter spheres. These viscosity increases are not anticipated from the rheological behavior of the fluids. The increase in viscosity is attributed to the adsorption of polymers onto the surface of the spheres, the adsorbed polymer causes a reduction in the water mobility. Figure (5.3) and (5.4) show the apparent viscosity departure for partially hydrolyzed polyacrylamide is much more than for the nonionic polyacrylamide. The variation in apparent viscosity for the different packing sizes is also greater for the partially hydrolyzed polyacrylamide. The apparent viscosity for a given polymer solution increases with decreasing particle size; alternatively, the smaller pore size produces a higher apparent viscosity. The latter also depends on polymer molecular weight, concentration and the degree of hydrolysis. At higher polymer concentrations, macromolecules become entangled resulting in a sharp increase in the solution viscosity. Although the molecular weights of 5.2×10^6 and 5.7×10^6 do not differ significantly, the ionic polyacrylamide exhibited a significantly higher viscosity compared to the nonionic polycrylamide at all polymer concentrations employed. This increase in the viscosity is due to the expansion of the polymer chain caused by repulsive forces.

Adsorption Characteristics

When a polymer solution flows through a bed pack, physical adsorption is presumed to take place onto the surface of the flow

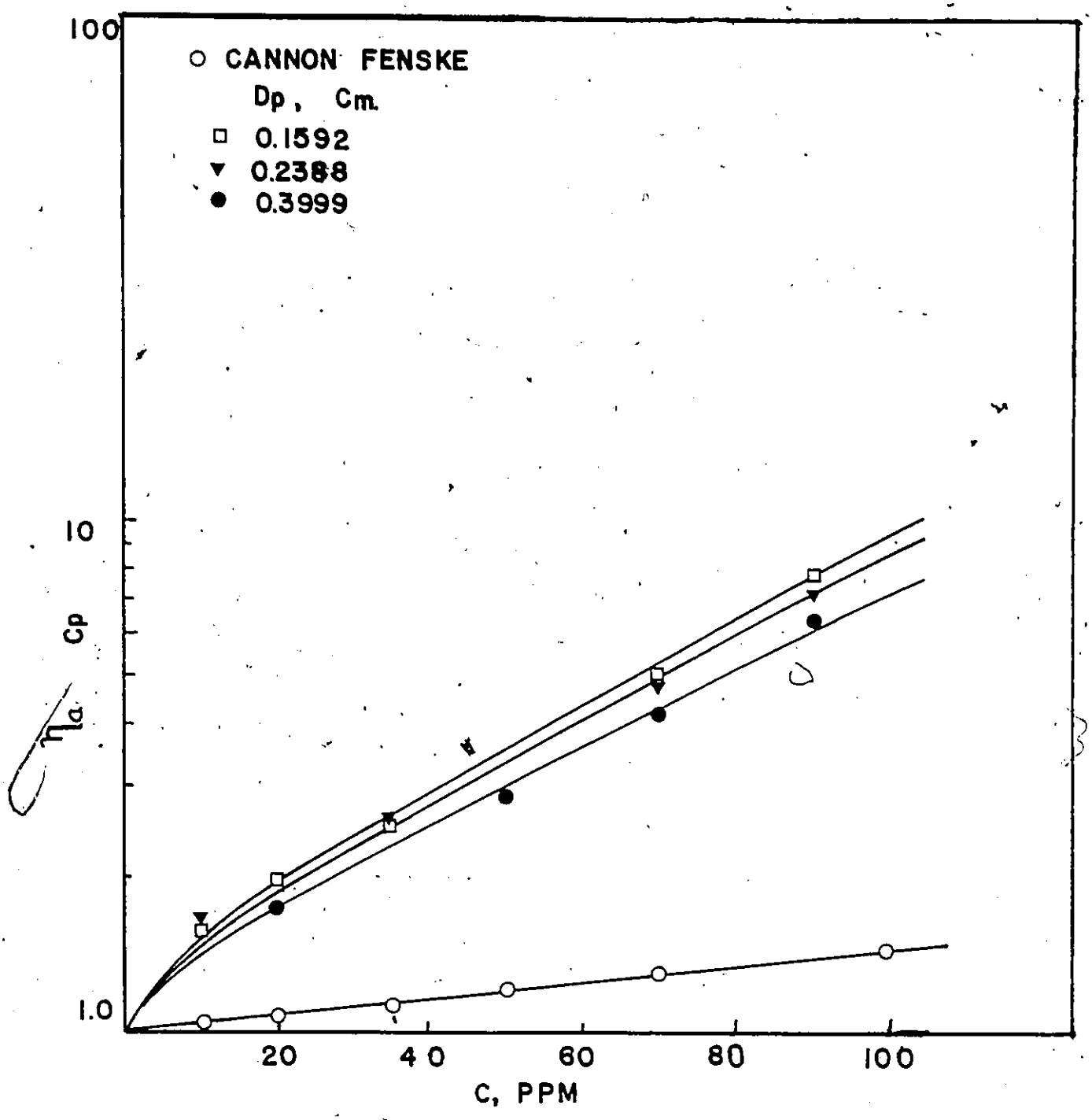


FIG. 5-3. APPARENT VISCOSITY Vs. CONC. OF POLYACRYLAMAIDE EVALUATED FROM VISCOMETER & POROUS BED DATA.

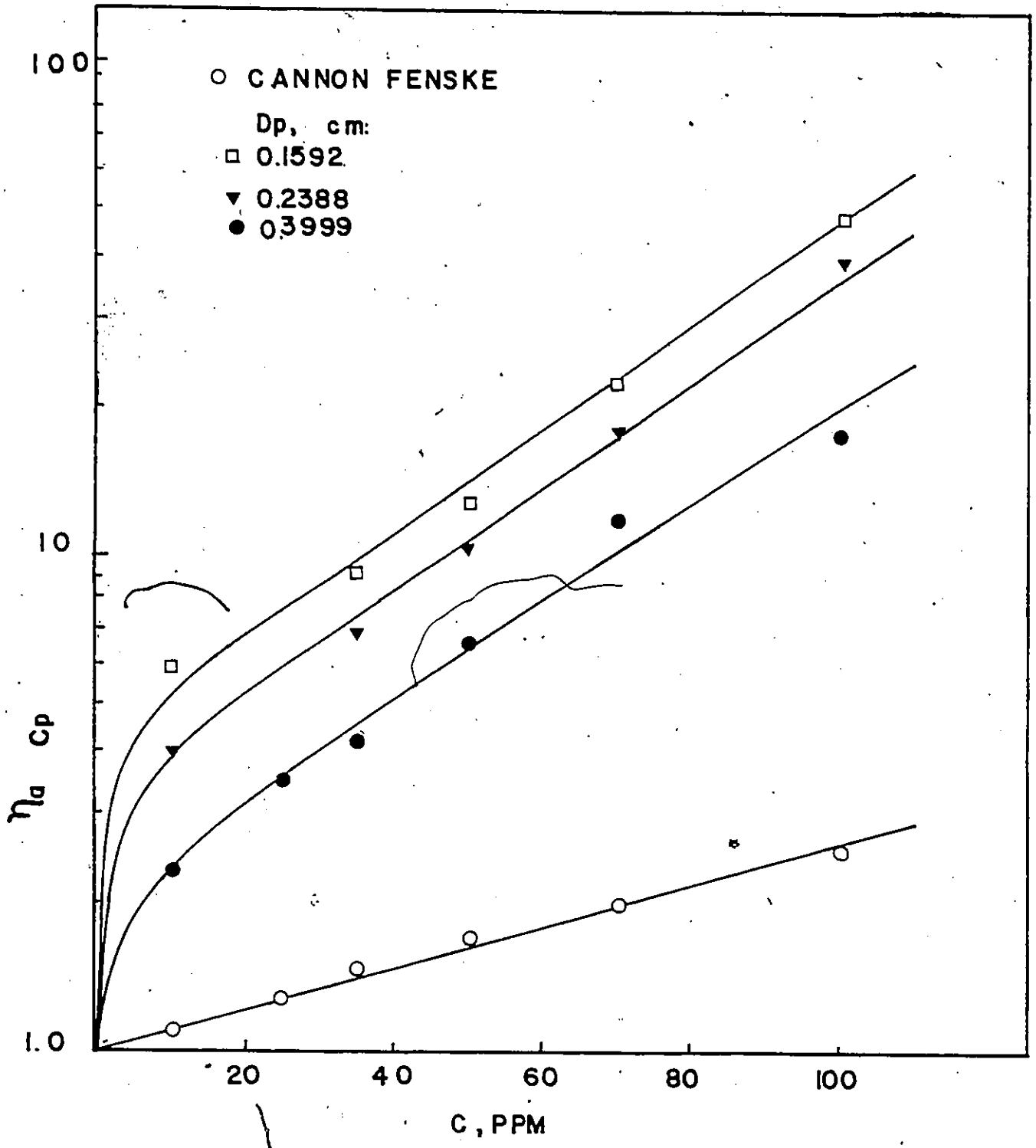


FIG. 5-4. APPARENT VISCOSITY Vs. CONC. OF PUSHER EVALUATED FROM VISCOMETER & POROUS BED DATA

channels. Although the channels are presumed large enough to allow polymer molecules to pass, the openings at contact points of spheres may trap molecules. These entrapped polymer molecules may restrict the fluid motion in the bed resulting in further reduction in the permeability of the medium. In high permeability beds, the polymer is retained mainly by physical adsorption within the voids, the retention by physical entrapment being assumed negligible. In steady-state flow, the flowing polymer concentration is uniform along the entire length of bed. This polymer concentration determines a constant adsorption layer thickness in every location in the packed bed.

Adsorption Layer Thickness

The dimensionless adsorption layer thickness $\bar{\Delta} = \Delta/R$ was calculated by means of equation (3.23). Since $\bar{\Delta}$ is determined from η/η_s, it is function of the variables affecting η/η_s i.e. "shear stress", polymer concentration in the bulk solution and packing size.

Effect of Polymer Concentration

The evaluations of the adsorption layer thickness are shown in figure (5.5) and (5.6) for the two polymer systems investigated as a function of polymer concentration, with particle diameter as parameter. It is observed that the adsorption layer thickness increases with increasing polymer concentration. The adsorption layer thickness for ionic polyacrylamide is greater than that for

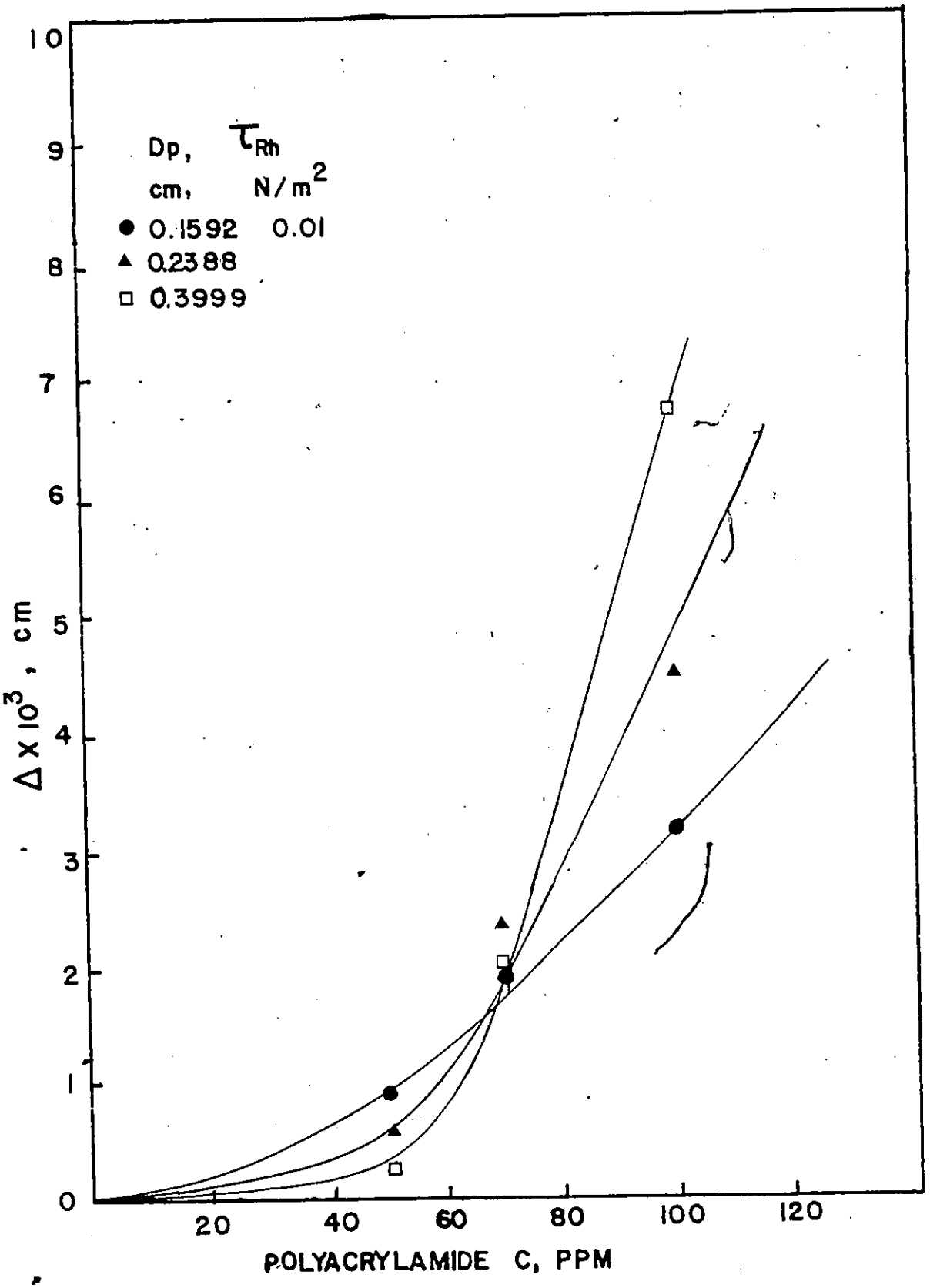


FIG. 5-5. PLOT OF Δ Vs. POLYMER CONC. WITH Dp AS PARAMETER

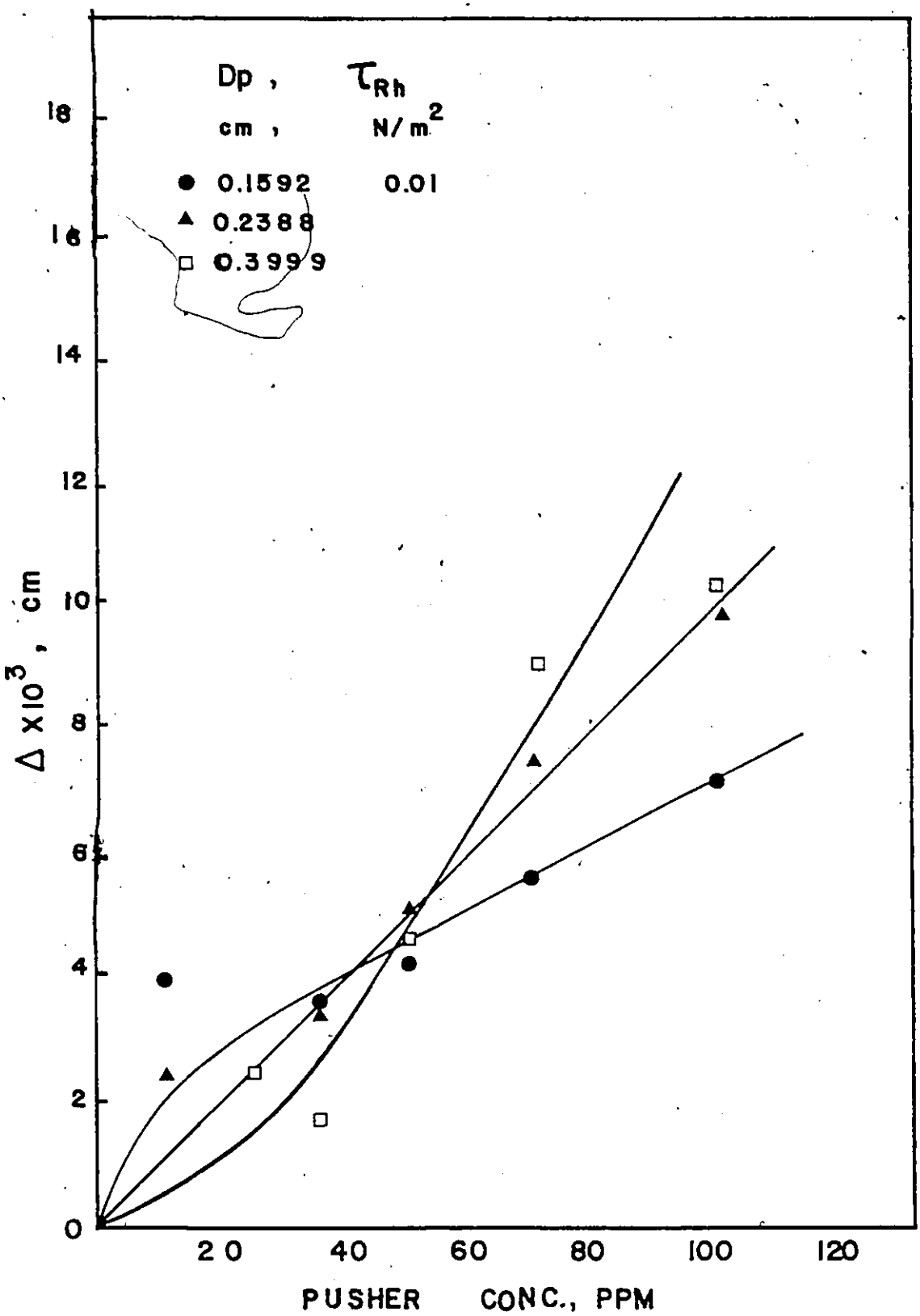


FIG.- 5-6. PLOT OF Δ Vs. POLYMER CONC. WITH Dp AS PARAMETER.

the nonionic polyacrylamide solution. This indicates higher polymer-wall interaction for ionic polymer compared to nonionic polymer. The adsorption layer thickness also increases with the size (diameter) of the packing. It is also observed that to a certain lower polymer concentration, the smallest particle size has a higher associated adsorption layer thickness than the largest particle size. Beyond this concentration, adsorption layer thickness for larger particle size increases more sharply.

Effect of packing diameter

Figures (5.7) and (5.8) show the influence of the diameter of the packing on the adsorption layer thickness. For the 50 ppm and 70 ppm nonionic polyacrylamide solution concentrations, the adsorption layer thickness attains a limiting value. For the 100 ppm solution, it appears that the plateau occurs at higher particle size. In figure (5.8) adsorption layer thickness for the 35 and 50 ppm ionic polyacrylamide solution concentration also approaches asymptotic value and stabilizes. Adsorption layer thickness for 70 and 100 ppm concentration solution first increases and also tends to stabilize at limiting values. The indication is that for a particular solution concentration a maximum adsorption layer thickness exists for each packing size.

Effect of Shear Stress, τ_{R_h}

In figure (5.9) through (5.11), the adsorption layer thickness is shown as a function of ionic polymer concentration at different

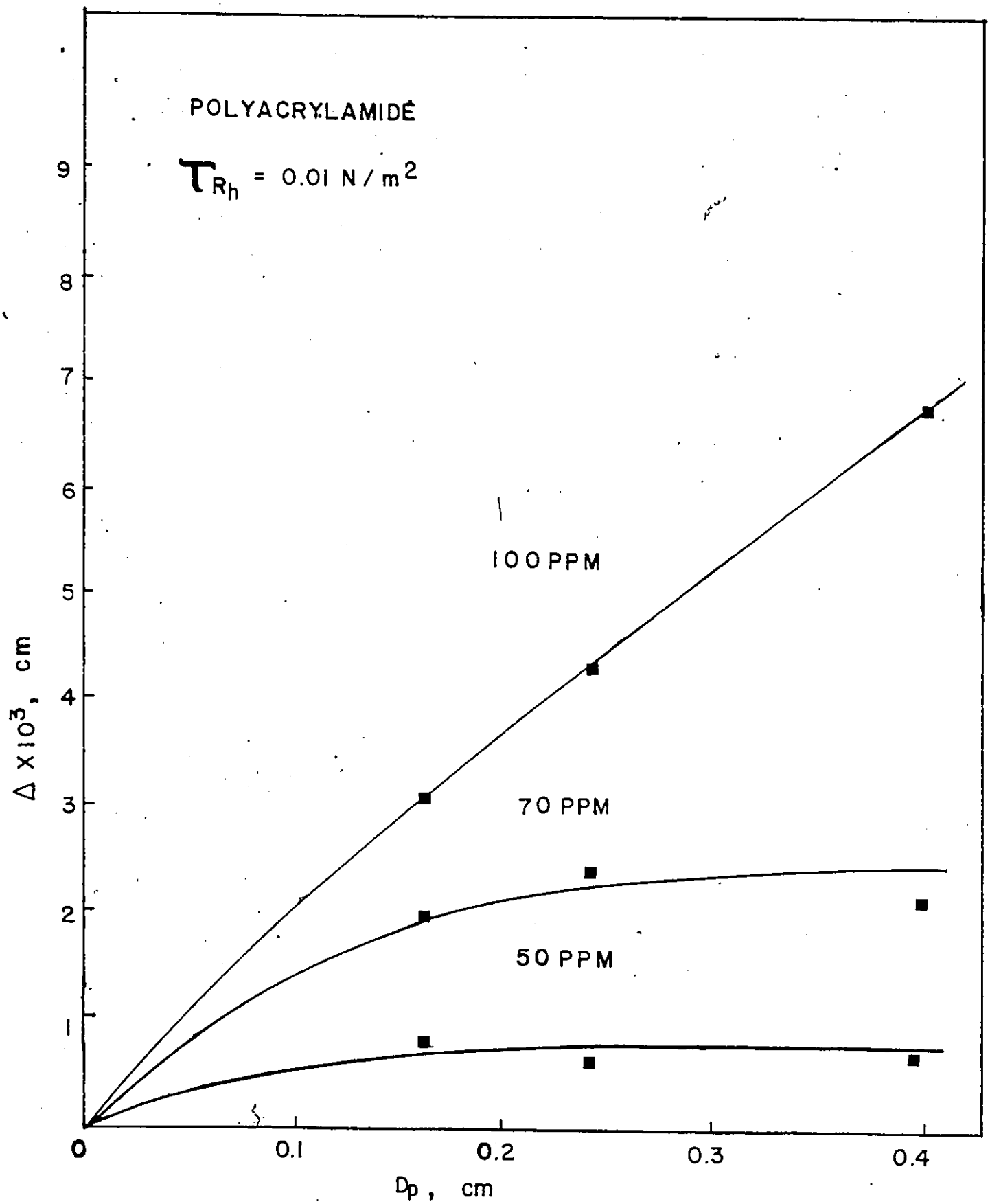


FIG. 5-7 PLOT OF Δ vs. PARTICLE DIAMETER

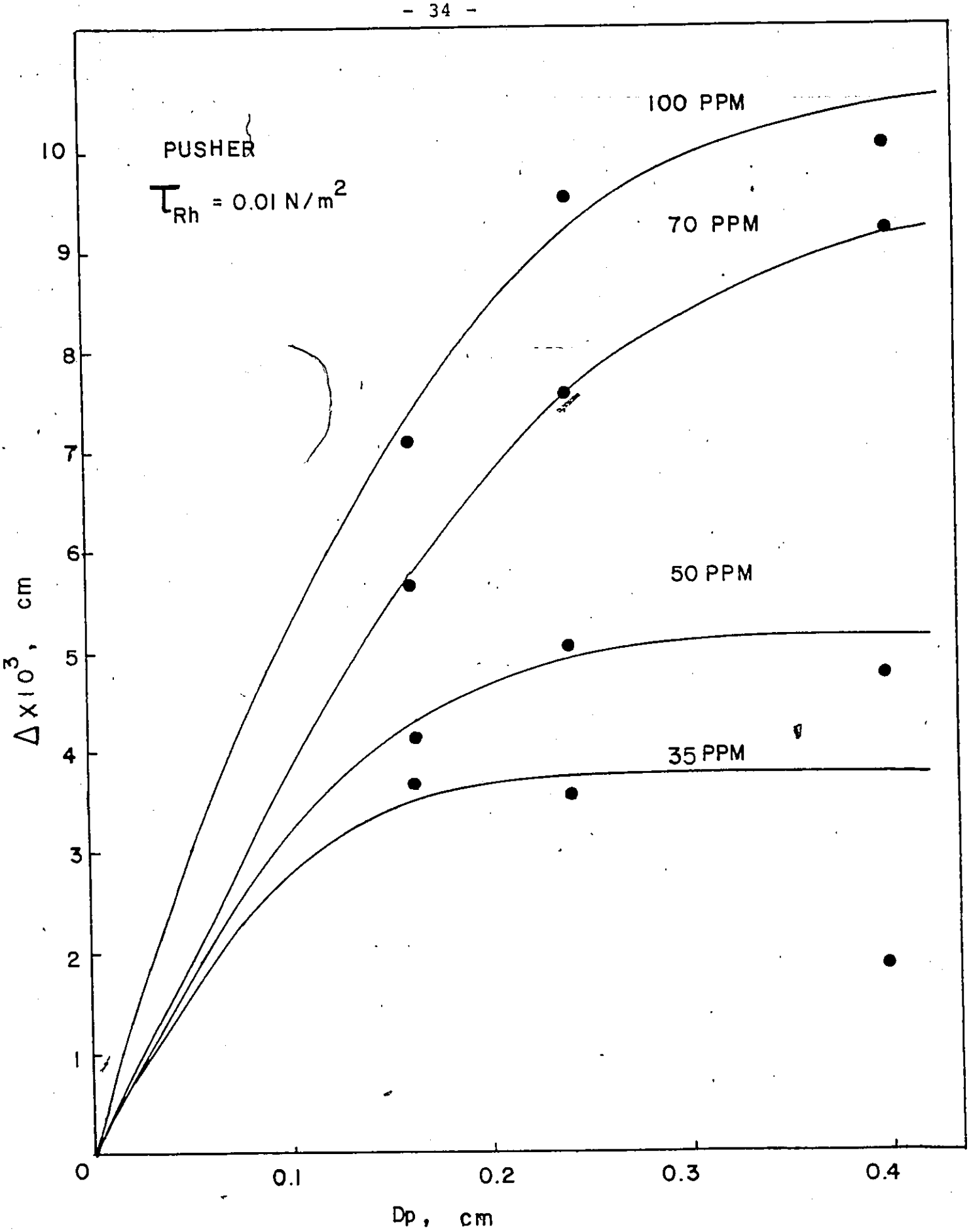


FIG. 5-8 PLOT OF Δ VS. PARTICLE DIAMETER.

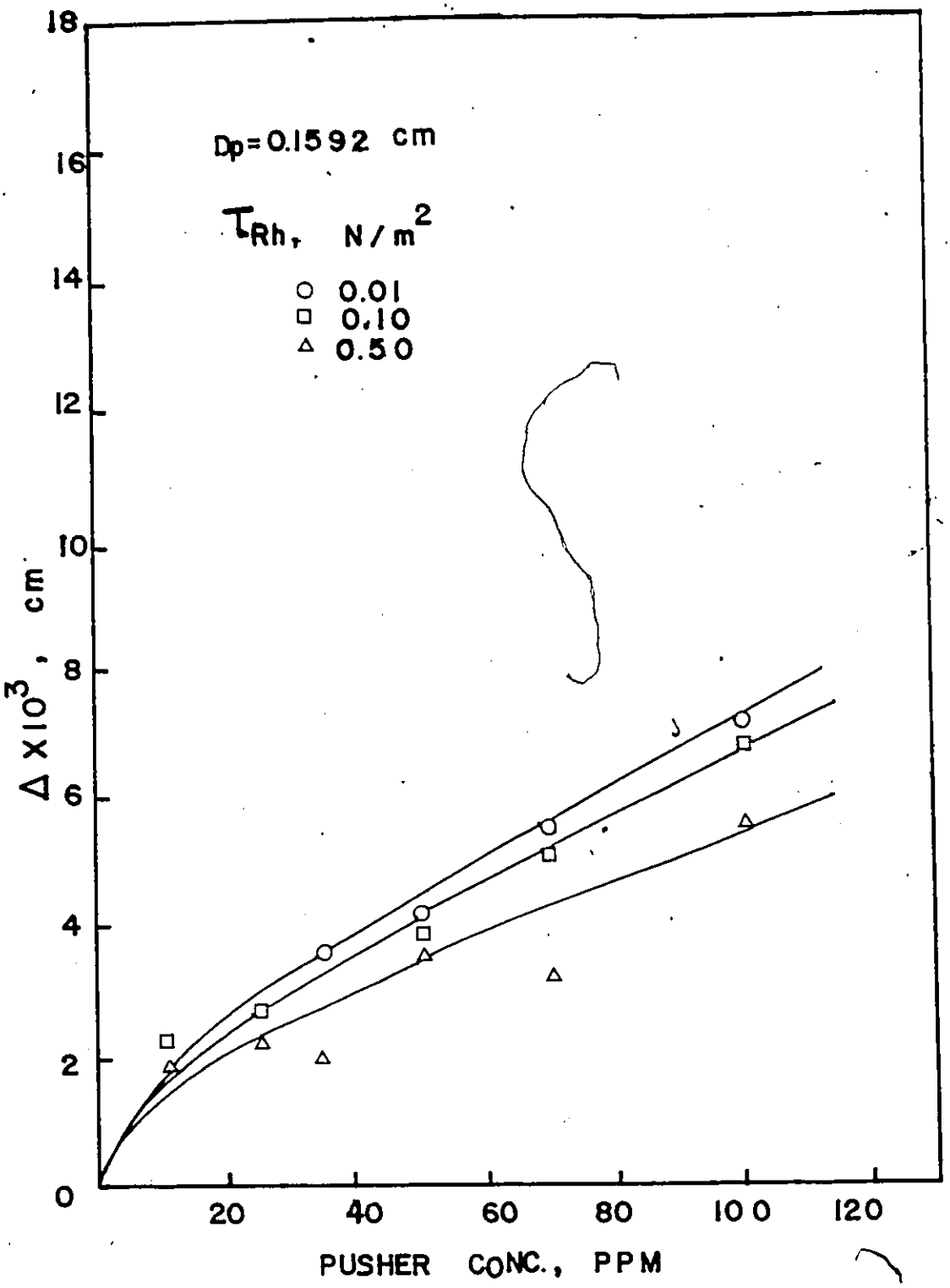


FIG. 5-9. PLOT OF Δ VS. POLYMER CONCENTRATION

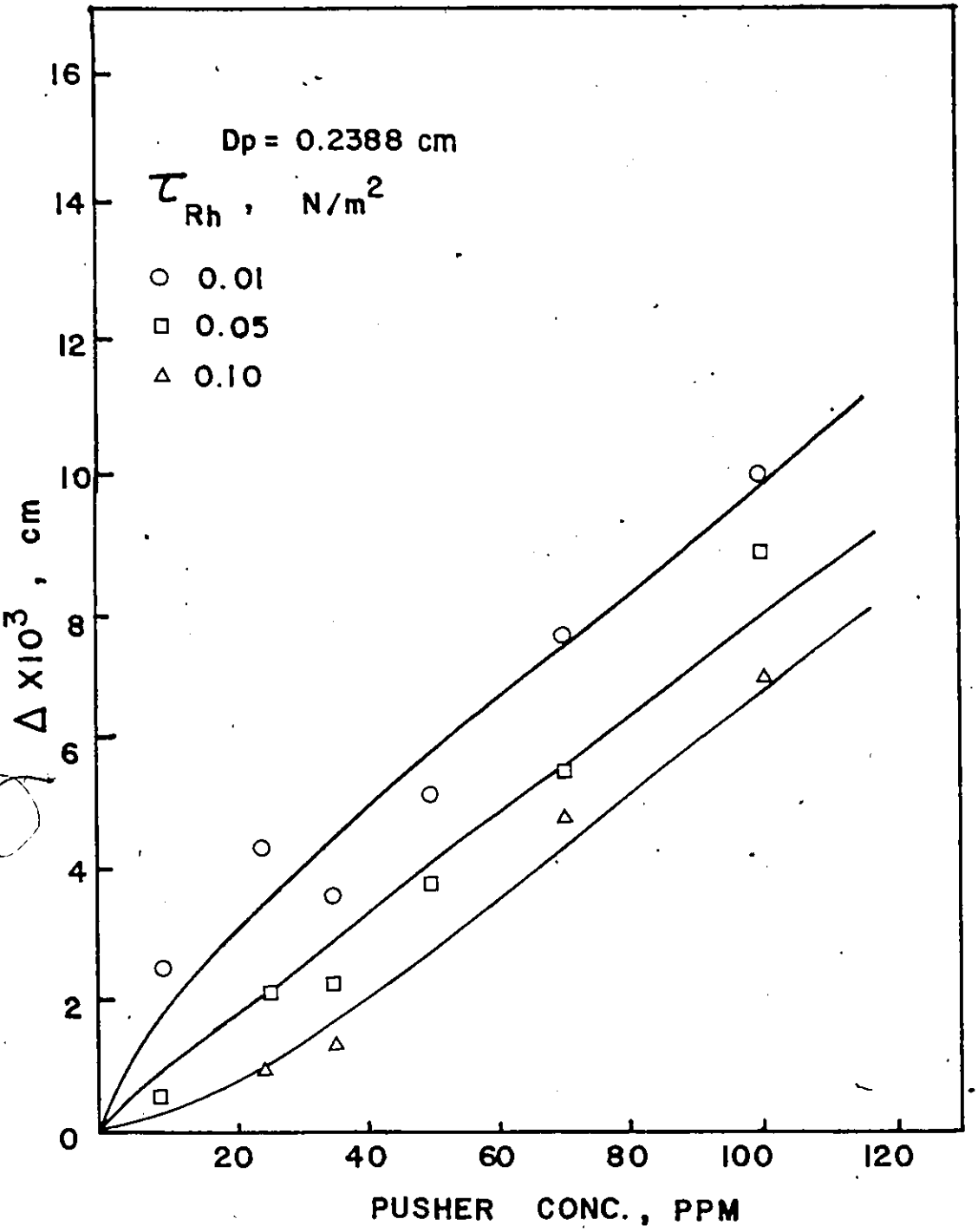


FIG. 5-10. PLOT OF Δ VS. POLYMER CONCENTRATION.

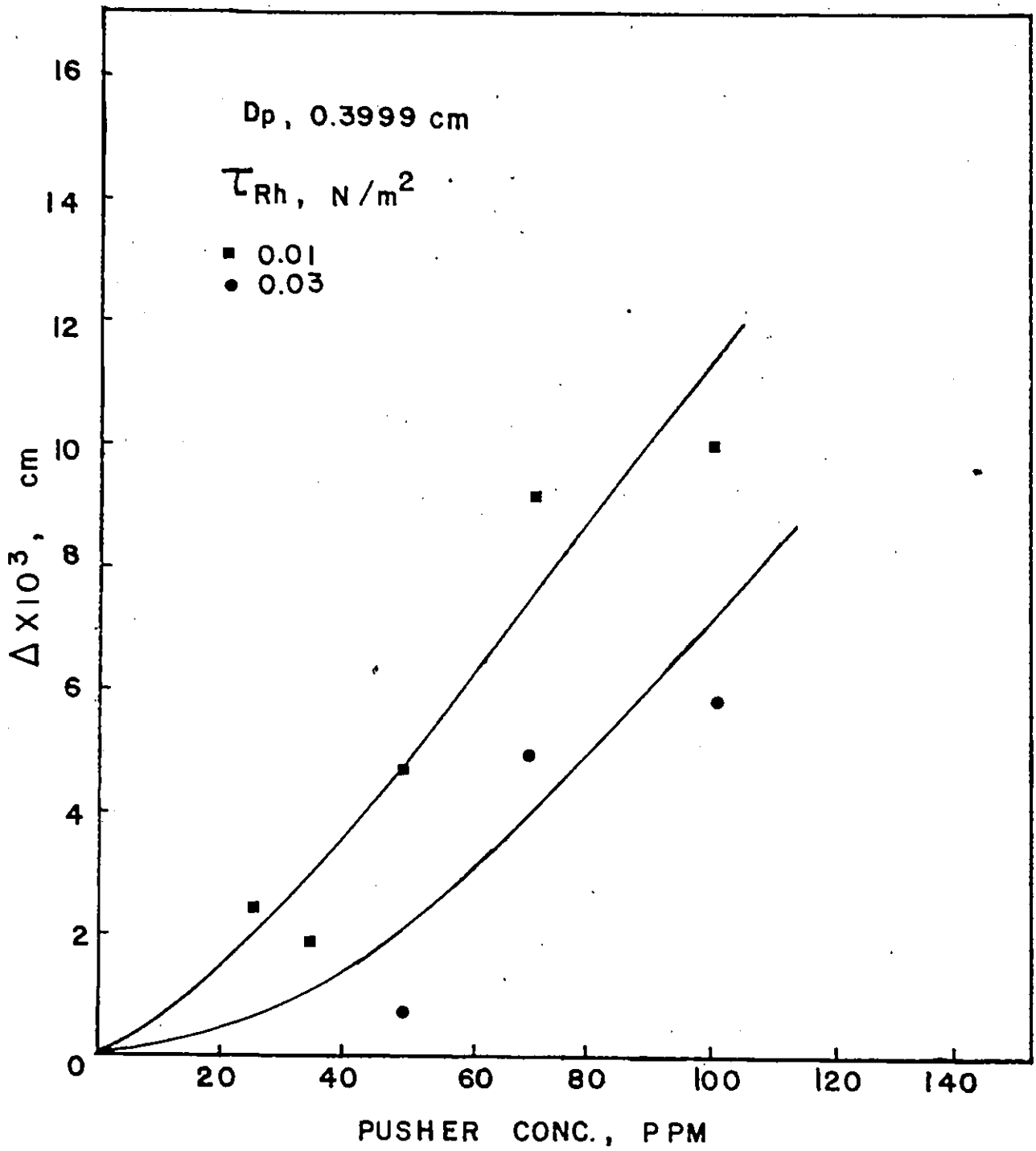


FIG. 5-11. PLOT OF Δ VS. POLYMER CONCENTRATION

values of the parameter τ_{R_h} for each of the particle sizes of diameter 0.1592, 0.2388 and 0.3999 cm. The adsorption layer thickness is observed to decrease with increase in shear stress parameter at the polymer solution concentrations involved. The polymer molecules dissolved in water by means of hydrogen bonding retain some of the structural identity while in solution. The random coil structure is easily deformed under an applied stress, and changes from its generally spherical orientation into elongated ellipsoids which extend more freely in the solvent and are released into the main stream from the adsorbed layer. The molecule, extending into the bulk fluid also acts as an attachment site for other molecules from immediately adjacent surfaces and for molecules still in the bulk fluid.

Adsorption layer thickness are plotted in figures (5.12) through (5.15) for both polymers investigated as a function of shear stress with solution concentration as parameter for two bed particle sizes. The behavior is similar for both the polymers. The adsorption layer thickness decreases with increasing shear stress initially then tends to approach a limiting value. The decrease in thickness from the initial thickness is almost twice in the case of 0.2388 cm sphere diameter to that of the 0.1592 cm sphere diameter. Assuming a monomolecular layer of polymer, the polymer molecules line up side by side, each with one end attached to the solid surface. It appears that relatively low levels of shear are required to remove the more loosely bound macromolecules from the adsorption zone. At the higher shear stress or flow rate conditions, the polymer macromolecules that are retained are more entangled and

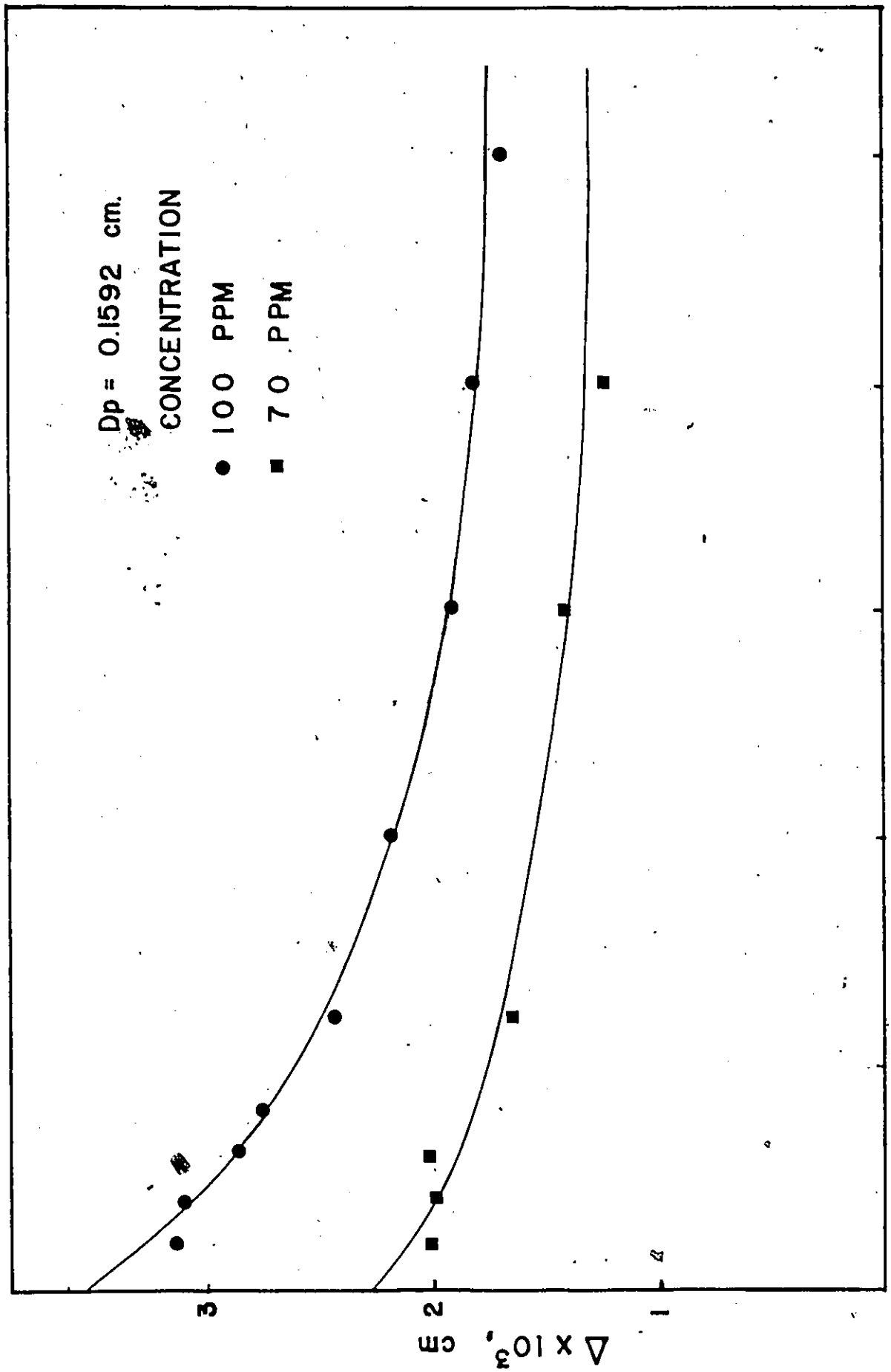


FIG. 5-12. PLOT OF Δ VS. τ_{Rh} FOR POLYACRYLAMIDE SOLUTIONS

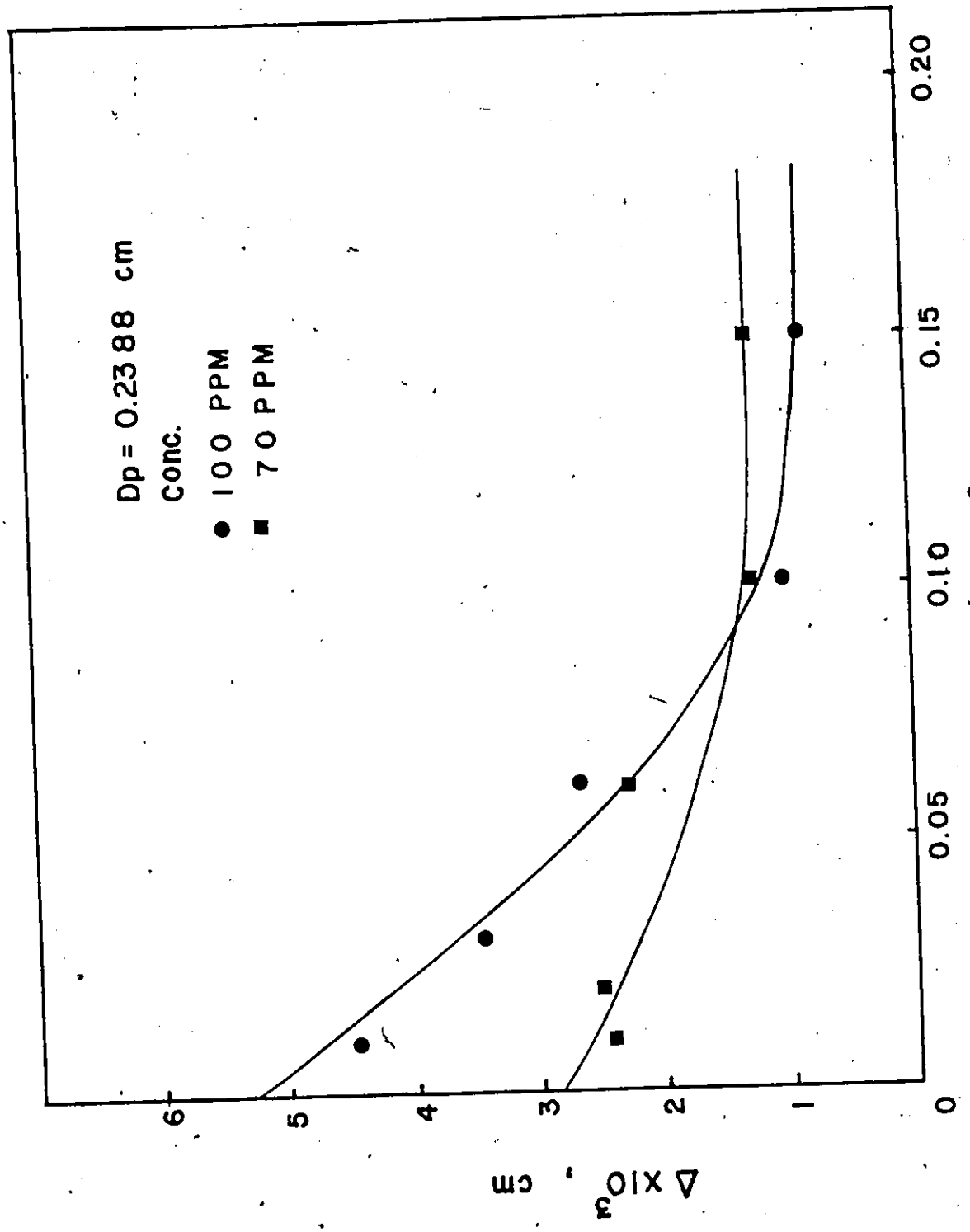


FIG. 5.13 PLOT OF Δ VS. τ_{Rh} FOR POLYACRYLAMIDE SOLUTIONS

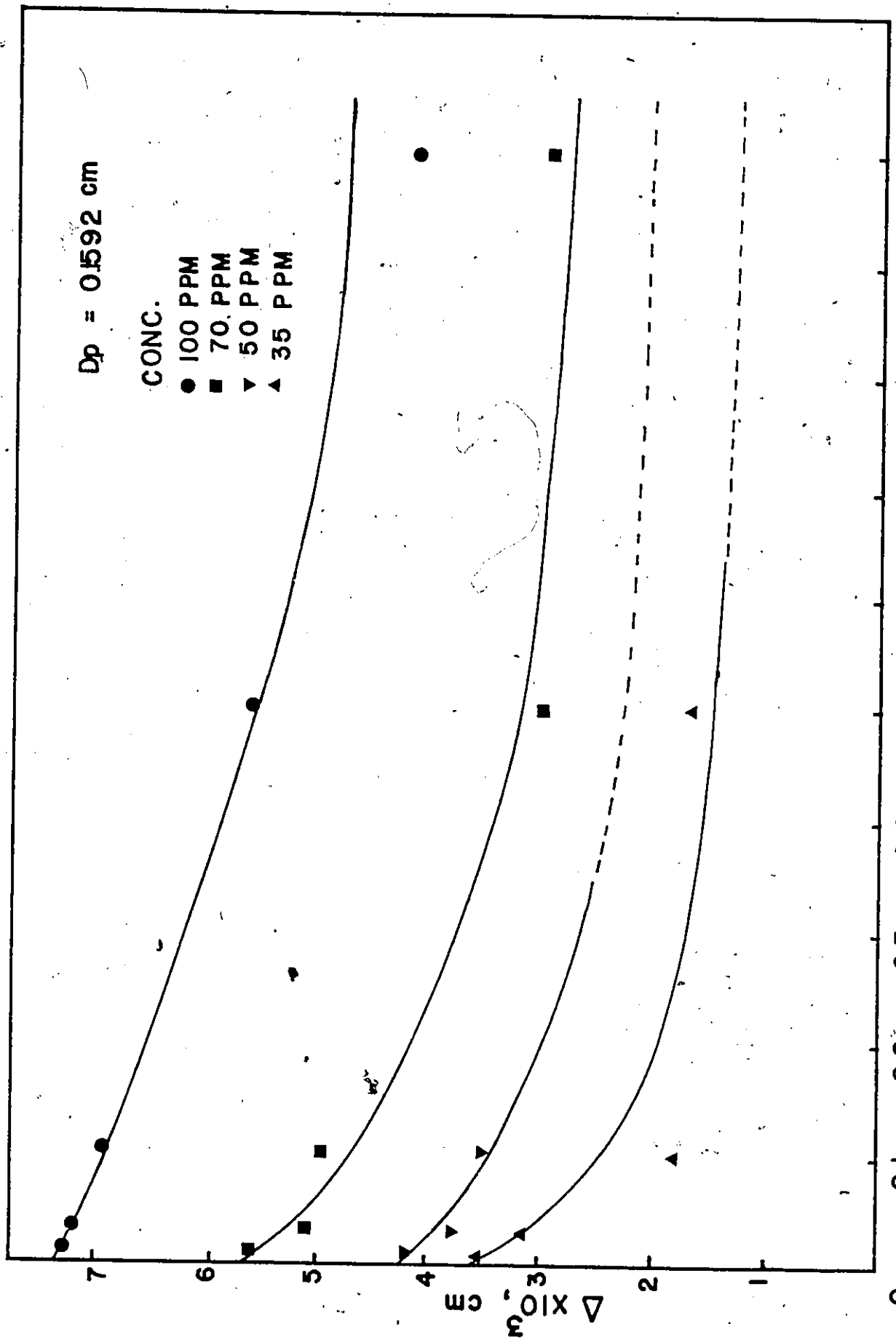


FIG. 5-14. PLOT OF Δ VS. τ_{Rh} FOR PUSHER SOLUTIONS

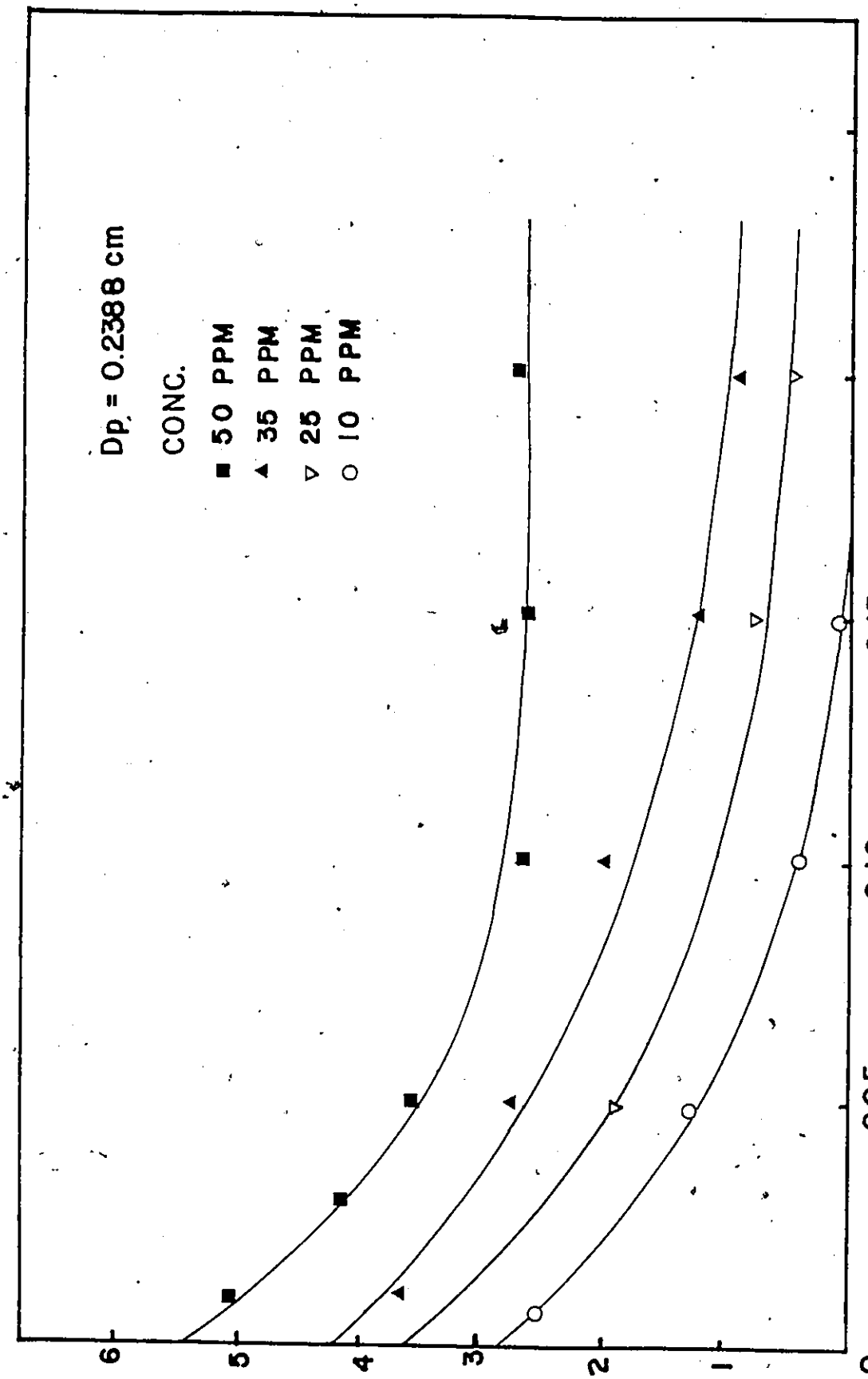


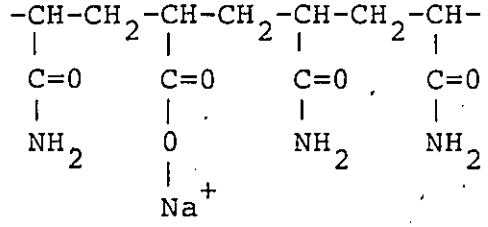
FIG. 5-15 PLOT OF Δ VS. τ_{Rh} FOR PUSHER SOLUTIONS

simultaneously invade formely inaccessible pores due to the deformation of macromolecules. The adsorption layer may also be laterally compressed.

Effect of polymer molecular size

Adsorption layer thicknesses expressed as multiples of the macromolecular diameter, Δ/De, are plotted in figures (5.16) and (5.17) as a function of polymer concentration for the three beds with different sphere sizes. It is observed that the adsorption layer thickness is higher for the ionic polyacrylamide solution than for the nonionic polyacrylamide solution for the same particle size and polymer concentration. However, Δ/De for the nonionic polyacrylamide is higher than for the ionic polyacrylamide at the same conditions. In other words, the number of macromolecules adsorbed in the case of nonionic polyacrylamide is higher than for the ionic polyacrylamide.

The greater molecular size achieved by hydrolysis of the polyacrylamide results from changing some of the amide groups to carboxyl ones.



The ratio of amine and carboxyl groups determine the degree of hydrolysis (in this case 25%). Ionizable carboxyl groups have

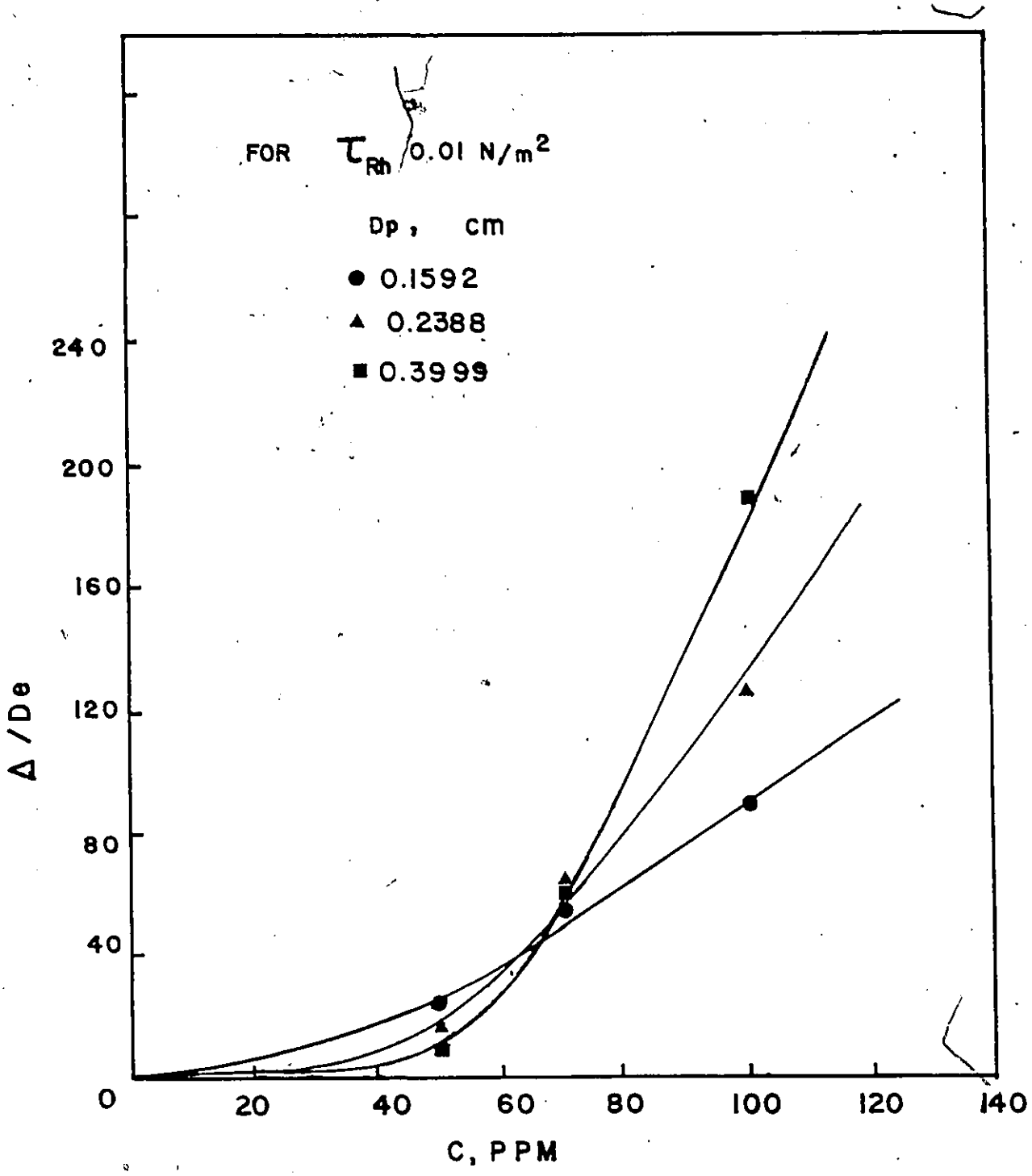


FIG. 5-16 PLOT OF Δ / De VS. POLYACRYLAMIDE CONCENTRATION

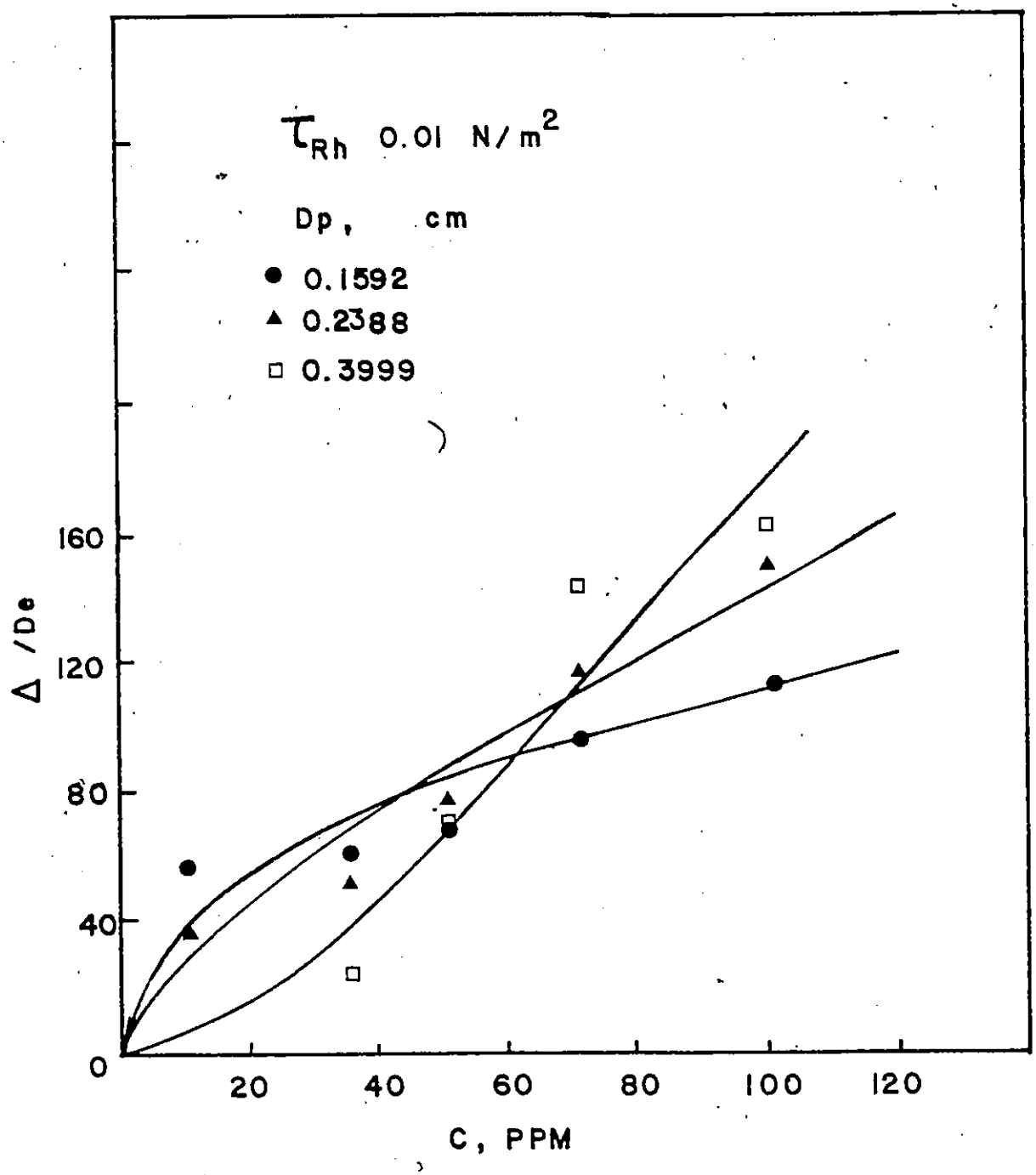


FIG. 5-17 PLOT OF Δ/De VS. PUSHER CONCENTRATION

an effect on molecular size when the polymer is dissolved in water. Electrical repulsion of like charges along the polymer chain causes the expansion of the molecule into larger spherical form. A molecular diameter of 6300Å for ionic polyacrylamide compared to 3500Å for nonionic polyacrylamide is realizable. The carboxyl groups are also highly polar and give the polymer a great affinity for water. The size of the polymer units that exist in solution and in the adsorbed layer can be quite large. These units may be single polymer molecules, molecular aggregates, held together by entwining of the long chain molecules, or a mixture of both.

CONCLUSIONS

The following conclusions have been reached from this investigation.

1. Partially hydrolyzed polyacrylamide develops a greater viscosity than the nonionic polyacrylamide for comparable molecular weights, at the concentrations investigated.

2. The apparent viscosities of aqueous solutions of these polymers evaluated for packed beds were much higher than yielded in the viscometer measurements.

3. The apparent viscosities of these solutions in packed bed increases with decrease in pore size.

4. The adsorption layer thicknesses were determined to be of the order of 0.001cm and a function of polymer concentration, packing size and the shear stress parameter, τ_{R_h}.

5. The adsorption layer thickness was found to increase with polymer concentration and to approach a limiting value with increasing τ_{R_h} and packing size.

6. The adsorption layer thickness increased with the macromolecular size of the polymer.

REFERENCES

1. Kozicki, W., and Wu, F.F.H., "Characterization of Polymer Adsorption in Tube Flow of Drag Reducing Fluids" Chem. Engng. Sc. (1978) 33 1603-1614.

2. Sadowski, T.J., Ph.D. Thesis, University of Wisconsin, Madison, (1963).

3. Gogarty, W.B., "Mobility Control with Polymer Solutions" Society of Petroleum Engineers Journal (June 1967) 161-173.

4. Jennings, R.R. Rogers, J.H. and West, T.J., "Factors Influencing Mobility Control by Polymer Solutions" J.Pet.Tech. (March 1971) 391-401.

5. Rowland, F.W., "Thickness and structure of Layers of High Polymer Adsorbed From Solution onto Solid Surfaces" Ph.D Thesis, Brooklyn Polytechnic Institute, Brooklyn, N.Y. (1963)

6. Smith, F.W., "The Behaviour of Partially Hydrolyzed Polyacrylamide Solution in Porous Media" J.Pet.Tech. (February 1970) 148-156.

7. Mungan, N., Smith, F.W., Thompson, J.L., "Some Aspects of Polymer Floods" J.Pet.Tech. (September 1966) 1143-1150.

8. Mungan, N., "Rheology and Adsorption of Aqueous Polymer Solutions" The Journal of Canadian Petroleum Technology (April-June 1969) 45-50.

9. Pye, D.J., "Improved Secondary Recovery by Control of Water Mobility". J.Pet.Tech. (August 1964) 911-916.

10. Sadowski, T.J., "Non-Newtonian Flow Through Porous Media", Transactions of the Society of Rheology (1965) 251-271.

11. Rowland, F.W. and Eirich F.R., "Flow Rates of Polymer Solutions Through Porous Disks as a Function of Solute", J. Polymer Sci. (1966) Part A-1 4 2401-2421.

12. Dauben, D.L. and Menzie, D.E., "Flow of Polymer Solution Through Porous Media" J.Pet.Tech. (August 1967) 1063-1073.

13. Kozicki, W., Hsu, C.J. and Tiu, C., "Non-Newtonian Flow Through Porous Media" Chem. Engng Sci. (1967) 22 487-502.

14. Kozicki, W., Pasari, S.N., Rao, A.R.K. and Tiu, C., "Anomalous Effects in Laminar Capillary Flow of Polymer Solutions" Chem. Engng Sci. (1970) 25 41-52.

15. Harrington, R.E. and Zimm, B.H., "Anomalous Plugging of Sintered Glass by High Molecular Weight Polymers", J. Polymer Sci. (1968) Part A-2 6 294-299.

16. Burcik, E.J., "The Mechanism of Microgel Formation in Partially Hydrolyzed Polyacrylamide" J.Pet.Tech. (April 1969) 373-374.

17. Arunachalam, VR. and Fulford, G.D., "Adsorption Measurement in Dilute Solutions of a Drag Reducing Polymer" Chem. Engng Sci. (1971) 26 1065-1073.

18. Hand, J.H. and Willians, M.C., "The Adsorbed-Entangled Layer in Drag Reduction" Chem. Engng Sci. (1973) 28 63-68.

19. Hiraski, G.J., and Pope, G.A., "Analysis of Factors Influencing Mobility and Adsorption in the Flow of Polymer Solution Through Porous Media", Society of Petroleum Engineers Journal (August 1974) 337-346.

20. Szabo, M.T., "Some Aspects of Polymer Retention in Porous Media Using a C^{14} Tagged Hydrolyzed Polyacrylamide" Society of Petroleum Engineers Journal (August 1975) 323-337.

21. Entov, V.M. and Polishchuk, A.M., "Role of Sorption Process During the Motion of Polymer Solution in a Porous Medium". Izv Akad Nauk (SSSR) Mekh Zhidk Gaza (May-June 1975) n3 68-78.

22. Thomas, C.P., "Mechanism of Reduction of Water Mobility by Polymers in Glass Capillary Arrays", Society of Petroleum Engineers Journal (June 1976) 130-136.

23. Dominguez, J.G. and Willhite, G.P., "Retention and Flow Characteristics of Polymer Solutions in Porous Media" Society of Petroleum Engineers Journal (April 1977) 111-121.

24. Hanna, M.R., Ph.D. Thesis, University of Ottawa, (1977)

25. Son, J.E., Ph.D. Thesis, University of Ottawa, (1978)

26. Scholtan, W., Markromol Chem. (1954) 14 169

27. American Cyanamid Corporation Publication (1950) No MDD-9236-5M.

28. Flory, P.J., "Principles of Polymer Chemistry" Cornell University Press, Ithaca, N.Y. (1953)

29. Foshee, W.C., Jennings, R.R., and West, T.J., "Preparation of Partially Hydrolyzed Polyacrylamide Solutions" paper SPE 6202 presented SPE-AIME 51st Annual Fall Technical Conference held in New Orleans, Oct. 3-6, 1976.

Appendix 1

Characteristics of the polymers used in the present work.

Nonionic polyacrylamide

Polymer Concentration C, p.p.m.	Cannon-Fenske Viscosity, cp, η	$\frac{\eta - \eta_o}{\eta_o C}$ dl gm^{-1}
10	1.01423	16.39121
20	1.04236	22.29099
35	1.11687	34.07125
50	1.19556	39.62147
70	1.30998	44.68216
100	1.45520	45.83004

$$\left(\frac{\eta_{sp}}{C}\right)_{C=0} = 18.02866 \text{ dl gm}^{-1}$$

and $\left(\frac{\eta_{sp}}{C}\right)_{C=0} = 6.51 \times 10^{-5} \bar{M}w^{.81}$ For nonionic Polyacrylamide at 20°C

$[\eta] = 2.1 \times 10^{21} \left(\frac{\bar{r}^2}{\bar{M}w}\right)^3$ Flory Fox Equation

$\sqrt{\bar{r}^2}$: root mean square end to end distance of polymer macromolecule, Å

$\bar{M}w = 5.235 \times 10^6$

$\sqrt{\bar{r}^2} = 3552.8$Å

Pusher-500, Partially hydrolyzed polyacrylamide

Polymer Concentration C, p.p.m.	Cannon-Fenske Viscosity, η, cp.	$\frac{\eta - \eta_o}{\eta_o C}$ dl gm^{-1}
10	1.08227	84.58235
25	1.25828	104.38604
35	1.44494	128.00417
50	1.69659	140.04153
70	1.95319	136.76473
100	2.47704	148.23107

$$\left(\frac{\eta_{sp}}{C}\right)_{C=0} = 92.22 \text{ dl gm}^{-1}$$

$$\left(\frac{\eta_{sp}}{C}\right)_{C=0} = 6.51 \times 10^{-5} \bar{M}w^{.91}$$ (For partially hydrolyzed Polyacrylamide at 21°C)

$$[\eta] = 2.1 \times 10^{21} \sqrt{\frac{\bar{r}^2}{\bar{M}w}}^3$$ Flory Fox Equation

$\sqrt{\bar{r}^2}$: root mean square end to end distance of polymer macromolecule, Å

$\bar{M}w = 5.749 \times 10^6$

$\sqrt{\bar{r}^2} = 6320.38$Å

Appendix 2

Evaluation of impermeability factor, k_i

For bed packed with 0.1592 cm diameter shperes by circulating distilled water.

Q $cc/_{min}$	u_s $cm/_{Sec}$	X cm.	$\frac{\Delta P}{L}\left(\frac{\varepsilon}{6/D_p(1-\varepsilon)+2/r}\right)\frac{2\varepsilon}{\mu}$
20.50	0.061482	3.549	0.3187
21.10	0.063282	3.621	0.3252
29.30	0.087875	5.190	0.4661
36.80	0.110368	5.944	0.5339
42.95	0.128813	6.545	0.5878
51.70	0.155060	8.108	0.7282
60.30	0.180841	10.886	0.9777
71.30	0.213840	11.641	1.0456

k_i = 5.00

For bed packed with 0.2388 cm diameter spheres

23.06	0.037378	1.235	0.1794
29.60	0.039455	1.317	0.1913
36.80	0.049052	1.695	0.2462
49.18	0.065554	1.397	0.3482
90.20	0.120231	4.351	0.6322
117.80	0.157022	5.620	0.8116
132.00	0.175949	6.084	0.8840
144.40	0.192477	6.355	0.9233
166.40	0.221803	7.936	1.1531

Appendix 3

Flow measurements of polymer aqueous solutions in packed beds

D_p = diameter of packing spheres

Q = flow rate, cc/min.

u_s = superficial velocity, cm/sec.

X = pressure drop, cm Meriam oil

T = τ_{R_h} shear stress, N/m^2

U = $2\langle u\rangle/R_h$, sec^{-1}

u_s, T and U represents intermediate values in calculation process.

For bed packed with 0.3999 cm diameter shperes

Q $cc/_{min}$	u_s $cm/_{Sec}$	X cm	$\frac{\Delta P}{L}\left(\frac{\varepsilon}{6/D_p\ (1-\varepsilon)+2/r}\right)^2\frac{\varepsilon}{\mu}$
23.28	0.011075	0.134	0.0546
40.53	0.018965	0.245	0.0998
60.00	0.028448	0.347	0.1414
73.80	0.039915	0.471	0.1919
103.70	0.049168	0.579	0.2359
129.00	0.061164	0.760	0.3097
164.20	0.077853	0.975	0.3973
250.00	0.118550	1.469	0.5986
294.00	0.139397	1.708	0.6960
396.70	0.188091	2.260	0.9209

$k_i = 5.02$

u_s represents intermediate values in calculation process.

Table 3 - 1

Nonionic polyacrylamide in distilled water

10 ppm conc. solution.

D_p = 0.1592 cm

Q	u_s	X	T	U
19.87	0.064845	2.599	0.03803	22.395786
26.75	0.087297	3.390	0.04960	30.150341
35.20	0.114873	4.501	0.06586	39.674468
39.40	0.128580	5.622	0.08226	44.408353
59.40	0.193197	8.030	0.11750	66.725241
76.80	0.250634	11.142	0.16304	86.562475

D_p = 0.2388 cm

19.46	0.025939	0.513	0.00811	5.956819
33.73	0.044960	1.063	0.01682	10.324950
49.80	0.066380	1.277	0.02020	15.244071
71.20	0.094906	2.106	0.03332	21.794737
101.40	0.135161	3.423	0.05416	31.039133
131.00	0.174616	4.290	0.06788	40.099859
152.80	0.203674	5.118	0.08098	46.772974
177.60	0.236732	5.826	0.09218	54.364399
206.70	0.275520	7.261	0.11489	63.272079

D_p = 0.3999 cm

Q	u_s	X	T	U
35.20	0.016689	0.151	0.00400	2.288536
65.10	0.030866	0.290	0.00768	4.232492
67.00	0.031767	0.349	0.00924	4.356022
112.20	0.053198	0.552	0.01462	7.294711
172.00	0.081552	0.761	0.02016	11.182622
225.40	0.106871	1.021	0.02705	14.654436

Table 3 - 2

Nonionic polyacrylamide aqueous solution, 20 ppm conc.

D_p = 0.1592 cm

13.06	0.042621	1.873	0.02741	14.720129
22.26	0.072644	3.586	0.05247	25.089592
28.73	0.093759	4.534	0.06637	32.382031
34.60	0.112915	5.466	0.07998	38.998198
44.00	0.143592	6.948	0.10167	49.593085
54.60	0.178185	8.521	0.12469	61.540513
68.80	0.224526	11.035	0.16148	37.545551
82.60	0.269562	13.215	0.19338	93.099745
97.50	0.318187	15.813	0.23139	109.893771

D_p = 0.2388 cm

23.60	0.031457	1.001	0.015838	7.224098
32.60	0.043454	1.350	0.021361	9.979051
43.20	0.057583	1.495	0.023655	13.223773
58.12	0.077471	2.118	0.033513	17.790951

... ... contd.

D_p = 0.2388 cm ... ... Table 3 - 2 contd.

Q	u_s	X	T	U
77.20	0.102903	2.688	0.04095	23.63137
86.90	0.115833	3.161	0.05001	26.60059
101.09	0.134747	3.821	0.06046	30.94424
117.00	0.155955	4.494	0.07112	35.81431
134.80	0.179681	5.009	0.07926	41.26307

D_p = 0.3999 cm

25.50	0.012091	0.098	0.00259	1.65788
41.80	0.019819	0.154	0.00408	2.71763
68.20	0.032336	0.268	0.00710	4.43404
98.20	0.046561	0.367	0.00973	6.38449
105.40	0.049974	0.497	0.01317	6.85261
119.20	0.056517	0.532	0.01409	7.74982
144.60	0.068561	0.622	0.01648	9.40121

Table 3 - 3

Nonionic polyacrylamide aqueous solution, 35 ppm conc.

D_p = 0.1592 cm

14.20	0.046341	2.078	0.03041	16.00504
23.35	0.076202	3.487	0.05102	26.31815
28.90	0.094314	4.446	0.06506	32.57364
35.00	0.114221	5.601	0.08192	39.44904
43.90	0.143266	7.286	0.10662	49.48037
54.70	0.178511	8.859	0.12963	61.65322
67.20	0.219305	11.663	0.17067	75.74216
80.30	0.262056	13.494	0.19746	90.50738
96.00	0.313292	17.177	0.25136	108.20309

D_p = 0.2388 cm

Q	u_s	X	T	U
20.53	0.027365	0.939	0.01485	6.28435
25.60	0.034123	1.170	0.01851	7.83631
36.00	0.047986	1.524	0.02411	11.01981
53.40	0.071179	2.239	0.03542	16.34605
71.80	0.095706	2.938	0.04648	21.97840
89.57	0.119392	3.774	0.05971	27.41790
104.90	0.139826	4.604	0.07284	32.11050
125.57	0.167378	5.346	0.08459	38.43771
145.20	0.193544	5.981	0.09464	44.44657

D_p = 0.3999 cm

30.10	0.014271	0.434	0.01150	1.95696
64.50	0.030582	0.541	0.01433	4.19348
88.80	0.042103	0.654	0.01733	5.77335
109.40	0.051871	0.761	0.02016	7.11267
131.82	0.062501	0.928	0.02459	8.57031
157.60	0.074724	1.031	0.02732	10.24640
185.00	0.087716	1.129	0.02991	12.02782

Table 3 - 4

Nonionic polyacrylamide aqueous solution, 50 ppm conc.

D_p = 0.1592 cm

14.02	0.045754	3.242	0.04744	15.80216
21.73	0.070915	5.009	0.07329	24.49222
23.60	0.077177	6.443	0.09428	26.59992
29.38	0.095880	7.547	0.11044	33.11465
37.66	0.122902	9.106	0.13325	42.44717
46.65	0.152240	11.054	0.16175	52.57994
57.24	0.186800	13.611	0.19917	64.51609
64.88	0.211733	15.642	0.22863	73.12725

D_p = 0.2388 cm

Q	u_s	X	T	U
18.18	0.024233	1.140	0.01804	5.56500
25.07	0.033417	1.590	0.02315	7.67407
34.36	0.045800	2.025	0.03204	10.51779
49.00	0.065314	2.749	0.04349	14.99919
65.28	0.087015	3.690	0.05839	19.98259
80.64	0.107489	4.543	0.07188	24.68437
92.00	0.122631	5.200	0.08228	28.16174
103.30	0.137693	5.744	0.09088	31.62073
116.44	0.155208	6.440	0.10190	35.64296
134.42	0.179174	7.281	0.11521	41.14675
151.68	0.202181	8.081	0.12787	46.43013

D_p = 0.3999 cm

25.90	0.012280	0.201	0.00533	1.68389
50.30	0.023849	0.260	0.00689	3.27026
82.83	0.039273	0.539	0.01428	5.38521
109.00	0.051681	0.855	0.02266	7.08666
137.60	0.065242	1.040	0.02756	8.94609
155.10	0.073539	1.177	0.03119	10.08386
171.80	0.081457	1.285	0.03405	11.16962

Table 3 - 5

Nonionic polyacrylamide aqueous solution, 70 ppm conc.

D_p = 0.1592 cm

15.52	0.050489	6.103	0.08931	17.49283

... ... contd.

D_p = 0.1592 cm

... ... Table 3 - 5 contd.

Q	u_s	X	T	U
23.04	0.075190	8.585	0.12563	25.96874
31.94	0.104235	11.500	0.16828	36.00007
36.01	0.117517	12.512	0.18309	40.58743
40.18	0.131126	13.925	0.20377	45.28750
48.64	0.158734	16.259	0.23792	54.82290
56.10	0.183080	18.256	0.26715	63.23118
66.90	0.218332	21.322	0.31201	75.40403

D_p = 0.2388 cm

19.78	0.026366	1.294	0.02047	6.05477
26.81	0.035736	1.958	0.03098	8.20669
41.20	0.054917	2.583	0.04087	12.61156
52.30	0.069713	3.053	0.04831	16.00933
64.82	0.086401	4.610	0.07294	19.84178
80.60	0.107436	5.656	0.08949	24.67213
93.80	0.125030	6.469	0.10236	28.71273
105.62	0.140786	7.400	0.11709	32.33090
125.40	0.167152	8.271	0.13087	38.38567
137.34	0.183067	9.323	0.14752	42.04058
160.24	0.213592	10.671	0.16885	49.05040

D_p = 0.3999 cm

Q	u_s	X	T	U
29.24	0.013864	0.239	0.00633	1.90105
50.38	0.023887	0.449	0.01189	3.27547
79.66	0.037769	0.692	0.01834	5.17911
105.98	0.050230	0.941	0.02494	6.88771
127.76	0.060576	1.153	0.03055	8.30635
155.24	0.073606	1.453	0.03850	10.09297
179.62	0.085165	1.688	0.04473	11.67804
201.84	0.095700	1.865	0.04942	13.12268
224.46	0.106425	2.086	0.05528	14.59332

Table 3 - 6

Nonionic polyacrylamide aqueous solution, 100 ppm conc.

D_p = 0.1592 cm

13.83	0.045133	6.726	0.09842	15.58800
18.45	0.060211	8.729	0.12773	20.79528
23.76	0.077539	10.735	0.15708	26.78027
29.24	0.095424	12.942	0.18938	32.95686
36.22	0.118202	15.628	0.22869	40.82413
45.56	0.148683	18.952	0.27733	51.35138
54.86	0.179033	22.312	0.32649	61.83356
63.01	0.205631	25.378	0.37136	71.01955
74.04	0.241627	29.252	0.42805	83.45164

Nonionic polyacrylamide aqueous solution, 100 ppm conc.

D_p = 0.2388 cm

Q	u_s	U	T	U
13.98	0.018635	1.408	0.02228	4.27936
21.18	0.028232	1.950	0.03085	6.48332
30.62	0.040815	2.729	0.04318	9.37296
43.40	0.057849	3.740	0.05918	13.28499
57.81	0.077057	4.659	0.07372	17.69598
63.96	0.085255	5.311	0.08404	19.57853
76.12	0.101464	6.185	0.09786	23.30078
84.82	0.113060	6.824	0.10797	25.96389
94.92	0.126523	7.687	0.12163	29.05557
101.22	0.134921	8.009	0.12672	30.98403
114.16	0.152169	8.514	0.13471	34.94504
124.96	0.166565	9.344	0.14785	38.25098

D_p = 0.3999 cm

21.43	0.010161	0.369	0.00978	1.39327
41.48	0.019667	0.633	0.01677	2.69683
60.84	0.028846	0.781	0.02069	3.95553
75.91	0.035991	0.941	0.02494	4.93553
91.32	0.043298	1.159	0.03071	5.93719
114.90	0.054478	1.411	0.03739	7.47025
137.04	0.064976	1.646	0.04362	8.90969
149.38	0.070827	1.749	0.04635	9.71198
170.98	0.081068	1.988	0.05268	11.11631
192.20	0.091129	2.237	0.05928	12.49593
212.10	0.100565	2.423	0.06421	13.78973

Table 3 - 7

Ionic polyacrylamide aqueous solution, 10 ppm conc.

D_p = 0.1592 cm

Q	u_s	X	T	U
16.76	0.054695	8.511	0.12454	18.89045
20.81	0.067913	10.180	0.14896	23.45521
28.32	0.092421	12.642	0.18499	38.91991
33.32	0.109738	13.034	0.19073	37.55549
41.64	0.135890	15.427	0.22574	46.93309
49.51	0.161573	17.573	0.25715	55.80349
57.06	0.186213	19.959	0.29206	64.31321
67.22	0.219369	23.000	0.33656	75.76470
76.62	0.250046	26.421	0.38662	86.35959

D_p = 0.2388 cm

14.31	0.019074	1.321	0.02088	4.38037
21.80	0.029058	1.408	0.02227	6.67310
28.14	0.037509	1.725	0.02729	8.61382
31.70	0.042254	1.932	0.03056	9.70355
40.44	0.052560	2.334	0.03696	12.07021
48.75	0.064981	2.830	0.04478	14.92266
57.98	0.077284	3.217	0.05090	17.74802
65.56	0.087388	3.572	0.05652	20.06830
74.02	0.098665	4.081	0.06457	22.65795
80.02	0.106663	4.230	0.06693	24.49459
86.32	0.115060	4.534	0.07174	27.29556
92.82	0.123724	4.817	0.07622	28.41273
102.42	0.136520	5.278	0.08351	31.35136
109.84	0.146411	5.923	0.09371	33.62266

D_p = 0.3999 cm

Q	u_s	X	T	U
24.21	0.011479	0.175	0.00464	1.57402
33.82	0.016035	0.206	0.00546	2.19882
48.42	0.022958	0.264	0.00699	3.14804
67.62	0.032061	0.354	0.00938	4.39633
93.80	0.044474	0.418	0.01107	6.09843
116.20	0.055095	0.499	0.01322	7.55477
142.00	0.067328	0.782	0.02072	9.23216
158.64	0.075217	0.852	0.02257	10.31140
175.48	0.083202	0.901	0.02387	11.40887

Table 3 - 8

Ionic polyacrylamide aqueous solution, 25 ppm conc.

D_p = 0.1592 cm

20.98	0.068467	10.241	0.14986	23.64688
29.18	0.095228	14.570	0.21320	32.88923
36.31	0.118496	16.962	0.24821	40.92556
47.32	0.154427	21.029	0.30772	53.33510
53.90	0.175900	23.485	0.34366	60.75150
67.66	0.220806	27.680	0.40505	76.26064
79.56	0.259641	32.428	0.47453	89.67331

Table 3 - 8

Ionic polyacrylamide aqueous solution, 25 ppm conc.

D_p = 0.2388 cm

Q	u_s	X	T	U
19.71	0.026272	1.898	0.03003	6.03334
26.26	0.035003	2.461	0.03894	8.03834
34.04	0.045374	3.135	0.04960	10.41984
46.00	0.061316	3.583	0.05669	14.08087
60.00	0.079977	3.978	0.06294	18.36635
76.82	0.102397	5.128	0.08114	23.51505
100.58	0.134068	6.658	0.10534	30.78812
121.94	0.162539	8.023	0.12694	37.32654
139.96	0.186559	8.935	0.14137	42.84258

D_p = 0.3999 cm

25.44	0.012062	0.237	0.00628	1.65398
35.47	0.016818	0.373	0.00988	2.30609
48.38	0.022939	0.426	0.01129	3.14543
67.02	0.031777	0.544	0.01442	4.35732
85.98	0.040766	0.653	0.01730	5.59001
108.64	0.051511	0.835	0.02212	7.06325
137.02	0.064967	1.013	0.02684	8.90838
161.16	0.076412	1.240	0.03286	10.47786
192.40	0.091224	1.481	0.03924	12.50893

Table 3 - 9

Ionic polyacrylamide aqueous solution, 35 ppm conc.

D_p = 0.1592 cm

Q	u_s	X	T	U
19.11	0.062364	8.894	0.13014	21.53918
26.31	0.085862	11.920	0.17443	29.65441
36.08	0.117746	15.055	0.22030	40.66632
43.88	0.143291	19.366	0.28339	49.45783
54.08	0.176488	23.018	0.33683	60.95441
67.34	0.219761	28.558	0.41789	75.89996
81.84	0.267081	34.620	0.50660	92.24314

D_p = 0.2388 cm

20.92	0.027885	2.004	0.03171	6.40373
29.15	0.038855	2.602	0.04259	8.92298
37.04	0.049372	3.772	0.05968	11.33816
48.70	0.064914	4.620	0.07310	14.90735
65.36	0.087121	5.765	0.09122	20.00708
82.48	0.109941	7.038	0.11136	25.24761
104.44	0.139213	8.254	0.13060	31.96969
123.30	0.164353	9.085	0.14375	37.74285
145.64	0.194131	10.839	0.17150	44.58126

Ionic polyacrylamide aqueous solution, 35 ppm conc.

D_p = 0.3999 cm

Q	u_s	X	T	U
29.28	0.013883	0.350	0.00927	1.90365
42.76	0.020274	0.421	0.01116	2.78329
66.02	0.031303	0.489	0.01296	4.29231
83.64	0.039657	0.692	0.01833	5.43788
95.23	0.045152	0.852	0.02258	6.19140
134.42	0.063734	0.942	0.02496	8.73935
157.68	0.074762	1.098	0.02909	10.25160
187.40	0.088854	1.224	0.03243	12.18386

Table 3 - 10

Ionic polyacrylamide aqueous solution, 50 ppm conc.

D_p = 0.1592 cm

Q	u_s	X	T	U
18.11	0.059101	14.794	0.21648	20.41206
24.78	0.080868	19.778	0.28941	27.92992
30.00	0.097904	26.308	0.38497	33.81347
37.38	0.121988	32.881	0.48116	42.13158
46.32	0.151164	40.226	0.58864	52.20799
57.80	0.188638	47.202	0.69072	65.14728
67.76	0.221132	52.744	0.77182	76.32335
81.08	0.264601	60.012	0.87817	91.38653

Ionic polyacrylamide aqueous solution, 50 ppm conc.

D_p = 0.2388 cm

Q	u_s	X	T	U
20.82	0.027752	3.882	0.06142	6.37312
29.38	0.039162	4.497	0.07115	8.99339
34.02	0.045347	4.835	0.07650	10.41372
44.02	0.058676	5.110	0.08085	13.47477
51.32	0.068407	6.087	0.09631	15.70935
57.64	0.076831	6.714	0.10623	17.60394
75.39	0.100491	9.233	0.14609	23.07732
96.00	0.127963	12.383	0.19593	29.38616
115.66	0.154169	15.093	0.23881	35.40420
141.92	0.189172	18.957	0.29995	43.44254

D_p = 0.3999 cm

32.91	0.015604	0.514	0.01362	2.13965
48.24	0.022872	0.691	0.01831	3.13633
71.82	0.034053	0.835	0.02212	4.66939
98.00	0.046466	1.470	0.03895	6.37149
124.24	0.058907	2.401	0.06323	9.95105
180.84	0.085743	2.973	0.07878	11.75736

Table 3 - 11

Ionic polyacrylamide aqueous solution, 70 ppm conc.

D_p = 0.1592 cm Meriam oil specific gravity = 1.75

Q	u_s	X	T	U
19.62	0.064029	4.826	0.27563	22.11401
25.46	0.083087	5.813	0.33200	28.69636
31.81	0.103811	6.688	0.38198	35.85355
39.22	0.127993	7.983	0.45594	44.20547
47.86	0.156189	9.953	0.54790	53.94375
57.86	0.188824	11.590	0.66195	65.21491
70.24	0.229225	13.916	0.79480	79.16859
81.56	0.266168	16.599	0.94804	91.92754

D_p = 0.2388 cm

18.76	0.025006	4.867	0.07701	5.74258
31.44	0.041908	6.762	0.10699	9.62397
41.22	0.054944	7.279	0.11517	12.61767
51.96	0.069259	10.241	0.16204	15.90526
63.62	0.084802	12.037	0.19046	19.47445
73.84	0.098425	14.262	0.22566	22.60286
88.04	0.117353	16.823	0.26619	26.94956
99.66	0.132841	19.485	0.29676	30.50651
120.00	0.159954	22.821	0.36109	36.73269

Ionic polyacrylamide aqueous solution, 70 ppm conc.

D_p = 0.3999 cm

Q	u_s	X	T	U
29.82	0.014148	0.754	0.01998	1.94005
42.04	0.019932	0.820	0.02332	2.73323
53.94	0.025575	0.966	0.02559	3.50692
66.74	0.031644	1.106	0.02930	4.33911
86.38	0.040956	1.384	0.03667	5.61602
110.64	0.052459	1.915	0.05074	7.19329
138.84	0.065829	2.565	0.06792	9.02672
174.46	0.082718	3.178	0.08421	11.34256
213.80	0.101371	3.991	0.10576	13.90026

Table 3 - 12

Ionic polyacrylamide aqueous solution, 100 ppm conc.

D_p = 0.1592 cm Meriam oil specific gravity = 1.75

16.54	0.053977	8.943	0.51077	18.64249
23.48	0.076626	11.634	0.66447	26.46467
34.82	0.113634	13.288	0.75894	39.24616
45.02	0.146921	17.395	0.99351	50.74274
52.64	0.171788	18.587	1.06159	59.33136
63.24	0.206381	21.891	1.25029	71.27878
80.24	0.261860	28.003	1.59938	90.43975

Ionic polyacrylamide aqueous solution, 100 ppm conc.

D_p = 0.2388 cm

Q	u_s	X	T	U
15.52	0.020687	6.768	0.10709	4.75076
23.56	0.031404	8.635	0.13663	7.21185
36.02	0.048013	10.314	0.16319	11.02593
53.42	0.071206	12.011	0.19005	16.35217
63.44	0.084562	12.990	0.20554	19.41935
70.60	0.094106	14.802	0.23421	21.61107
94.32	0.125724	17.514	0.27712	28.87190
112.20	0.149556	19.389	0.30679	34.34507
130.24	0.173603	24.226	0.38332	39.86722

D_p = 0.3999 cm

23.21	0.011005	0.746	0.01976	1.50900
32.42	0.015372	0.958	0.02538	2.10779
55.02	0.026087	1.198	0.03174	3.57714
77.24	0.036623	1.503	0.03982	5.02178
90.81	0.043056	1.608	0.04261	5.90403
117.78	0.055844	1.814	0.04807	7.65749
156.48	0.074193	2.739	0.07258	10.17358
184.04	0.087261	3.380	0.08956	11.96541

APPENDIX 4

SUMMARY OF RESULTS

Table 4 - 1

Nonionic polyacrylamide aqueous solution through bed packed with 0.1592 cm diameter spheres.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
50 ppm				
	0.01	0.0307	0.90919	25.5908
70 ppm				
	0.01	0.0532	1.96235	55.2340
	0.02	0.0537	1.99894	56.2637
	0.03	0.0543	2.04230	57.4844
	0.06	0.0489	1.63624	46.0549
	0.15	0.0467	1.44837	40.7672
	0.20	0.0442	1.21949	34.3247
100 ppm				
	0.01	0.0800	3.11302	87.6216
	0.02	0.0800	3.11302	87.6216
	0.03	0.0750	2.87371	80.8860
	0.04	0.0727	2.75704	77.6021
	0.06	0.0673	2.46478	69.3757
	0.10	0.0633	2.22897	62.7383
	0.15	0.0583	1.90590	53.6451
	0.20	0.0572	1.83590	51.6748
	0.25	0.05405	1.61019	45.3219

Table 4 - 2

Nonionic polyacrylamide aqueous solution through bed packed with 0.2388 cm diameter spheres.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
50 ppm				
	0.01	0.0303	0.52775	14.8544
70 ppm				
	0.01	0.0487	2.42020	68.1209
	0.02	0.0497	2.54730	71.6985
	0.03	0.0475	2.27088	63.9180
	0.06	0.0040	1.22383	34.4468
100 ppm				
	0.01	0.0769	4.45201	125.3098
	0.03	0.0674	3.70566	104.3026
	0.06	0.0560	2.62628	73.9216
	0.10	0.0425	0.95527	26.8878
	0.15	0.0415	0.80645	22.6990

Table 4 - 3

Nonionic polyacrylamide aqueous solution through bed packed with 0.3999 cm diameter spheres.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
50 ppm				
	0.01	0.0307	0.25231	7.1019
	0.03	0.0306	0.19707	5.5469
70 ppm				
	0.01	0.0400	2.04944	57.6854
	0.02	0.0391	1.18322	51.0365
	0.03	0.0387	1.70621	48.0244
	0.06	0.0372	1.31185	36.9244
100 ppm				
	0.01	0.0714	6.75759	190.2046
	0.03	0.0566	4.45029	126.7438
	0.06	0.0488	3.00825	84.6726

Table 4 - 4

Ionic polyacrylamide aqueous solution through bed packed with 0.1592 cm diameter spheres.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
10 ppm				
	0.01	0.0617	4.07845	64.5285
	0.03	0.0600	3.14399	49.7437
	0.10	0.0488	2.36623	37.4382
	0.50	0.0441	1.97127	31.1891
35 ppm				
	0.01	0.0909	3.60277	57.0025
	0.03	0.0811	3.18842	50.4466
	0.10	0.0555	1.74700	27.6408
	0.50	0.0565	1.81337	28.6909
50 ppm				
	0.01	0.1250	4.15882	65.8001
	0.03	0.1110	3.73968	59.1685
	0.10	0.1052	3.55309	56.2165
	0.50	0.1130	3.80726	60.2378
	1.00	0.1129	3.80567	60.2126
70 ppm				
	0.01	0.2222	5.58885	88.4258
	0.03	0.1898	5.08671	80.4810
	0.10	0.1851	5.00658	79.2132
	0.50	0.1053	3.03968	48.0933
	1.00	0.1053	3.03968	48.0933

... ... contd.

... ... Table 4 - 4 contd.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
100 ppm				
	0.01	0.5000	7.26005	114.8673
	0.03	0.4918	7.21519	114.1576
	0.10	0.4545	6.99883	110.7343
	0.50	0.2924	5.70383	90.2451
	1.00	0.1934	4.17744	66.0947
	1.50	0.1886	5.36878	84.9439

Table 4 - 5

Ionic polyacrylamide aqueous solution through bed packed with 0.2388 cm diameter spheres.

10 ppm				
	0.01	0.0408	2.50484	39.6300
	0.03	0.0333	1.27096	20.1090
	0.05	0.0289	0.40342	6.3833
	0.10	0.0276	0.04155	0.6574
25 ppm				
	0.01	0.0398	1.44752	22.9024
	0.03	0.0422	1.79852	28.4559
	0.05	0.0444	2.11320	33.4347
	0.10	0.0360	0.82514	13.0512
	0.15	0.0335	0.36961	5.8479

... ... contd.

... ... Table 4 - 5 contd.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
35 ppm				
	0.01	0.0645	3.49379	55.2768
	0.03	0.0571	2.78954	44.1376
	0.05	0.0505	2.15879	34.1561
	0.10	0.0439	1.20069	18.9972
	0.15	0.0414	0.82480	13.0499
50 ppm				
	0.01	0.1000	5.05182	79.9291
	0.03	0.0852	4.16609	65.9152
	0.05	0.0769	3.58340	56.6961
	0.10	0.0655	2.65155	41.9524
	0.15	0.0659	2.68401	42.4660
	0.20	0.0666	2.77796	43.9524
70 ppm				
	0.01	0.1886	7.59916	120.2327
	0.03	0.1428	6.30400	98.0956
	0.05	0.1219	5.36364	84.8626
	0.10	0.1105	4.82829	76.3925
	0.15	0.1017	4.36747	69.1014
	0.20	0.0995	4.24538	67.1698
100 ppm				
	0.01	0.4000	9.95739	157.5443
	0.03	0.3614	9.51593	150.5594
	0.05	0.3105	8.83379	139.7668
	0.10	0.2105	6.96752	110.2390
	0.15	0.1579	5.47479	86.6211
	0.20	0.1212	4.01857	63.5812

Table 4 - 6

Ionic polyacrylamide aqueous solution through bed packed with 0.3999 cm diameter spheres.

	τ_{R_h}	η_s	$\Delta X10^3$	Δ/D_e
25 ppm				
	0.01	0.0364	2.46512	39.0027
	0.01	0.0289	0.08857	1.3980
35 ppm				
	0.01	0.0417	1.45199	22.9732
50 ppm				
	0.01	0.0671	4.66971	73.8834
	0.03	0.0428	0.39990	6.3270
70 ppm				
	0.01	0.1250	9.20394	145.6228
	0.03	0.0802	5.03872	79.7218
100 ppm				
	0.01	0.1694	9.79419	154.9621
	0.03	0.1086	5.67664	89.8148