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EFFECT OF POLYMER ADDITIVES ON THE MECHANICS OF SLOW DRAINING OF LARGE TANK UNDER GRAVITY

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ABSTRACT

A mathematical equation for efflux time for gravity draining of a Newtonian liquid from a large cylindrical tank through an exit pipe located at the bottom of tank when the flow in the pipe line is turbulent is developed based on macroscopic balances. The equation is fine tuned with the experimental data and an empirical equation for friction factor is developed. The efflux time equation so developed will be of use in arriving at the minimum time required for draining the tank.

When the flow is mixed, i.e. partly laminar and partly turbulent, gravity driven and once through (as is the case in the above), the effect of addition of water soluble Polyacrylamide Polymer on drag reduction is expressed in terms of % reduction in efflux time. Based on the efflux time for different solutions, empirical equations for friction factor are developed. The concentration of Polymer which gives maximum drag reduction is also established.

Keywords: polymer, additives, drag reduction, efflux time, model, flow, tank, draining.

INTRODUCTION

Processing and storage vessels in the chemical and allied industries appear in a large variety of shapes. They are almost as many reasons for this variability as there are shapes. The reasons may include convenience, insulation requirements, land and material costs, safety considerations, tradition, advertising etc.

The time required to drain these vessels (**known as efflux time**) of their liquid content can be of crucial importance in many emergency situations or accident scenarios aside from shear productivity considerations [Peter W. Hart, 1995]. Present work considers the slow draining of a Newtonian liquid from a large cylindrical tank under gravity through an exit pipe when the flow in the pipe line is turbulent.

The drag reduction effect is extremely interesting from a practical point of view. Liquids are mostly transported through pipes, and drag reduction by adding a small amount of polymers can offer large economic advantages and a larger effectiveness of this transportation. In addition to drag reduction, the polymer also causes a reduction in heat transfer, which is advantageous in maintaining low oil viscosity [Hoyt, 1990]. A similar application is the addition of polymers to oil being pumped from offshore platforms to shore facilities [Beaty, 1984]. Also, in sewage pipes and storm-water drains polymers have been used to increase the flow rates so that the peak loads do not result in overflowing; if only relatively infrequent use is required, this can be much cheaper than constructing new pipes [Sellin,1988]. Another application is the increase in the range and coherence of water jets from firefighting hoses, but this idea has not been widely exploited [Fabula, 1971]. A military application which has been patented is the reduction of drag acting on a torpedo by ejecting a sea-water-polymer solution from the torpedo nose [Fabula, 1980]. A possible medical application: the addition of low concentrations of polymers might be capable of improving blood flow through stenotic vessels without altering flow through normal vessels [Unthak, 1980]. Also Drag Reducing Polymer reduces the effect of Corrosion [Jennifer Nelson, 2003].

In addition to these practical considerations, the phenomenon of drag reduction by polymer additives is very interesting from a fundamental fluid dynamics point of view as well. The fact that such small changes in the fluid can so drastically alter the flow characteristics strongly hints at the existence of a key mechanism of momentum transport with which the polymer interferes. That means that a study of polymeric drag reduction can help in gaining more knowledge about the phenomena.

The phenomenon of drag reduction using polymers has been studied experimentally mainly in horizontal channels and pipes. Most of the work reported is on turbulent drag reduction and only a limited work on laminar drag reduction. When the flow is mixed i.e. partly laminar and partly turbulent and gravity driven (as is the case of slow draining of a Newtonian liquid from a large Cylindrical tank through an exit pipe), some drag reduction is possible. Whether this drag reduction is significant enough to warrant the use of Polymer additives is also investigated in the present work.

REVIEW OF LITERATURE

a) Efflux time

Most of the work reported in the literature considered evaluation of efflux time for draining a Newtonian liquid through restricted orifice under the action of gravity at atmospheric pressure. Analytical expressions for gravity drainage for annular and torodial containers through a restricted orifice is reported [Petet Hart, 1995]. Modeling and experimentation of gravity drainage of a Newtonian liquid from a Cylindrical tank

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through a restricted orifice is also available in the literature [Jouse, 2003].The present work considers drainage of liquid from a cylindrical tank through an exit pipe.

Efflux time from tanks with exit pipes and fittings is reported in the Reynolds number range of 40,000-60,000 [David B.Vandogen *et al.,* 1999]. The maximum pipe length considered is one meter. The tank is filled a few centimeters above the top mark in the tank to provide enough liquid to hydraulically fill the exit pipe. The effect of pipes and fittings are expressed in terms of Equivalent Length.

Simulation and experimental work is done for draining a Newtonian liquid from a cylindrical tank through an exit pipe in Reynolds number of 6,000 for a fixed pipe length [Ken Morrison, 2001]. The equation for friction factor can be used for Reynolds number > 5000.

In the present experiment, the valve is located at the exit point of the pipe and the analysis is based on macroscopic balances [R Byron Bird, 2005]

Macroscopic balances provide global description of large systems without much consideration to fluid dynamics within the system. Often they are useful for making order of magnitude estimate of various quantities. Some times they are used to derive approximate relations which can be modified with the help of experimental data to compensate for terms which have been omitted or about which there is insufficient information.

b) Laminar drag reduction

Drag reduction in Laminar flow using compliant surfaces fabricated by silicon wafers has given pressure reductions up to 40% [Jia O.U, 2004]. However, the development of hydrophobic surfaces is theoretically complicated [V.T.Truang, 2001]. Drag reduction in Laminar flow using Polyox WSR301 (i.e. Polythene Oxide, (PEO)) dissolved in water is carried out [M.R.Driels et al, 1972]. The results are expressed in the form of Resonance test where the frequency of forcing pressure is varied and the amplitude of oscillation of manometer liquid is measured. The reasons for Drag reduction in this case are attributed to pulsed flow [Thomas L.Dariel, 1981]

c) Turbulent drag reduction

Turbulent drag reduction using Complaint surfaces is also reported [Koji *et al.,* 2006 and K.S.Choi, 1997]. Ionic- non ionic surfactants are also used for drag reduction but at high concentrations of few percent [V.T.Truang, 2001]. Even though drag reduction by micro-bubbles is the cheapest [Victor, 2005], the control and injection of micro-bubbles poses technical challenges [V.T.Truang, 2001].

The pioneering work of Toms documented the ability of a small amount of soluble polymer additives to reduce the friction resistance of turbulent pipe flows of Newtonian fluids. Many theories have been developed since then to explain the way in which polymers reduce drag. The approach that has found support in most of the experimental results that followed those of Toms, is the

proposal [Lumely, 1977] that the mechanism for drag reduction is an increased viscosity near the wall, caused by elongational deformation of the molecules by the turbulence. New arguments based on the kinetics of the molecules have been introduced in the development of drag reduction theories [Ryskin 1987, Degennes 1986 and Tabor *et al.,* 1989].

The drag-reducing abilities of polymer solutions are known to be triggered by a critical level of shear stress parameterized by the so-called "Onset Reynolds number." Such condition should be enough for the flow to stretch the polymer, which in turn introduces an anisotropic effect by which the turbulence structure is changed, and drag reduction induced.

The behavior of polymer solutions is governed by many parameters. The most obvious one being the solvent type, the polymer concentrations. Very dilute polymer solutions have been shown to have viscosity that is very close to that of water [Koskie *et al.,* 1991], the velocity and length scales governing the flow and the type of polymers characterized by its chemical composition, molecular weight distribution, and poly-dispersity index among others.

A large number of studies reported in the literature regarding polymer drag reduction are concerned with homogeneous polymer solutions. Most of them involve the study of fully developed turbulent channel flows where either a polymer ocean is established. [Den toonder *et al.,* 1995 and Vlachogiannis *et al.,* 2003] or polymer is injected in such a way to achieve a homogeneous distribution of the polymer at the test section [Fortuna *et al.,* 1972, Rieschman *et al.,* 1975, Mccomb *et al.,* 1982, Tiederman *et al.,* 1985, Willmarth *et al.,* 1987 , Luchik *et al.,* 1988, Wei T *et al.,* 1992]. Most of the numerical studies in this area consist of direct numerical simulation DNS of polymer flows in turbulent channels [Suresh Kumar *et al.,* 1997 and Dimitropoulos *et al.,* 2001].

A few experimental studies have also been conducted on polymer drag reduction on external flows, such as flow over a flat plate [Fontaine *et al.,* 1992 and Somandepalli *et al.,* 2003].

Experimental studies concerning heterogeneous drag reduction in internal flows have also received attention in the past [Vleggar *et al.,* 1973, Smith R.E *et al.,* 1991 and Bewersdroff *et al.,* 1993]. In these studies, highly concentrated polymer solutions of long chain, high molecular weight polymer, are injected into the core region of a turbulent pipe or channel. For a certain range of concentrations, it is observed that a single coherent thread is formed that preserved its identity for long distances after injection.

The studies [Shen *et al.,* 2003 and Kim *et al.,* 2003] address comparisons of homogeneous and heterogeneous drag reduction cases for the same concentration at the channel test section but with the polymer injected at the wall. The latter studies concluded that a substantial increase of drag reduction could be accomplished by heterogeneous polymer solution

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compared to homogeneous polymer solution. These studies also showed that polymer structures, even if not present in the prepared solution, could be induced by the injection system.

When the flow is partly laminar and partly turbulent and gravity driven, no experimental evidence of drag reduction using polymer solutions is available.

The objective of the present experiment was to study the effect of water soluble polymer on the gravity draining of a Newtonian Liquid from a large open cylindrical tank (where the flow is laminar) through an exit pipe (when the flow is turbulent). The scope of work included:

1) Development of mathematical model for efflux time.
2) Verification of efflux time with the experimental data and fine tuning of friction factor equation and checking the validity of fine tuned equation with experimental data.
3) Study of tank draining pattern with and without Polymer addition.
4) Development of empirical equation for friction factor to accommodate the effect of various polymer solutions.

1. DEVELOPMENT OF MATHEMATICAL MODEL
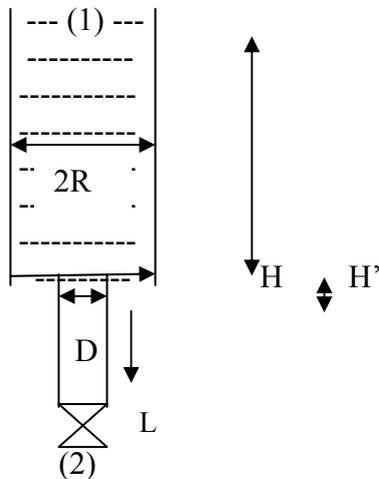
Figure-1. Tank along with exit pipe.

In Figure-1, a Newtonian fluid enters the system at station -1, a cylindrical open tank with diameter 2R and leaves at station-2, an exit pipe whose diameter is D. At stations 1 and 2 the density and other physical properties are uniform over the cross section. The fluid leaves the pipe under turbulent conditions.

Using unsteady state mass balance

Rate of mass accumulated = Rate of mass in at station 1 – Rate of mass out at station 2

$$\frac{d}{dt}(m_{tot}) = W_1 - W_2 \quad \text{--(1)}$$

For the present system
$$W_1 = 0$$
$$\frac{d}{dt}(m_{tot}) = -W_2 \quad \text{------------------------------------(2)}$$

The mechanical energy balance equation can be written as:

$$P_1/\rho + V_1^2/2 + gZ_1 = P_2/\rho + V_2^2/2 + gZ_2 + 4f(L/D)V_2^2/2 \text{-(3)}$$

For the present system $P_1 = P_2$ (Since the inlet and outlet are open to atmosphere)

$V_1 = 0$ (Since the tank is very large and liquid drains so slowly and this assumption gives a simple solution)

At any height h and for a given length of pipe L and assuming constant friction factor, equation 3 becomes

$$g(h+L) = (V_2^2/2)*(1+4fL/D) \quad \text{-----------------------------(4)}$$

$$V_2 = \sqrt{2g(h+L)/(1+4fL/D)} \quad \text{---------------------(5)}$$

Hence $W_2 = \rho\sqrt{2g(h+L)/(1+4fL/D)} * (\pi/4)* D^2$
$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad (6)$$

Substituting the value of W_2 in equation 2, equation-2 becomes:

$$\frac{d}{dt}(\pi R^2 h \, \rho) = -\rho\sqrt{2g(h+L)/(1+4fL/D)} * (\pi/4)* D^2$$

For incompressible liquid

$$\frac{d}{dt}(\pi R^2 h) = -\sqrt{2g(h+L)/(1+4fL/D)} * (\pi/4)* D^2 \text{ --- (7)}$$

The above equation, upon integration between the limits H and complete draining yields

$$t_{eff} = (\sqrt{(H+L)} - \sqrt{L}) * \sqrt{[1+4f(L/D)]/g} * A_t/A_p * \sqrt{2} \text{ --(8)}$$

$$t_{eff} = (\sqrt{(H+L)} - \sqrt{L}) * \sqrt{[1+4f(L/D)]*(A_t/A_p)^2/g} * \sqrt{2} \text{ ---(9)}$$

The above equation can be written as:

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$$t_{eff} = \sqrt{2} * (\sqrt{(H+L)} - \sqrt{L})/\sqrt{g_m} \text{ ---(10)}$$

g_m is modified form of acceleration due to gravity and Equation -109 is modified form of Torricelli's Law.

$$g_m = g/[(1 + 4fL/D)*(A_t/A_p)^2] \text{----------------------------(11)}$$

$$g_m / g = 1/[(1 + 4fL/D)*(A_t/A_p)^2] \text{ ------------------------(12)}$$

Where g_m/g is proportional to (Froude number)^2 for the system of tank with exit pipe which is similar to that defined for draining a liquid through a restricted orifice [Jouse, 2003].

Unlike a free falling particle which travels downward with constant acceleration, a free falling surface decelerates continuously and the deceleration is given by g_m

The Equation suggests that the graph of $(\sqrt{(H+L)} - \sqrt{L})$ Vs Efflux time is a straight line having a slope of $\sqrt{2/g_m}$

For a frictionless flow through an exit pipe, the equation -10 can be written as:

$$t_{eff} = \sqrt{2} * (\sqrt{(H+L)} - \sqrt{L})/\sqrt{g_m} \text{ -----------(13)}$$

where

$$g_m/g = 1/(A_t/A_p)^2 \text{ --- (14)}$$

While deriving the above equation, the contraction coefficient term is neglected. The fluid motion within the Cylinder is also neglected.

From the equations, When $A_t/A_p \rightarrow \infty$, the modified acceleration due to gravity $g_m \rightarrow 0$, and hence liquid drains infinitely slowly there by justifying the assumption of steady state.

Even though it is theoretically possible to drain the liquid completely, it is observed during experimentation that complete draining is not possible due to surface tension forces and hence it is felt necessary to modify the equation as under:

$$t_{eff} = (\sqrt{(H+L)} - \sqrt{H'+L}) * \sqrt{[1 + 4f(L/D)]*(At/Ap)^2/g} * \sqrt{2} \text{ ---(15)}$$

Where H' is the final height as shown in the Figure-1.

Experimental Procedure

The apparatus consists of a stainless steel cylindrical tank of diameter 34cm provided with a level indicator and a 4mm I.D mild steel pipe directly welded to the tank at the centre of the bottom of the tank. The pipe is connected with a gate valve at the bottom most point. The outlet valve is closed and water is filled up to the mark and allowed to stabilize. The stop watch is started immediately after the opening of the bottom valve. The drop in level is read from the level indicator. The time is recorded for every 4cm drop in level. Once the level reaches 2cm from the bottom of the vessel, the watch is stopped. The experiments are repeated to check the consistency of data. The experiments are performed for the following cases as shown in Table-1.

Table-1. List of experiments performed with out polymer addition.

S. No.	Initial height of liquid in the tank (cm)	Pipe length (m)	At/Ap
1	44 40 32 20	1	7225
2	44 40 32 20	0.75	7225
3	44 40 32 20	0.5	7225
4	44 40 32 20	0.25	7225

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2. VERIFICATION OF EFFLUX TIME WITH EXPERIMENTAL DATA AND FINE TUNING THE FRICTION FACTOR EQUATION AND VERIFYING THE VALIDITY OF FINE TUNED EQUATION WITH EXPERIMENTAL VALUES

Since the experimental values are based on fluid motion within the cylinder and unsteady state condition prevailing within the tank, deviations between theoretical and experimental values are expected. Hence comparisons between theoretical and experimental values are done.

While comparing, the following friction factor equation [Warren Mccabe, 1993] used for steady state fully developed turbulent flow is used for calculating the efflux time.

$$f = 0.0014 + 0.125/\mathrm{Re}^{0.32} \text{ ----------------------------- (16)}$$

The advantage of the above equation is that it can be used for wide range of Reynolds numbers starting from 3000 to 3×10^6

The difference between theoretical and experimental values are shown in Figure-2.
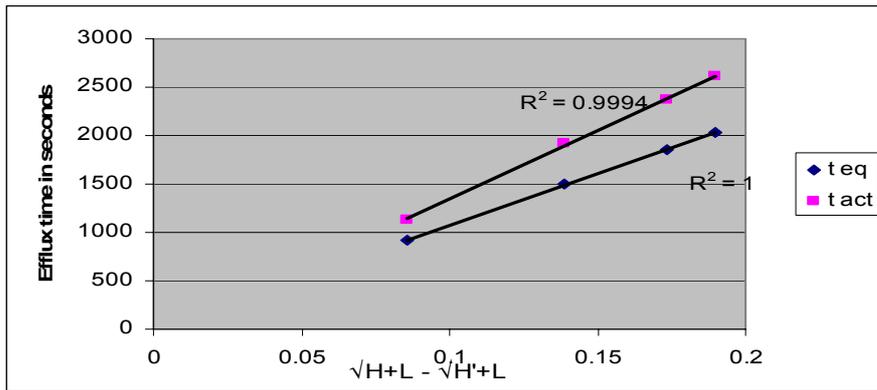
Figure-2. Comparison of efflux time equation based on equation-16 and experimental values (1meter pipe length).

There is a maximum deviation of 28%.
Since there is a difference between theoretical and experimental values, it is felt necessary to fine tune the friction factor equation and this is done by changing the coefficient of Reynolds number in equation-16 and corrected the equation as under:

The fine tuned equation is

$$f = 0.0014 + 0.125/\mathrm{Re}^{0.25} \text{ --------------------------- (17)}$$

With equation-17, the graphs are redrawn and are shown in the Figure-3 for one meter long pipe.
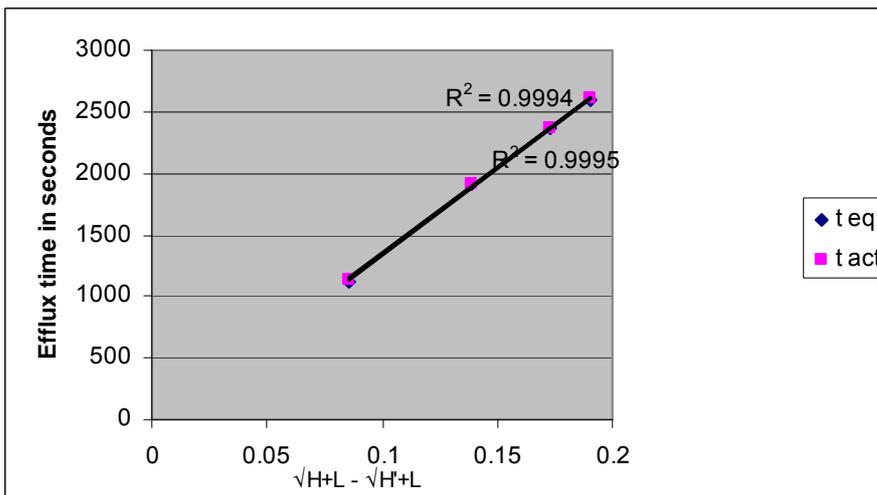
Figure-3. Comparison of efflux time using friction factor equation-17 and experimental values (1meter length pipe).

The difference between efflux time values arrived by equation-16 and experimental values are shown in Table-2 for 0.75m long pipe.

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Table-2. Comparison of efflux time using friction factor equation-16 for 0.75m pipe length.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-16)	Experimental efflux time in seconds	Error (%)
1	44	2011	2621	27
2	40	1837	2367	26
3	32	1497	2059	34
4	20	924	1209	28

Equation-17 is compared for its validity for calculation of efflux time with the experimental values and the results are shown in the Table-3 for 0.75 m long pipe.

Table-3. Comparison of efflux time using equation-17 and experimental values for 0.75m pipe length.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-17)	Experimental efflux time in seconds	Error (%)
1	44	2551	2621	2.76
2	40	2329	2367	1.62
3	32	1895	2059	8.66
4	20	1171	1209	3.3

The difference between efflux values arrived by using equation-16 and actual values are shown in Table-4 for 0.5 m long pipe.

Table-4. Comparison of efflux time using equation-16 for 0.5m pipe length.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-16)	Experimental efflux time in seconds	Error (%)
1	44	1962	2540	29.5
2	40	1799	2315	29
3	32	1459	1840	26
4	20	928	1258	36

Equation-17 is compared for its validity for calculation of efflux time with the experimental values and the results are shown in Table-5 for 0.5m pipe length.

Table-5. Comparison of efflux time using friction factor equation-17 for 0.5m pipe length.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-17)	Experimental efflux time in seconds	Error (%)
1	44	2462	2540	3.18
2	40	2257	2315	2.58
3	32	1830	1840	0.537
4	20	1162	1258	8.3

Table-6 gives comparison of efflux time calculated using equation-16 and experimental values for 0.25m long pipe.

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Table-6. Comparison of efflux time calculated using equation-16 and experimental values for 0.25m pipe length.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-16)	Experimental efflux time in seconds	Error (%)
1	44	1868	2389	28
2	40	1725	2201	28
3	32	1422	1810	27
4	20	930	1300	39

The data suggests that there is a maximum error of 39% when the pipe length is 20cm.

Table-7. Gives comparison of efflux time calculated using equation-17 and experimental values (0.25m pipe length).

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-17)	Experimental efflux time in seconds	Error (%)
1	44	2282	2389	5
2	40	2106	2201	4.5
3	32	1736	1810	4.2
4	20	1193	1300	14.64

The data suggests that there is more than 14% deviation between fine tuned friction factor equation-17 and experimental values necessitating the applicability of equation-17 for pipe length > 0.25meters and initial height of liquid >20cm.

The Reynolds numbers for all the above cases are calculated and are found to be in turbulent region only.

Some of the conclusions of the above study were:

- The Friction factor is more than that of a steady state fully developed turbulent flow as indicated by the efflux time.
- The friction factor equation -17 takes into account the cumulative effect of contraction coefficient, fluid motion within the cylinder and unsteady state behavior in the tank.
- The empirical equation is valid for Pipe length greater than 0.25 meters and initial height of liquid >20cm.

- When a liquid is drained under frictionless conditions, equation-14 is written as $gm/g = 1/(At/Ap)2$ is proportional to square of Froude number. Hence, slow draining of a liquid through an exit pipe is a process that keeps Froude number constant. The fact that ratio does not vary with time can be explained as follows. Draining causes the free surface to fall and hence potential energy of the liquid is converted to kinetic energy of exiting fluid.
- In case of frictional flow, equation-12 can be written as $gm/g = 1/[(1 + 4fL/D)*(At/Ap)2]$ and is proportional to square of Froude number. Hence Froude number is constant only when $1 + 4fL/D$ is constant and hence depends on the length of pipe and friction factor.

Table-8 gives the data of $(1 + 4fL/D)$ for pipe lengths of 1, 0.75, 0.5 and 0.25 meter.

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Table-8. Data of 1 + 4fL/D for different pipe lengths.

S. No.	Initial height of liquid in the tank (cm)	1 + 4fL/D	Pipe length (m)
1	44	17.53	1
	40	17.55	
	32	17.64	
	20	17.59	
2	44	13.42	0.75
	40	13.41	
	32	13.68	
	20	13.62	
3	44	13.42	0.5
	40	13.41	
	32	13.68	
	20	13.62	
4	44	5.05	0.25
	40	5.06	
	32	5.10	

It is observed from the table that for a given length, (1+4fL/D) remained constant and is independent of initial level of the liquid in the tank. This also justifies constant friction factor assumption.

Hence, slow draining of a liquid through an exit pipe is a process that keeps Froude number constant. This can be explained as follows.

The potential energy of the draining fluid is

partly converted into kinetic energy of the exiting fluid and part of it is used to overcome the frictional resistance in the pipe.

▪ Even though the mathematical equation for efflux time developed is applicable for the case where the tank top surface and exit point are open to the atmosphere, it can also be used for pressurized system by rewriting the equation as under:

$$t_{eff} = \left(\left(\sqrt{(P_1 - P_2)/\rho g + (H+L)} \right) - \sqrt{(P_1 - P_2)/\rho g + (H'+L)} \right) * \sqrt{1 + 4f(L/D)*(At/Ap)^2/g} * \sqrt{2} \quad \text{------------------(18)}$$

Since, the efflux time is more than what is anticipated for a fully developed flow resulting in more drag, drag reduction options are to be explored. Drag reducing agents increases the modified acceleration due to gravity g_m.

The present study considers the case of drag reduction using water soluble polyacryl amide (PAM), since PAM is able to endure shear drag reduction than PEO (Polythene Oxide). More over, Drag reduction by PAM is higher than PEO [Den Tonnder *et al.,* 1995]. The polymer also does not degrade during storage [W. Jones *et al.,* 1969].

Preparation of polymer solution

Even though procedures for polymer solution preparation are available in the literature [Den Toonder *et al.,* 1995 and R. Sinchee fore *et al.,* 2005], the following procedure is adopted for the present case.

The present system under consideration is once through, a homogeneous polymer solution is prepared by weighing 1.6gm of Polyacrylamide (Polyacryalamide is

obtained from Otto Chemie- Mumbai and having a molecular weight of 5,000,000) and suspending the polymer in small quantity of isoproponal and dissolving it in 400ml of water and the solution is kept at room temperature while stirring for 4 hours. After 4 hours, the sample is allowed to hydrate for 24 hours. After 24 hours, the solution is clear without any non homogeneity. Isoproponal acts like a disinfecting agent. From this master solution, the required concentrations are prepared by diluting with water for preparing required concentration of polymer solutions.

Experimental procedure

The thoroughly mixed solution is transferred into the same tank assembly by closing the outlet valve. The outlet is Valve is opened and simultaneously stops watch also started. The time taken for different concentrations of polymer solution at different heights is noted. The following experiments are performed with the polymer solutions which are useful in comparing the efflux time data with that in Table-1.

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Table-9. List of experiments performed with polymer solutions.

S. No.	Initial height of liquid in the tank (cm)	Pipe length (m)	At/Ap	Remarks
1	44 40 32 20	1	7225	Efflux time experiments are performed for 10ppm, 20ppm, 30ppm solutions
2	44 40 32 20	0.75	7225	
3	44 40 32 20	0.5	7225	
4	44 40 32 20	0.25	7225	

3. STUDY OF TANK DRAINING PATTERN WITH AND WITHOUT POLYMER SOLUTION

The drop in liquid level with respect to time for different concentrations of polymer is shown in Figure-4 when the initial height of liquid in the tank is 44cm and 1 meter pipe length as well.
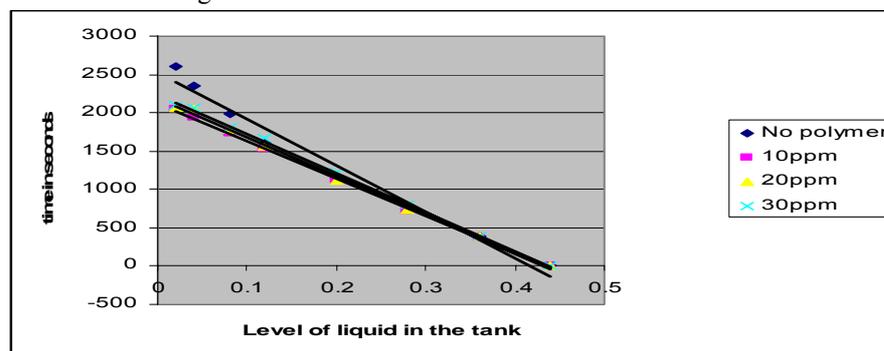
Figure-4. Study of draining pattern with and without polymer addition for 1m pipe length.

The figure suggests that lower the concentration of polymer, faster the draining of liquid from the tank. Similar trend is observed for other initial heights of 40cm, 32cm, and 20cm when the pipe length is 1 meter.

The trend is also similar for initial heights of 44cm, 40cm, 32cm and 20cm for all the other three pipe lengths (0.75m, 0.5m and 0.25m).

4. FINE TUNING OF EMPIRICAL EQUATION FOR POLYMER SOLUTIONS

a) For 10 ppm polymer concentration

The Efflux time based on friction factor equation-16 and experimental values are plotted in Figure-5 for 1m pipe length.

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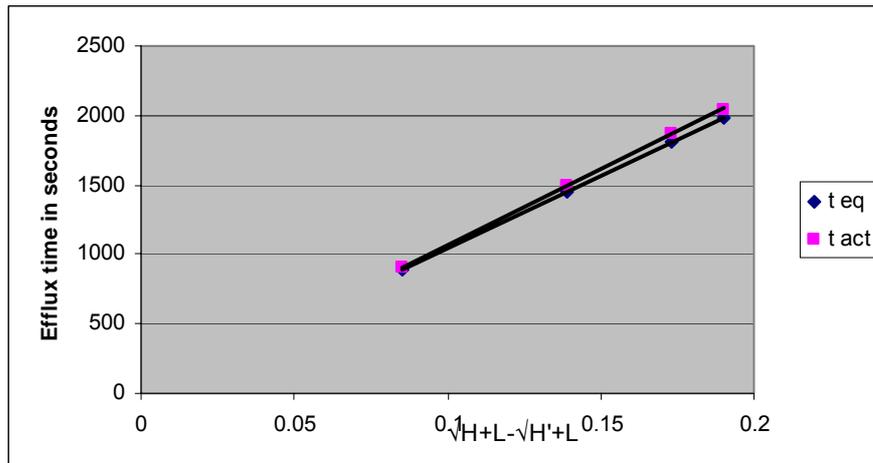
Figure-5. Comparison of efflux time using equation-16 and experimental values
for 10 ppm polymer and 1m pipe length.

Similar comparisons are shown in the figure for pipe length of 0.75m (Figure-6) and with different initial heights of liquid in the tank.
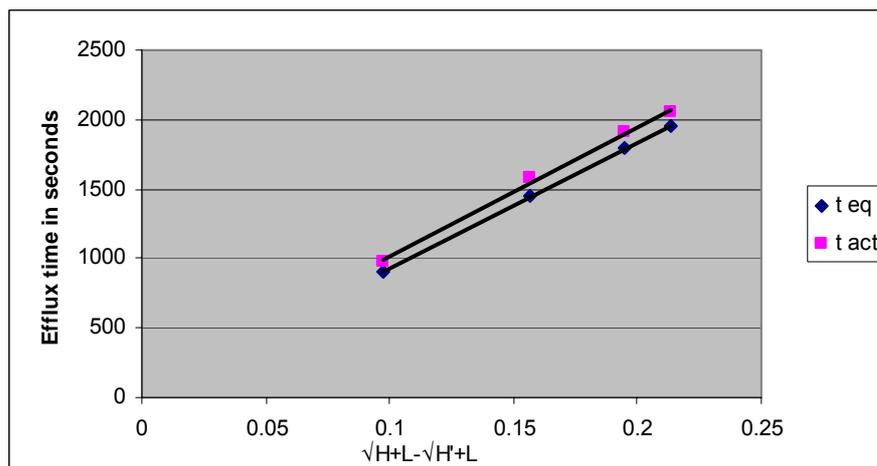
Figure-6. Comparison of efflux time using equation-16 and experimental values
for 10 ppm polymer and 0.75m pipe length.

This is in good agreement with the friction factor equation-(16) and hence this equation is accepted as friction factor equation for 10 ppm polymer concentration.

The equation is further compared for 0.5m length and 0.25m length and the comparison is shown in Table-10.

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Table-10. Comparison of efflux time using equation-16 and experimental values for 10 ppm solution.

S. No,	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-16)	Experimental efflux time in seconds	Error (%)	Remarks
1	44	1899	1900	0.045	Pipe length = 0.5 meter
	40	1744	1765	1.16	
	32	1426	1503	5.4	
	20	905	1011	11.72	
2	44	1842	2060	11.82	Pipe length = 0.25 meter
	40	1703	1936	13.64	
	32	1405	1593	13.42	
	20	906	1000	10.35	

The above table suggests that equation -16 is valid only when the initial height of liquid in the tank is > 20cm for 0.5 meter length and for all initial heights of liquid for 0.25 m length pipe.

b) **For 20ppm polymer concentration**

Figure-7. Comparison of efflux time using equation-16 and experimental values for 1 meter length pipe.

However, with the equation $f = 0.0014 + 0.125/\mathrm{Re}^{0.315}$ -(19) the error is minimum and hence accepted as fine tuned friction factor equation.

For 20ppm Polymer concentration and 1m pipe length, comparisons are made using friction factor equation-16 and experimental values and are shown in Figure-7.

The efflux time comparison based on equation-19 and experimental values for 1m and 0.75m pipe length are shown in Figures-8 and 9.

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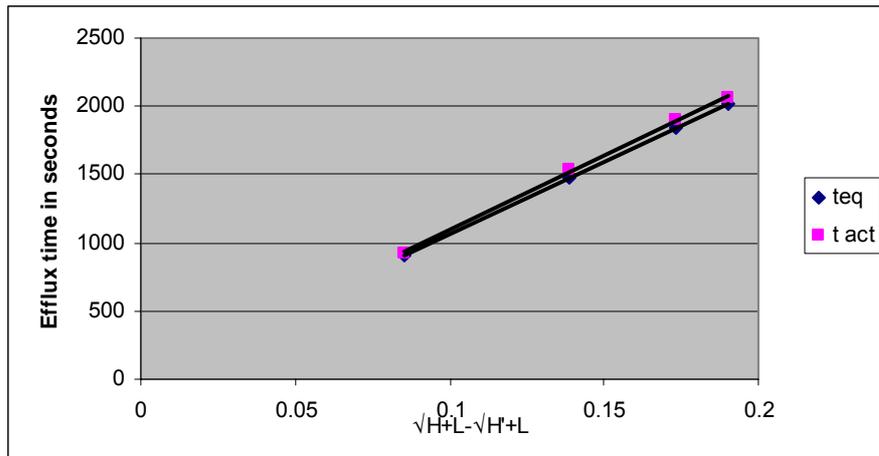
Figure-8. Comparison of efflux time using equation-19 and experimental values for 1m pipe length.
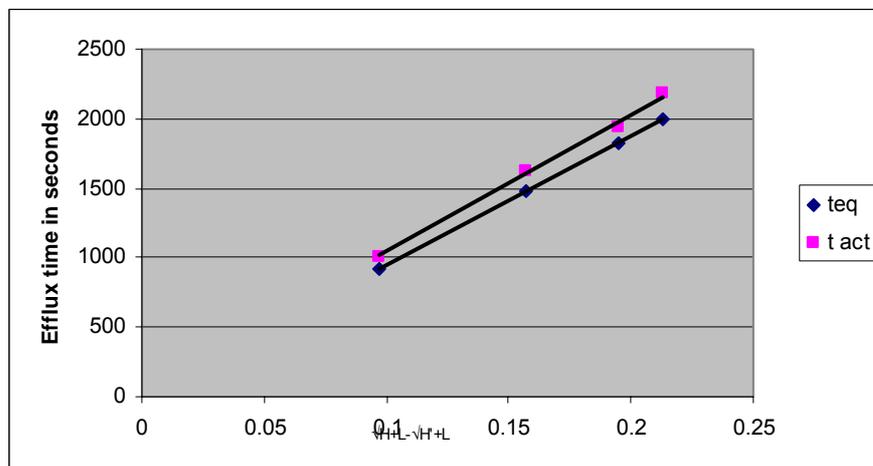
Figure-9. Comparison of efflux time using equation-19 and experimental values for 0.751m pipe length.

For 0.5m length pipe and 0.25m length pipe, efflux time using equation-19 and experimental values are shown in Table-11.

Table-11. Comparison of efflux time using equation-19 and experimental values
for 20ppm Polymer solution (0.25m pipe length).

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation-19)	Experimental efflux time in seconds	Error (%)	Remarks
1	44	1939	2005	3.364	Pipe length = 0.5 meter
	40	1774	1790	0.88	
	32	1450	1525	5.163	
	20	921	1040	12.83	
2	44	1928	2142	11.08	Pipe length = 0.25 meter
	40	1777	1975	11.14	
	32	1458	1611	10.47	
	20	938	1052	12.11	

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The above table suggests the equation -19 is valid only when the initial height > 20cm for 0.5meter pipe length and for all initial heights for 0.25meter length pipe.

c) For 30ppm polymer concentration
Figure-10 compares the efflux time bases on equation-16 and experimental values.
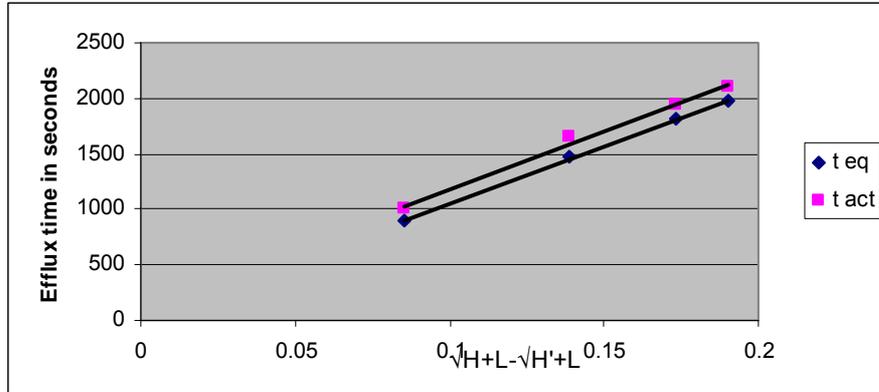
Figure-10. Comparison of efflux time using equation-16 and experimental values for 1m pipe length.

The maximum error is 11%
The fine tuned equation in this case is
$$f = 0.0014 + 0.125/\mathrm{Re}\,0^{0.31} \text{ - (20)}.$$

Comparisons are made between efflux time using friction factor equation-20 and experimental values for 1m and 0.75m length pipes respectively and are shown in the following figures (Figures-11 and 12).
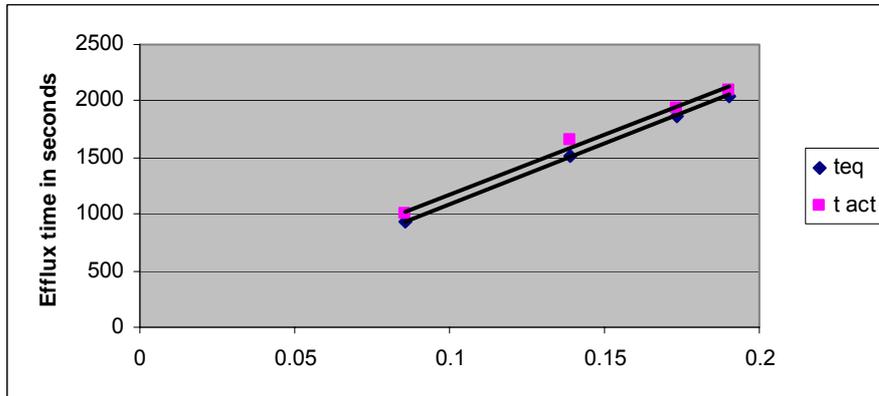
Figure-11. Efflux time comparison using equation-20 and experimental values for 1m pipe length.
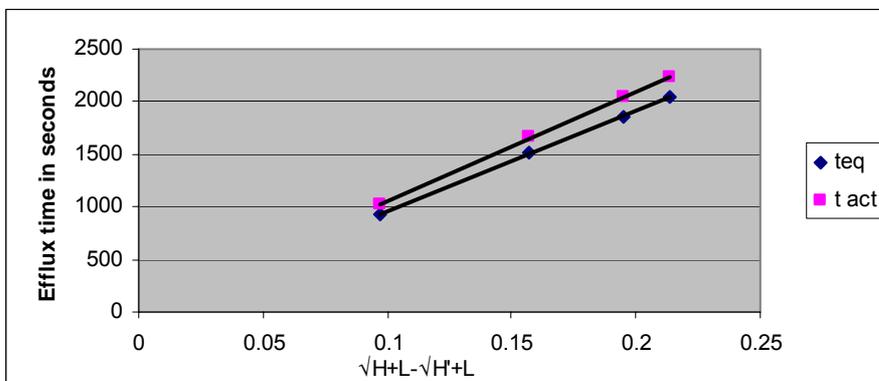
Figure-12. Comparison of efflux time using equation-20 and experimental values for 0.75m pipe length.

The efflux time data using equation-20 for 0.5m and 0.25m pipe lengths are shown in Table-12.

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Table-12. Efflux time comparison using equation-20 and experimental values.

S. No.	Initial height of liquid in the tank (cm)	Efflux time in seconds (using equation -20)	Experimental efflux time in seconds	Error (%)	Remarks
1	44	1978	2077	5	Pipe length = 0.5 meter
	40	1814	1900	4.75	
	32	1474	1541	4.5	
	20	938	1061	13.11	
2	44	1962	2236	13.95	Pipe length = 0.25 meter
	40	1804	2011	11.49	
	32	1486	1711	15.11	
	20	953	1083	13.58	

The data also suggests the validity of equation-20 for initial height >20cm for 0.5m pipe length and for all initial heights for 0.25m pipe length.

Calculation of % drag reduction

The % drag reduction for a given height and length of pipe is calculated by the following formula.
% Drag reduction =) (t_{eff} without Polymer addition − t_{eff} with polymer addition)*100 /t_{eff} without polymer addition) (21)

Table-13 gives drag reduction data for various polymer concentrations.

Table-13. Drag reduction for different pipe lengths and different initial heights of liquid in the tank

S. No.	Polymer concentration	% Drag reduction for an initial height of 44cm			
		1 m pipe	0.75m pipe	0.5m pipe	0.25m pipe
1	10	21.72	21.86	25.19	13.77
2	20	20.99	16.82	21.06	10.33
3	30	19.54	14.42	18.22	6.4
		% Drag reduction for an initial height of 40cm			
1	10	21.09	19.34	23.75	12.03
2	20	19.83	18.03	22.67	10.26
3	30	18.14	13.39	17.93	8.63
		% Drag reduction for an initial height of 32cm			
1	10	21.875	23.26	18.31	11.98
2	20	19.79	21.17	17.11	10.99
3	30	14.06	19.86	16.25	5.46
		% Drag reduction for an initial height of 20cm			
1	10	20.70	18.94	19.63	23.07
2	20	18.23	16.45	17.32	19.07
3	30	11.89	14.80	15.65	16.69

As seen from the figures, as polymer concentration is reduced, drag reduction has increased and maximum drag reduction is limited to only 29%.

CONCLUSIONS

▪ When ever there is a transition from laminar to turbulent flow, drag reduction takes place.

▪ Lower the polymer concentration, higher the drag reduction.
▪ Since the system is once through, the maximum drag reduction is limited to 25% only.
▪ At Threshold Reynolds number, "Onset" to drag reduction takes place. The existence of such Reynolds number is a typical for drag reducing

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solutions and is related to exceeding a certain wall shear stress at which drag reduction sets in depending upon the specific solvent-polymer system [Virk, 1975]. In the present case, Drag reduction "Onset" occurred at low Reynolds number.

- Polymer addition decreases the friction factor as indicated by efflux time values and hence the value of gm and hence the Froude number.
- % Drag reduction is influenced by the initial height of liquid in the tank.

NOMENCLATURE

D = Diameter of Pipe, meters
f = Friction factor, dimensionless
g = Acceleration due to gravity, 9.8 m/sec^2
H = initial height of liquid in the tank, meters
H = final height of liquid in the tank, meters
h = Height of tank at any time t, meters
L = Length of exit pipe, meters
2R = Diameter of tank, meters
A_t = Area of tank, m^2
A_p = Area of pipe, m^2
g_m = Modified form of acceleration due to gravity m/sec^2
K_c = Contraction Coefficient, dimensionless
m_{tot} = Total mass of liquid in the tank , kg
P_1 & P_2 = Pressures at station 1 and station 2 respectively , N/m^2
t_{eff} = Efflux time in seconds
V_1 & V_2 = Velocities at station 1 and 2 respectively, m/sec
W_1 & W_2 = Mass flow rate at station 1 and station 2 respectively, kg/sec
Z_1 & Z_2 = Elevations at station 1 and 2 respectively, meters
ρ = Density of liquid kg/m^3

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