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Use of Polymer Solutions for Drag Reduction in Gravity Driven Flow Systems

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Abstract: Efflux time measurements are carried out for draining water, a Newtonian liquid (below its bubble point) from a large open cylindrical tank under the action of gravity through an exit piping system. The mathematical models reported in the literature for Newtonian liquid are used for verifying the validity of experimental data. Further, to reduce the efflux time (*i.e.* to reduce drag), measurements are also carried out in the presence of water soluble drag reducing polythene oxide polymer solutions. The variables considered for both the cases (with and without polythene oxide polymer solutions) are diameter of storage vessel, initial height of liquid in the tank, length of the exit pipe, diameter of exit pipe and concentration of polymer. The experimental data suggested that as the diameter of exit pipe is increased, addition of polymer solutions do not have a significant impact on efflux time. This also suggests that effect of polymers is felt at the contraction point only.

Keywords: Cylindrical tank; exit pipe; efflux time; polymers; gravity driven.

1. Introduction

Chemical industries use different shapes and geometries of process vessels for storage and processing. Efflux time is defined as the time required for emptying the vessels of their liquid content [1]. This time is important either to cater to the enhanced productivity or to take care of emergency situations and hence significant in chemical, food and pharmaceutical industries [2].

Efflux time equations for gravity draining of Newtonian liquid from a large open cylindrical tank (below its bubble point) through an exit piping system for turbulent flow conditions in the exit pipe are reported by Joye and Barret [3]. The authors assumed constant friction factor in the exit pipe line. They considered a contraction coefficient of 1.5 while computing the efflux time and comparing the theoretical efflux time with experimental values. This contraction coefficient value is used in this study to evaluate the theoretical efflux time.

Subbarao *et al.* [4] also made the same assumption of constant friction factor while deriving the efflux time equation when a Newtonian liquid is drained from a large cylindrical open tank through an exit piping system for turbulent flow in the exit pipe. The simplified form of efflux time equation is named as modified form of Torricelli equation.

The authors while comparing the efflux time data with the model used fine tuned friction factor equation which takes into account the cumulative effect of contraction losses, the flow within the

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cylindrical tank and roughness of the walls (These terms were ignored by the authors while deriving the efflux time equation). The authors further stated that during draining Froude number remains constant.

During draining, the liquid experiences some friction and this friction is a measure of drag. This drag increases drastically when flow transforms from laminar (in the tank) to turbulent flow in the exit pipe. Hence, drag reduction (reduction in efflux time) options are to be explored. Various techniques were identified for reducing drag and were subdivided into active and passive means of drag reduction [5]. Passive methods include use of riblets [6], outer layer manipulators [7] and convex structures [8]. The extent of drag reduction by these methods however is limited [4].

Drag reduction by additives was considered one among the active methods. This can be achieved by use of additives such as polymers [4], surfactants [9] and non-Newtonian rigid fibers [10]. Polymers and surfactants however were found to be more suitable as their additions gives substantial savings in energy [9]. To achieve a given amount of drag reduction, the concentration of surfactant solution required was much higher than that of polymers [11]. Hence, studies were carried out using polymer solutions for reducing the drag (*i.e.* reducing the efflux time) in gravity driven flow systems.

The effect of addition of water soluble polyacrylamide polymer solutions on drag reduction (reduction in efflux time) is carried out by some authors [4]. The authors reported an optimum concentration of 10 ppm. It is also reported that Froude number increases when polymer solutions are added to cylindrical storage tank when drained by means of an exit piping system.

Using polyacrylamide polymer solutions, drag reduction experiments for two exit pipe systems in a cylindrical tank were also investigated [12]. The extent of reduction in efflux time (Froude number) is observed to be more for two exit pipe systems compared to single exit pipe system in the absence and presence of polymer solutions. The authors further reported the ratio of cross sectional area of tank to exit pipe as 1600 below which addition of polymer solutions does not have any effect on drag reduction. Froude number can also be influenced by the geometry and type of the polymer used.

By changing the geometry of the vessel, efflux time comparisons are made between cylindrical and conical vessels [13], between cylindrical and spherical vessels [14] when the vessels are connected by an exit pipe of same diameter, the flow in the exit pipe being turbulent. Efflux time comparison for cylindrical, conical and spherical vessels for the case of laminar flow in the exit pipe is also available in the literature [15]. Efflux time determination for two exit pipe system is also reported by some authors [16].

Literature reports experimental works pertaining to drag reduction using polythene oxide [17] and polyacrylamide polymer solutions [18] since these polymers add value to the money [19]. Compared to polyacrylamide, polythene oxide is not shear resistant [20] in a closed system where pump is being used for transfer of liquid and does a better job of drag reduction in once through systems only (which is the case with the present system of emptying a liquid from a large open cylindrical tank). Moreover, polythene oxide is highly water soluble and hence considered for the present study. To the best of authors' knowledge, no experimental evidence of drag reduction using polythene oxide (PEO) in a cylindrical storage vessel drained by an exit pipe is reported in the literature. The experiments are performed with water and are verified with the theoretical model for efflux time for a Newtonian liquid reported in the literature. Experiments are also performed with aqueous solutions of polythene oxide polymer. The variables studied are initial height of liquid in the tank, diameter of the storage tank, Length of the exit pipe and diameter of exit pipe, concentration of polymer solutions. The scope of work includes:

(a) Experiments on efflux time with water and verification with the theoretical models reported in the literature.
(b) Preparation of polymer solutions of different concentrations and their effect on efflux time for the variables considered.

2. Materials and methods

2.1. Description of apparatus

The schematic diagram of the apparatus and the equipment are shown in Figure 1. The equipment used consisted of known diameter tank rigidly placed on a steel structure. A mild steel pipe of known diameter (d) is welded to the tank at the centre of the bottom of the tank, served as an exit pipe. A gate valve (GV) provided at the bottom most point of the exit pipe, served as control valve for draining of liquid from the tank. A transparent plastic tube (LI) provided to the tank served as level indicator during draining operation. Efflux times are measured with a stop watch of 1 sec accuracy. The lists of experiments performed are shown in Table 1.

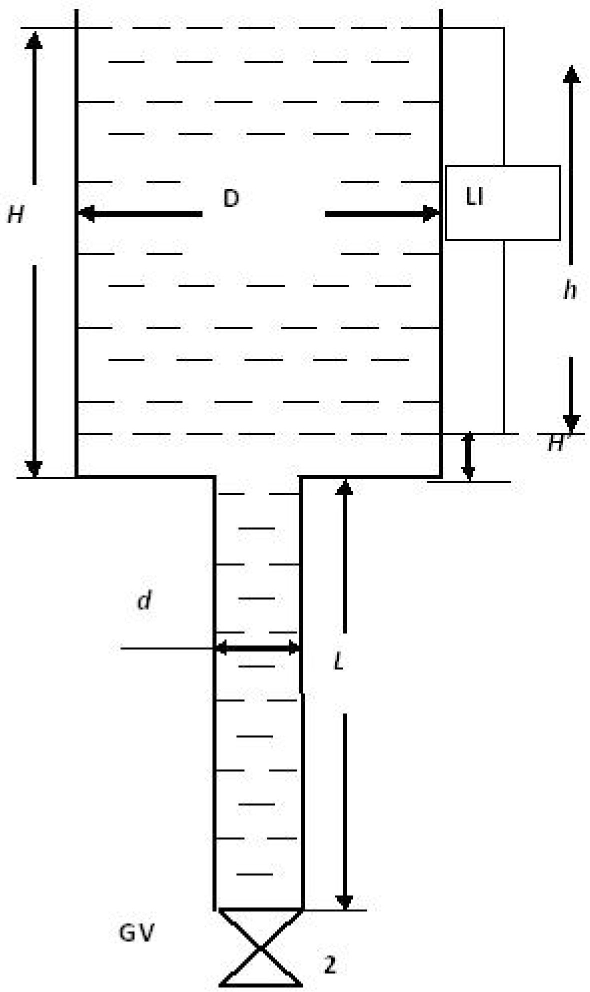

Figure 1. Tank along with exit pipe

2.2. Experimental procedure

Part A

Gate valve (GV) was closed and the tank and exit pipe assembly were filled with water and allowed to stabilize. The stopwatch was started immediately after the opening of the bottom gate valve. The drop in water level was read from the level indicator. The time was recorded for a fall in the liquid level to a predetermined level above the tank bottom. The experiments were repeated and the measurements are taken to check the consistency of data.

Part B

Polythene oxide polymer used in the present study is obtained from Otto Chemi-Mumbai. The average molecular weight of the polythene oxide polymer as reported by the supplier is 10,00,000. The stock solution of polymer is prepared by dissolving 1.6×10^{-3} kg (1.6 gm) of polymer in 400 mL of water. The solution is stirred for 4 hours and then allowed to hydrate for 24 hours. The clear solution without any non-homogeneity is diluted suitably to prepare desired concentration of polymer solutions. The ranges of concentrations considered are shown in Table 1. The pre-mixed solutions are added to the cylindrical tank and efflux time data are obtained in the manner described above in part A.

The lists of experiments performed in the absence and presence of polymer solutions are shown in Table 1.

Table 1. List of experiments in the presence and absence of polymer solutions

Dia. of tank (m)	Length of exit pipe (m)	Initial height of liquid in the tank (m)	Concentration of polymer solution (ppm)
0.30	1,0.75,0.5,0,25	0.3,0.24,0.18,0.12	0,10,20.30,60,65,70
0.32	1,0.75,0.5,0.25	0.3,0.24,0.18,0.12	0,10.20.30.60,65,70

3. Results and discussion

3.1. Verification of efflux time data for water

While arriving at theoretical efflux time, the following efflux time equation reported by Subbarao *et al.* [4] is used.

$$t_{eff} = \sqrt{\frac{2}{g_m}}\left(\sqrt{H+L} - \sqrt{H'+L}\right) \tag{1}$$

t_{eff} is the efflux time, H and H′ are initial and final height of liquid in the tank, L is the length of the exit pipe and g_m is modified form of acceleration due to gravity and is given by

$$\frac{g_m}{g} = \frac{1}{\left(1 + 4f\frac{L}{d} + K_c\right)\left(\frac{A_t}{A_p}\right)^2}$$

where f is the friction factor, L length of the exit pipe, d diameter of exit pipe, A_t and A_p are cross sectional area of tank and exit pipe respectively, K_c is the contraction coefficient. Joye and Barret [3] reported its value as 1.5 in their studies. This value is used for verifying the validity of the mathematical model.

The following equation for friction factor for turbulent flow reported in the literature is used to calculate the friction factor

$$f = 0.0014 + \frac{0.125}{\mathrm{Re}^{0.32}} \quad [21] \tag{2}$$

The advantage of the above friction factor equation is it can be used in the Reynolds number range of 3,000 to 3×10^6.

To verify whether the flow is turbulent or not, Reynolds number is calculated as

$$\mathrm{Re} = DV_{2\exp}\rho / \mu \tag{3}$$

$V_{2\exp}$ is experimental velocity which is obtained by

$$V_{2\exp} = \left[\frac{\pi}{4}D^2\left(H - H^{|}\right) / \left[\frac{\pi}{4}d^2 t_{act}\right]\right] \tag{4}$$

Where D is the diameter of tank, d is the diameter of exit pipe.

The density and viscosity of water as a liquid in the present study are assumed to be equal to 1000 kg/m^3 and 0.001 kg/m/sec, respectively. The Reynolds numbers for all the cases considered is calculated and found to be > 2100. By substituting $V_{2\exp}$, K_c, f in eq.1 to gives t eq.

The plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time is shown in Figure 2. In the Figure, the theoretical efflux time denoted as **t eq** and experimental efflux time is designated as **t act.**

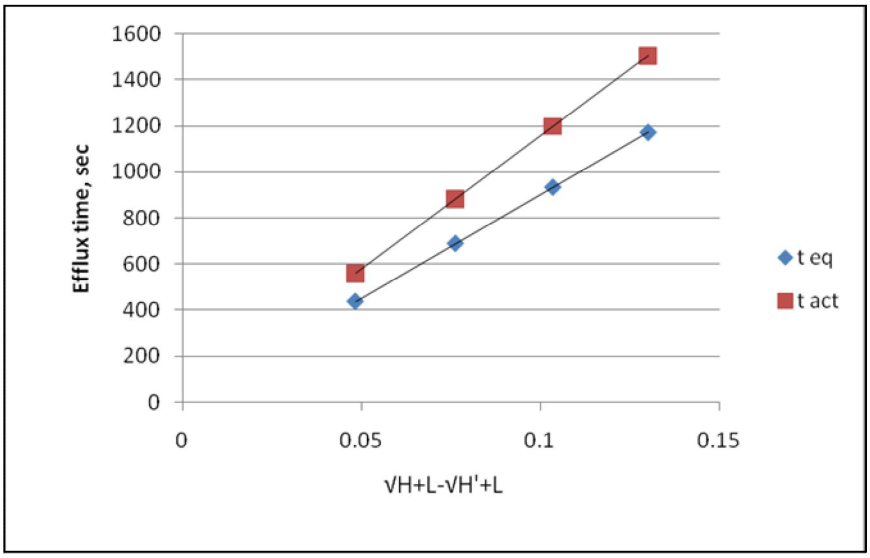

Figure 2. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.3 m, dia. of exit pipe = 0.004 m and length of exit pipe = 1 m)

Percentage deviation is calculated as the difference between experimental and theoretical efflux times. Maximum deviation of 28% is observed between experimental values and theoretical values. The trend observed is similar when the exit pipe length is changed to 0.75 m without changing the exit pipe dia. This is shown in Figure 3.

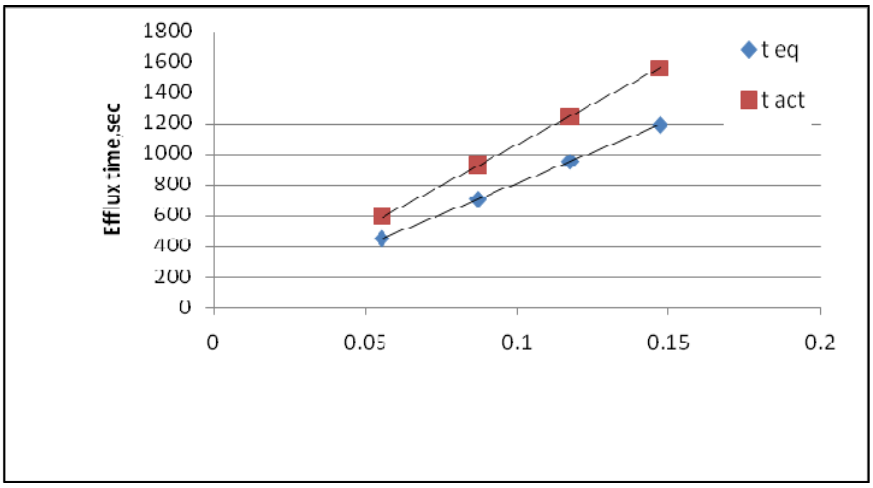

Figure 3. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.3 m, dia. of exit pipe = 0.004 m and length of exit pipe = 0.75 m)

When the tank dia. is changed to 0.32 m and exit pipe length is kept at 1m without changing the exit pipe dia., the trend observed is shown in Figure 4. Maximum deviation of 25% is obtained.

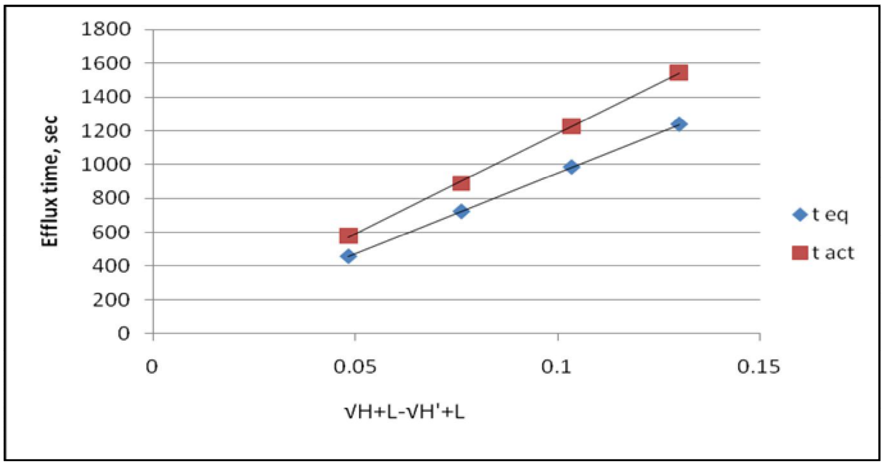

Figure 4. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.32 m, dia. of exit pipe = 0.004 m and length of exit pipe = 1 m)

The trend observed is shown in Figure 5 when the exit pipe length is changed to 0.75 m without changing the tank and the exit pipe diameters.

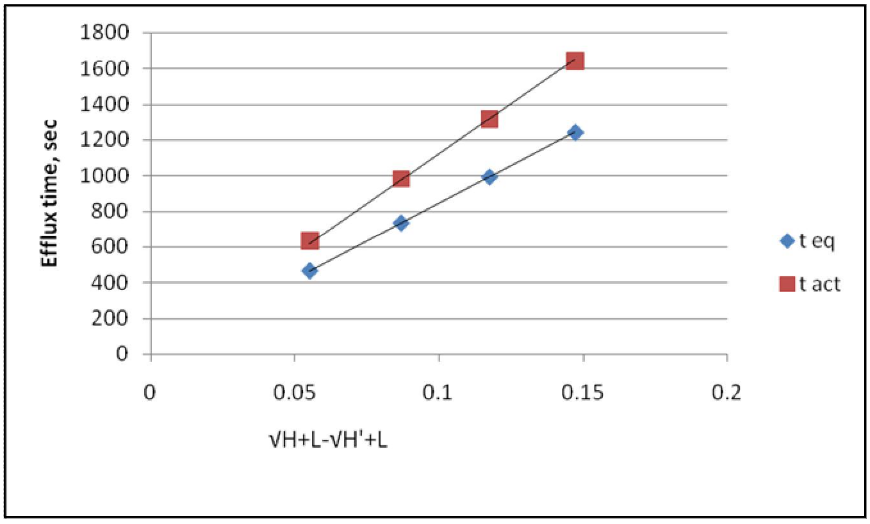

Figure 5. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.32 m, dia. of exit pipe = 0.004 m and length of exit pipe = 0.75 m)

The average Reynolds number for all the above cases is calculated and found to be 4,200. However, when the exit pipe dia is changed to 0.006 m, the plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs Efflux time is shown in Figure 6 for a tank dia. of 0.30 m and exit pipe length of 1 m.

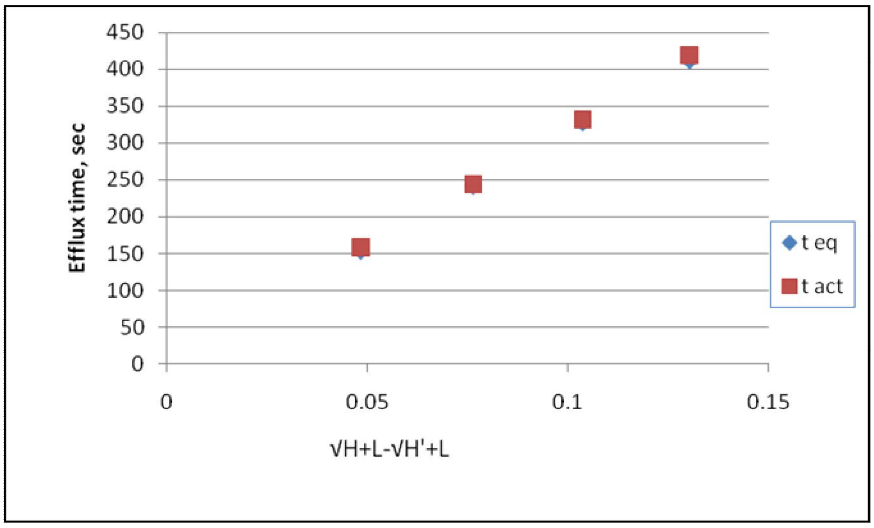

Figure 6. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.3 m, dia. of exit pipe = 0.006 m and length of exit pipe = 1 m)

The experimental and theoretical values deviated only by a maximum of 3%. The trend observed was similar when the tank dia. is changed to 0.32 m without changing the exit pipe length and exit pipe diameter (Figure 7). A maximum deviation of 7% is observed in these cases. The average Reynolds number when the exit pipe diameter is 0.006 is found to be 9,500.

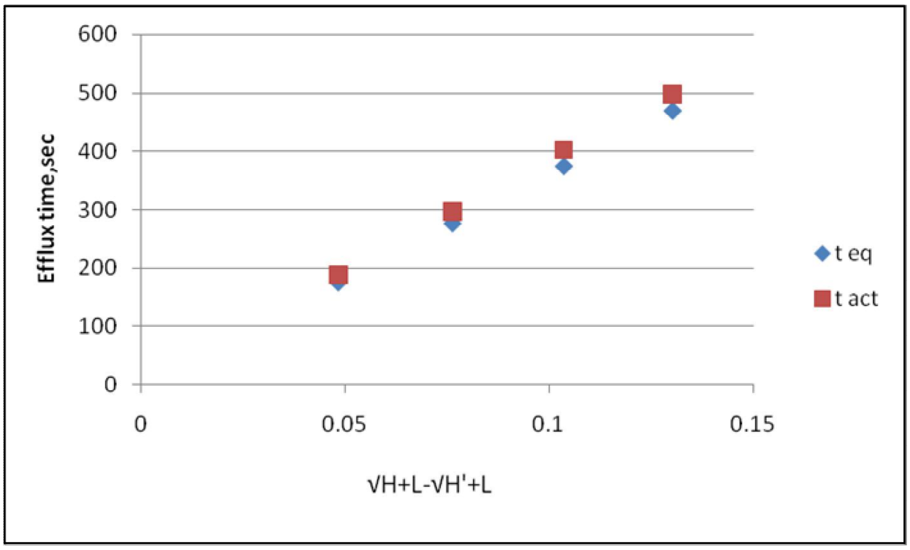

Figure 7. Plot of $\sqrt{H+L}$ - $\sqrt{H'+L}$ vs efflux time
(Tank dia = 0.32 m, diameter of exit pipe = 0.006 m and length of exit pipe = 1 m)

It can be concluded from the above plots (Figure 2 and 7) that the contraction coefficient value reported by Joye and Barret [3] is influenced by the diameter of exit pipe (and hence cross sectional area of tank to exit pipe) as seen in the deviation between experimental and theoretical values for 4 mm exit pipe and 6 mm exit pipe and hence valid for average Reynolds number $>$ 4200.

3.2. Variation of efflux time with length of the exit pipe

Variation of experimental efflux time for different exit pipe lengths for 0.30 m dia as well as 0.32 m diameter tank is shown in the following figure (Figure 8).

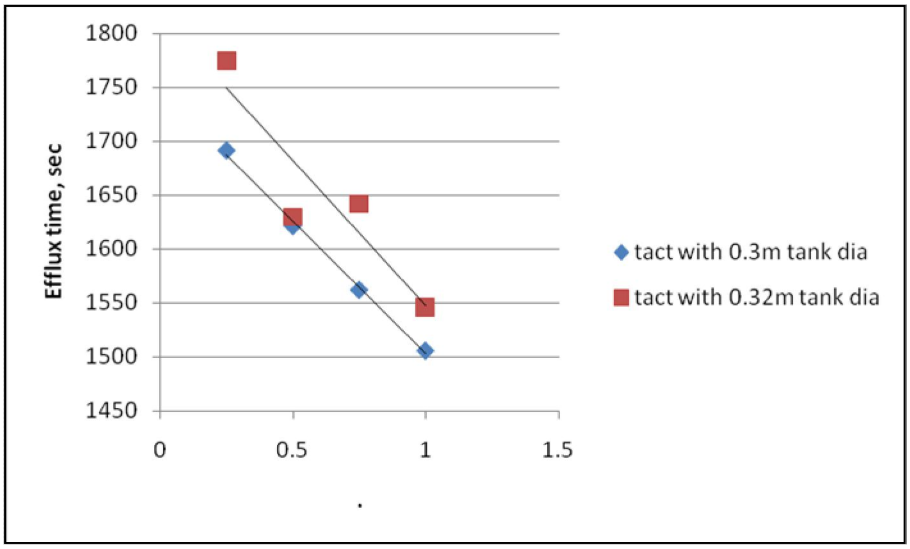

Figure 8. Variation of efflux time with length of exit pipe

It can be concluded from the plots that as the length of exit pipe increases, efflux time decreases. As the length of the exit pipe increases, there is a possibility of development of fully developed flow. Literature suggests that when the fluid entering the tube is laminar and becomes turbulent on entering the tube, transition length to the tune of 100 pipe diameters is required [22]. In this case, the transition length for 0.004 m diameter pipe is 0.4 m and for 0.006 m pipe, it is 0.6 m. Beyond this length, efflux time reduces due to development of fully developed flow.

3.3. Variation of efflux time with concentration of polymer

The following plot (Figure 9) illustrates the variation of efflux time with concentration of polymer for 0.3 m diameter tank.

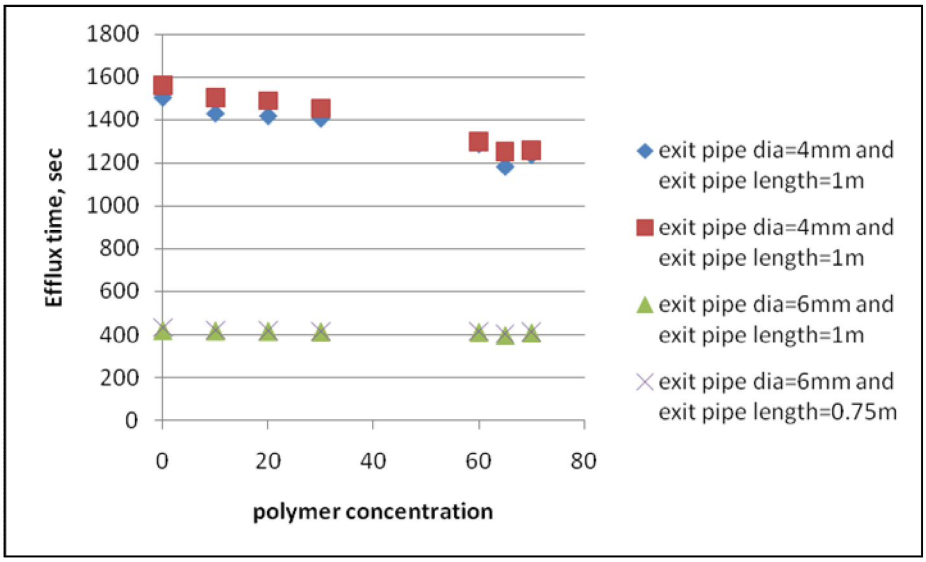

Figure 9. Variation of efflux time with concentration of polymer (diameter of tank = 0.3 m)

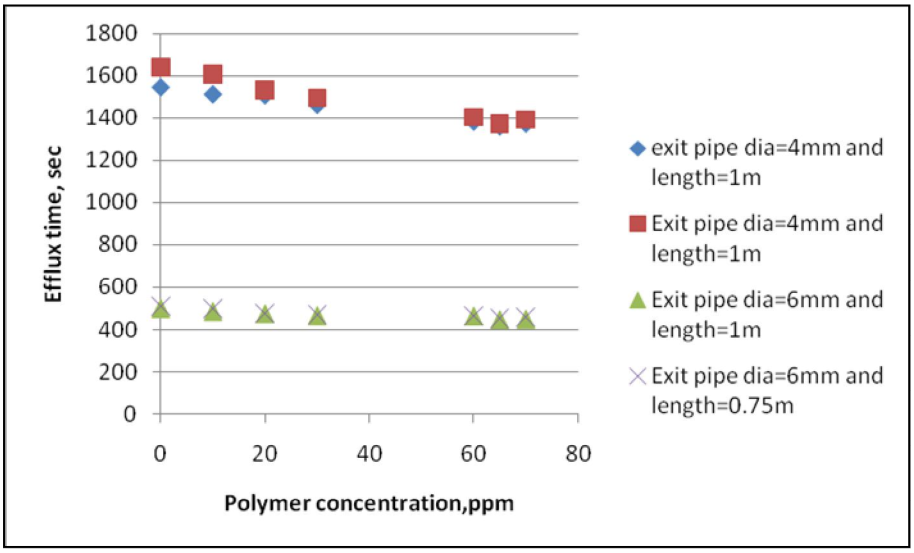

Figure 10. Variation of efflux time with concentration of polymer (diameter of tank = 0.32 m)

The plot suggests as the polymer concentration is increased, efflux time (*i.e.* drag) decreases, reaches a minimum at 65 ppm and then increases when the concentration is increased from 65 to 70 ppm for 4 mm exit pipe diameter. Hence, it can be concluded that the optimum concentration is 65 ppm when the exit pipe diameter is 4 mm. The plot also suggests that when the exit pipe diameter is changed to 6 mm, not much variation in efflux time is observed. It can possibly be concluded that polymers are influencing the contraction point only. The trend for 0.32 m diameter tank is found to be same and is shown in the following figure.

Hence, it can be concluded that the optimum concentration in case of polymer solutions is influenced by the diameter of exit pipe only and is independent of tank diameter, height of liquid in the tank and exit pipe length. However, efflux time is influenced by the diameter of tank, initial height of liquid in the tank and exit pipe length.

4. Conclusions

Some of the conclusions of the above study are:

Efflux time equation fits into experimental values when the exit pipe diameter is 0.006 m and a maximum of 28% deviation is observed when the exit pipe diameter is 0.004 m. This clearly suggests that contraction coefficient value is not constant and is influenced by the cross sectional area of tank to exit pipe. Efflux time decreases with increased length of exit pipe due to establishment of fully developed flow beyond transition length. Optimum concentration when polythene oxide polymer used in 65 ppm when the exit pipe diameter is 0.004 m.Optimum concentration is independent of the tank diameter as well as the length of the exit pipe. For exit pipe diameter of 0.006 m, no significant reduction in efflux time is observed when polymer solutions are added. This suggests that polymer solutions are influencing the contraction point possibly delaying the onset of turbulent (from laminar in the tank to turbulent in the exit pipe).

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References

[1] Hart, P. W. and Sommerfeld, J. T. 1995. Expressions for gravity drainage of annular and Toroidal containers. *Process Safety Progress,* 14: 238-243.

[2] Sommerfeld, J. T. and Stallybrass, M. P. 1992. Elliptical Integral solutions for drainage of horizontal cylindrical vessels with piping friction. *Industrial and Engineering Chemistry Research,* 31: 743-746.

[3] Donald, D. J. and Barret, B. C. 2003. The tank draining problem revisited: Do these equations actually work. *Canadian journal of Chemical Engineering,* 81: 1052-1057.

[4] Subbarao, Ch. V., King, P., and Prasad, V. S. R. K. 2008. Effect of polymer additives on the dynamics of a fluid for once through system. *International Journal of Fluid Mechanics*

Research, 35: 374-393.

[5] Bewersdorf, H. W., Gyr, S., and Tsinober, A. 1993. An investigation of possible mechanism of heterogeneous drag reduction in pipe channel flow. *Rheological Acta,* 32: 140-149.

[6] Peet, Y. and Sagaut, P. 2008. Turbulent drag reduction using sinusoidal riblets with triangular cross section. 38th AIAA Fluid Dynamics Conference and Exhibit, June 23-26 Seattle, WA.

[7] Sahlin, A., Johansson A. V., and Alfredsson H. 1988. The possibility of drag reduction by outer layer manipulators in turbulent boundary layer. *Physics of Fluids,* 31: 2814-2823.

[8] Alving, A. E. 1988. *"Boundary layer relaxation from convex curvature".* Ph.D. Thesis Princeton Univ., NJ.

[9] Li, F. C., Kawaguchi, Y., Yu, B., Wei, J. J., and Hishida K. 2008. Experimental study of drag reduction mechanism for a dilute surfactant solution flow. *International Journal of Heat and Mass Transfer,* 51: 835-843.

[10] Paschkewitz, J. S., Dubief, Y. V. E. S., Dimitropoulos, C. D., Shaqfeh, E. S. G., and Moin, P. 2004. Numerical Simulation of turbulent drag reduction using rigid fibers. *Journal of Fluid Mechanics,* 518: 281-317.

[11] Subbarao, Ch. V., Divya, P., Appala Naidum, D., and King, P. 2013. Drag reduction by anionic surfactant solutions in gravity driven flow systems. *Iranian Journal of Chemistry and Chemical Engineering,* 32, (In press).

[12] Subbarao, Ch. V., Mallikarjuna Rao, K., King, P., Bhaskara Sarma, C., and Prasad, V. S. R. K. 2010. Drag reduction by polymer additions in once through systems. *International journal of Fluid mechanics Research,* 37: 391-405.

[13] Subbarao, Ch. V. 2011. Efflux time comparison between cylindrical and conical tanks through an exit pipe. *International Journal of Applied Science and Engineering,* 9: 33-41.

[14] Reddy, G. V. S. K. and Subbarao, Ch. V. 2011. Comparison of efflux times between cylindrical and spherical tanks through an exit pipe. *International Journal of Applied Science and Engineering,* 3: 61-68.

[15] Subbarao, Ch. V., Gopal Singh, P.V., Kishore, S., Bhaskara Sarma, C., and Prasad, V. S. R. K. 2011. Efflux time comparison for tanks of different geometries. *International Journal of Fluid Mechanics Research,* 38: 26-37.

[16] Kumar, G. S., Subbarao, Ch. V., and King, P. 2011. Efflux time for two exit pipe system. *International Journal of Applied Science and Engineering,* 9: 277-286.

[17] Reischman, M. M. and Tiederman, W. G. 1975. Laser doppler anemometer measurement in drag-reducing channel flows. *Journal of Fluid Mechanics,* 70: 369-392.

[18] Viachogiannis, M. and Hanratty, T. J. 2003. Influence of wavy structure and large scale polymer structures on drag reduction. *Experiments in Fluids,* 36: 685-700.

[19] Bonn, D., Amarouchene, Y., Wagner, C., Douady, S., and Cadot, O. 2005. Turbulent drag reduction by polymers. *Journal of Physics: Condensed Matter,* 17: S1195-1202.

[20] Den Toonder, J. M. J., Draad, A. A., Kuiken, G. D. C., and Nieuwstadt, F. T. M. 1995. Degradation effects of dilute polymer solutions on drag reduction. *Applied Scientific Research,* 55: 63-82.

[21] Subash, N. S, Kamel, A., and Zhou, Y. 2006. Drag reduction characteristics in straight and coiled tubing. *Journal of Petroleum Science and Engineering,* 53: 179-188.

[22] McCabe, W. L., Smith, J. C., and Harriot, P. 2001. *"Unit operations of chemical engineering".* 7th editions, Mc.Graw Hill Publications, USA.