TECHNO–ECONOMIC EVALUATION OF CARROUSEL SYSTEM FOR DAIRY WASTEWATER TREATMENT

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Abstract

The carrousel system is a promising modification of well-known Pasveer oxidation ditch for treating larger wastewater flow to attain high quality effluent along with significant savings in land. However, its efficiency depends solely on proper design of its aeration system. Suitable mechanical designs of impeller, rotational speed and impeller submergence have significant bearing on the mass transfer efficiency for synthesizing an optimal aeration system. The paper deals with a study on performance of twelve different configurations of impeller design through a laboratory scale model of the carrousel ditch system for treating dairy wastewaters. Impeller speed ranges from 30 -200 rpm, with immersion depth between 10- 30 mm have been investigated to study their effect on mass transfer efficiency of the system. Rational scale up criteria have been adopted to transfer laboratory results to prototype design for evaluating techno-economic justification of carrousel ditch as compared to oxidation ditch and conventional activated sludge system.

Keywords: *Carrousel, Techno, Economic, dairy, Treatment*

Introduction

Dwars, Heedrik, and Verhey NV (DHV) patented the carrousel system in Holland, 1968. Basically carrousel ditches are deep oxidation to economize in land requirements. It has been found that carrousel system can be designed to require only two-third of the land required for the oxidation ditches. Reduction in land requirement in carrousel system is brought about by providing deeper ditches (2.5to5m), as compared to 1-1.5 m in oxidation ditches. Aeration is concentrated at one point only in carrousel as compared to distributed over the length of the oxidation ditch. This enhances oxygen transfer, which makes up the dissolved oxygen deficit from saturation.

Vertical shaft aerators provided in the carrousel system impart a spiral flow mixing pattern. This transfers angular momentum to the liquid, which is deflected into the channel by the dividing wall and provides turbulent flows over the entire cross section of the channel. The velocity of the mixed liquor in the channel is usually 0.2 – 0.5 m/s, depending on the submergence and rotational velocity of the aerators. Thus, all the solids are kept in suspension.

Earlier pilot plant studies on Carrousel systems have revealed that the liquid depth in the aeration zone should be at least equal to the aerator diameter (zeeper, 1970 and Arceivala, 1981). However, some carrousel systems have been designed with aeration zones deeper than the reactor channel (Zeeper, 1970). The carrousel plant at ASHVALE has an effective depth varying from 2.4 m to 3.4 m in aeration zone (Mandt, 1982). The minimum level of dissolved

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oxygen (DO) actually required in the extended aeration system is of the order of 0.5 to 2 mg/l (exact value depending upon the need of nitrification) (Arceivala, 1981).

Ditch geometry, aerator design and mode of aeration are key considerations for providing efficient oxygen mass transfer rates and mixing of aeration basins (Mandt et.al., 1982). Only a portion of power required for aeration is generally used to generate channel flow. With all the aerators at one end of the reactor basin only, very high power intensity normally occurs in aeration zone, which is mostly used in improving the oxygen transfer efficiency. Only a prudent aeration system for continuous loop carrousel reactor shall make it capable of providing a high quality effluent with minimum energy needs. Therefore, there is always a need to provide better aerator designs and aerator modes, which could make the system feasible alternative for treating larger wastewater flow economically. This is the intent of the present work.

The paper deals with the study on aeration performance of twelve different impeller configurations in a carrousel system. Significant design considerations taken into account include rotational speed and impeller submergence, which have significant bearing on mass transfer efficiency. Best impeller selected among the 12 is used for scale up process for treating dairy wastewater through carrousel ditch (CD) and compared for its cost effectiveness with other alternatives viz. activated sludge process (ASP) and oxidation ditch (OD).

Experimental Model

Figures 1 show the details of the laboratory experimental model of carrousel system. The power supply from AC mains was taken through a stabilizer and AC-DC converter to operate the motor on 220 V and 4A. The power was measured by a wattmeter. The AC-DC 746 watt motor was coupled to the impeller shaft through a V belt and pulley arrangement. Depth of water maintained was equal to the diameter of the impeller. Width to water depth ratio of 1.5 has been used. Experimental work done is brought out in two phases.

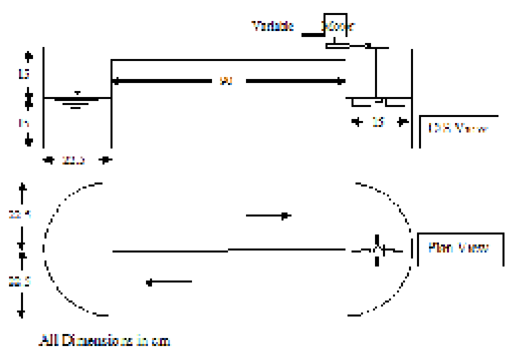

Fig. 1 Experimental Laboratory Model of Carrousel Ditch

Scheme of Experimentation

Phase I of the study was carried out to identify the best configuration which could affect maximum mass transfer. The experimentation involved twelve impellers, which were fabricated based upon configurations given by Nagata (Nagata, 1975). These impellers were operated with different speeds of rotation at varying depths of immersion.

To begin with the run, tap water was filled to a required height and DO brought to zero by addition of Sodium Sulphite and Cobalt Chloride. DO measurements were done with a DO digital meter employing a DO probe. The measurements were calibrated with standard

Winkler's method (Standard Methods, 1989). For each impeller varying values of rotational speed and immersion depths were fixed to evaluate oxygen transfer rate.

As is was not possible to run the studies under temperature control at 20ºC, oxygen transfer coefficient $(k_La)_{20}$ was computed on the basis of equations (Arceivala. 1981, Eckenfelder, 1970 and ASCE Manual, 1988) as below :

$$\frac{dc}{dt} = (k_L a)_T (c_s - c_t) \quad \text{and} \quad (k_L a)_{20} = (k_L a)_T / \theta^{T-20}$$

The measurement of power consumed (P) has been done with a recalibrated wattmeter, which provides for instantaneous power readings and cumulative power utilization. Oxygenation capacity (G) defined as the rate of oxygen transfer during aeration, at the time when the water is completely deoxygenated and at a specified temperature, either 10ºC or 20 ºC, can be obtained from the transfer coefficient (K_La) using the relationship (Arceivala, 1981 and ASCE Manual, 1988).

$$G = \frac{dc}{dt} = (K_L a)_{20} (c_s - c_t) V$$

and, oxygen transfer efficiency (OTE) shall be

$$\text{OTE} = (K_L a)_{20} (c_s - c_t) V / P$$

Where c_s = 9.28 mg/l at 20 ºC

Aeration Results:

Best impeller among the 12 impellers has been identified on the basis of two approaches: P/V (Tatterson, 1993), and Ognean's criteria (Ognean, 1993). The intent was to compare the approaches as well as identifying best impeller design.

P/V criteria**:** From the observations, $(K_La)_{20}$ and oxygen transfer efficiency values were calculated with different depths of immersion and speeds of rotation employed. From the data it was clear that lowest and highest ranges of mass transfer coefficient values were available for impeller 2 and 7 respectively. However, in general, the mass transfer coefficient increased with increase in submergence and speed of rotation. Also, oxygen transfer trend is of increasing nature with increasing values of speeds of rotation. There is mixed trend in case of changing immersion depths. Maximum OTE values were observed at 30 mm immersion for all the 12 impellers considered. It will appear that it is possible to identify useful configuration of impellers up to a rotational speed of 150 rpm only. At 200 rpm the values are less likely to prove useful, since it was found that over splashing takes place at this high speed. Table 1 shows the G, OTE and specific power values for al the 12 impellers employed in the study at 30 mm immersion. From the data, the maximum OTE values 2.921, 3.151 kg 0_2/kWh correspond to impeller configurations 3, 7 and 12 respectively attained at 150 rpm speed and 30mm depth of immersion.

Figure 3 shows the variation of oxygen transfer efficiency with specific power for all the 12 impellers. A clear inference can be drawn that at specific power values greater than 37 W/m^3, 3, 7 and 12 impellers gave higher OTE. Further from the figure, it can be concluded that impeller 12 at a speed of 150 rpm provides maximum oxygen transfer efficiency with lower specific power.

Oxygantion Capacity (OC) (kg O2/hr)													
Immersion(mm)	Impeller speed (RPM)	OC 1	OC 2	OC 3	OC 4	OC 5	OC 6	OC 7	OC 8	OC 9	OC 10	OC 11	OC 12
30	30	0.58	0.22	1.27	1.14	0.46	1.24	0.91	0.46	0.61	1.27	0.79	0.65
30	60	1.19	0.51	2.98	1.67	1.61	2.52	1.77	0.88	1.52	2.44	1.26	1.11
30	100	3.22	2.03	5.78	3.04	3.58	6.54	7.21	3.28	2.28	3.49	2.22	3.06
30	150	7.15	4.56	9.35	7.72	7.58	11.32	17.12	10.48	5.78	8.95	3.82	11.34
30	200	11.36	6.91	25.57	10.18	12.96	16.81	27.92	18.51	13.16	17.26	9.41	20.05
Oxygen Transfer Efficiency (OTE) (kg O_2/kwhr)													
Immersion(mm)	Impeller speed (RPM)	OTE 1	OTE 2	OTE 3	OTE 4	OTE 5	OTE 6	OTE 7	OTE 8	OTE 9	OTE 10	OTE 11	OTE 12
30	30	0.966	0.275	1.271	0.951	0.575	1.551	0.758	0.766	0.762	1.058	0.791	1.083
30	60	1.487	0.318	1.655	1.044	0.805	1.681	0.983	1.101	1.266	1.355	0.969	1.387
30	100	2.012	0.634	2.223	1.266	0.994	1.981	2.253	1.366	1.425	1.586	1.233	2.354
30	150	2.751	1.266	2.921	2.271	1.895	2.695	3.057	1.637	2.408	2.034	1.591	3.151
30	200	2.841	1.571	3.044	2.702	2.161	3.001	3.279	2.313	2.991	2.784	2.352	3.342
Specific Power (P/V) (W/m³)													
Immersion(mm)	Impeller speed (RPM)	(P/V) 1	(P/V) 2	(P/V) 3	(P/V) 4	(P/V) 5	(P/V) 6	(P/V) 7	(P/V) 8	(P/V) 9	(P/V) 10	(P/V) 11	(P/V) 12
30	30	6.126	8.163	10.196	12.232	8.163	5.185	12.250	6.127	8.168	12.248	10.191	6.124
30	60	8.166	16.365	18.373	16.322	20.408	15.297	18.373	8.155	12.251	18.374	13.268	8.1662
30	100	16.330	32.672	26.531	24.502	36.751	33.687	32.654	24.501	16.326	22.454	18.372	13.264
30	150	26.520	36.754	32.662	34.687	40.816	42.860	54.145	65.326	24.493	44.899	27.500	36.723
30	200	40.801	44.882	85.715	38.444	61.196	57.157	77.549	81.659	44.896	63.262	40.825	61.218

Table 1. OC, OTE and Specific Power or all the Twelve Impe::ers

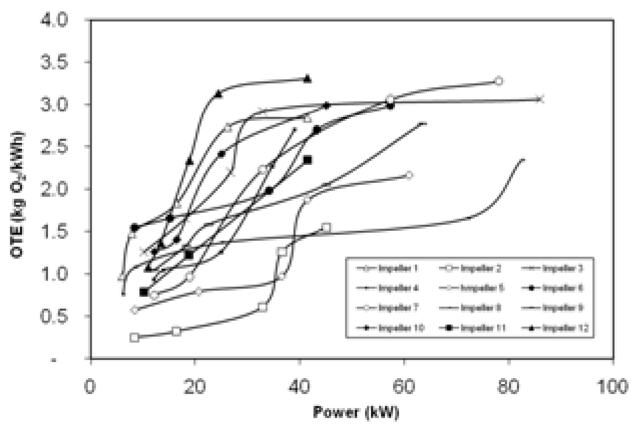

Figure 3. Effect of Specific Power on Oxygen Transfer Efficiecncy for all the 12 Impellers

***Ognean's approach*:** According to this approach, aerators having same diameters and the same rotational speed, but different geometrical shape, can be compared on the basis of To (efficiency number) and Fr* (Froude number) value. To and Fr* are given by

$$\text{To} = (G_s / P_s)(1/P^{1/2})(d^3 n^{3/2})(g^{5/6} p^{3/2} v^{1/3} \Delta^{-1}) \qquad \text{Fr*} \;\; n3/2P^{1/2}/(g^{3/2} p^{1/2} d)$$

Figure 4 present the variation between To and Fr*. An increase in the To number can generally be noticed as Fr* increases. Although for the tested aerators, a simple relationship between To and Fr* cannot be established. The profile of the curve tends to flatten in the location To > $5x10^{-5}$. Other workers have obtained similar results, but the flattening of curve was observed in the location To > $4x10^{-3}$. The difference can be attributed to the fact that the analyzed range (Fr = 0.004 - 0.17) was smaller than the analyzed range of other workers (Ognean, 1993) (Fr = 0.08 - 1.5), and also that the values of all the parameters are stated at 20ºC in the present work, as against 10ºC in the literature. Impellers 12 showed the maximum values of To (9.98 x 10^{-5}) and further this impeller is said to have maximum power consumption. So impeller 12 is said to be the best one among the 12 impellers.

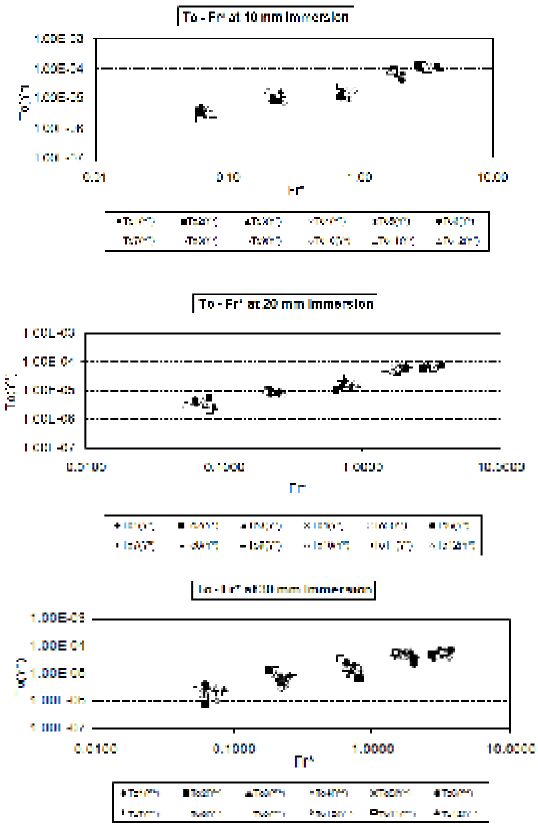

Fig 1. Variation Between Efficiency Number (To) and Froude Number (Fr') for Various Immersion Values (log log scale).

Both approaches provide similar results. However, P/V approach has been utilized for techno-economic study.

Treatment Efficiency

In the Phase II studies on the treatment of synthetic dairy wastewater on the laboratory model were done and then a comparative study with existing carrousel system, an activated sludge process and oxidation ditch was carried out. The results obtained from the experimentation are shown in Table 2.

Table 2. Treatability results from Laboratory Model

S. No.	Parameter	Value
1	BOD Removal Efficiency	96 %
2	Hydraulic Retention Rate	0.475 day
3	Mean Cell Residence Time	19.2 days
4	F/M Ratio	0.132 kg BOD/kg MLVSS/d
5	Sludge Loading Rate	0.08 kg BOD/kg MLVSS/d
6	Volumetric Loading	0.34 kg/m^3/d
7	Sludge Yield	0.51 kg/kg BOD
8	Sludge Volume Index	70

Scale Up

Many scale-up criteria are adopted in mixing applications, including equal impeller tip speed, equal torque volume, equal power per unit volume, and equal solids suspension (Tatterson, 1993). Therefore following criteria has been adopter for scale-up of carrousel system laboratory data for prototype design.

$$P = \rho n^3 \ d^5 \qquad P/V = \rho n^3 d^2 \qquad \frac{(P/V)_m}{(P/V)_p} \equiv \frac{(\rho n^3 d^2)_m}{(\rho n^3 d^2)_p} \equiv 1$$

***Cost formulations*:** Major decisive variables in the selection of a treatment system for wastewater from the alternatives may include (Arceivala, 1981).

a) Land cost and its availability;

b) Desired effluent quality; and

c) Capital and OMR cost for the treatment system.

Plant costs are stated as capital cost and annual costs which are made of various components as sated below.

***(a) Capital costs* :** Include all the initial costs incurred such as civil costs, land purchase, and equipment costs, Civil costs include cost of steel, concrete, earth work for excavation, and shuttering. In the present case structural design of aeration tanks, sedimentation tanks and aerobic digester have been done as per IS 3370-1967 (P35) and IS 3370 – 1975 (II) code. Costing has been done at 2001 rates as shown in Table 3. Equipment cost includes Cost of aerators and Cost of return sludge pumps. Power cost for both aerators and return sludge pumps.

Table 3. Cost adopted for design (India Values)

S. No.	Description	Magnitude
1	Unit Cost of Land	4000/-
2	Concrete (1:1.5:3)	3641/- (per Cum)
3	Earth Work	61/- (per Cum)
4	Cost of Lining	15.7/- (per sqm)
5	Cost of Shuttering	120/- (per m)
6	Power Cost	1.5/- (per kWh)

Manufacturing costs collected form the fabricators (EMICP-K. C.P. Pvt Ltd) have been analyzed and a best – fit regression curve fitted as shown in figure5.

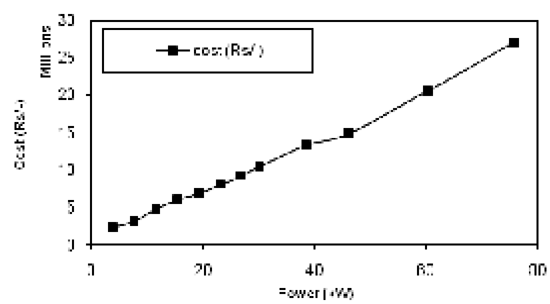

Figure 5.Cost of Aerators with Power (data collected from EMICO K C P India)

***(b) Annual costs* :** These include costs incurred after construction of the plant Interest charges on capital borrowings (loans), Amortization of loans, Depreciation of plant, Insurance of plant, Operation and maintenance of plant (including minor repairs) as follows :

i) Amortization: Fund raising has been considered on full amortized basis as per normal international standards with interest rates of 7.5% (World Bank) with repayment period of 20 years.

Annual repayment of annuity (A1) has been considered as (Arceivala, 1981).

$$A1 = \frac{Pi(1+i)^n}{(1+i)^n - 1}$$

Where

P = Principle amount , i = annual interest rates & n = design period

ii) Depreciation can be calculated by different methods of which, sinking fund method is generally considered suitable for public works. Typical values of depreciation rates have been taken as per Table 4.

Table 4. Estimated Life and Depreciation of a Plant

S. No.	Item	Estimated Life (Years)	Annual Depreciation as Percent of Capital Cost
1	Waste Treatment Plant (Average Applied to the Whole Plant)	20	5
2	Lift Station(machinery	10	10
3	Major Civil Structure	50	2
4	For Preliminary Estimates		
	All Equipment and Piping	10	10
	Masonry Building	33	3
	Frame Building	20-25	4-5

Annual amount (A2) required to set apart to produce a future sum F is given by

$$A2 = \frac{Fi}{(1+i)^n - 1}$$

iii) Operation and maintenance (O and M): includes staff, chemicals, transport rentals and maintenance, which have been considered as a percentage of civil cost and electromechanical costs (equipment costs). Therefore,

OMC = 1.5% of civil costs + 3% electromechanical costs.

Now, Total Annual Cash Flow (TACF) is calculated as:

TACF = Loan Amortization + Depreciation + Power cost.

Systems Evaluated:

Techno- economic efficacy of carrousel system for dairy wastewater treatment has been evaluated in comparison to conventional activated sludge process system (Fig 6.a) and oxidation ditch (Fig 6.b) for the same treatment efficacy and input characteristics. In the present work, a detailed design and estimation of activated sludge process, oxidation ditch and carrousel system for the treatment of dairy wastewater. Prototype design of carrousel system has been done on treatability results of model study on synthetic dairy wastewaters (Table 5) with a design period of 20 years.

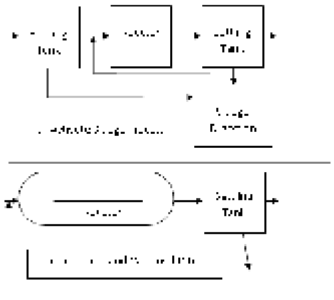

Table 5. Characteristics of Synthetic Dairy Wastewater for Model study on Carrousel Ditch

Characteristics	Typical Values of Combined Effluent from Indian Dairies (Indian Standard,1987)	Synthetic Sample of Study*
pH	8.0-10.1	8.2
Color	White	White
Total Solids (mg/l)	790-1600	1580
Volatile Solids (%)	-	67
Suspended Solids(mg/l)	470-670	690
BOD (mg/l)	806-930	810
COD (mg/l)	1340	1200
BOD/COD	0.6-0.75	0.62
Total Nitrogen (mg/l)	-	84
Phosphate (mg/l)	-	12
Chloride (mg/l)	-	112

*- The synthetic dairy wastewater was prepared out of "every day" spray milk powder of Amul (India)Ltd. Make by dissolving 12 gms of the powder in half a liter water and then diluted to 10 liters.

Results

The results obtained by the design have been plotted figures 7 to 12. It can be seen that carrousel ditches are techno-economically superior to activated sludge system as well as oxidation ditches to treat dairy wastewater. Variations of oxidation ditch (OD) and carrousel ditch (CD) have been expressed as quotient of activated sludge process in Table 6. On average Total capital cost, Power cost, and Total annual cash flow for Carrousel system are 71%, 60% and 74% of activated sludge process and 89%, 83%, 92% of oxidation ditches for the same BOD removal efficiency.

Table 6. Relative Cost of Carrousel, Oxidation Ditch and ASP Systems

Type of Cost	ASP	OD	CD
Land Cost	1	1.33	0.81
Equipment Cost	1	0.80	0.74
Total Capital Cost	1	0.79	0.71
Running Cost (power Cost)	1	0.70	0.58
Operating and Maintenance	1	0.72	0.60
Total Annual Cash Flow	1	0.85	0.74

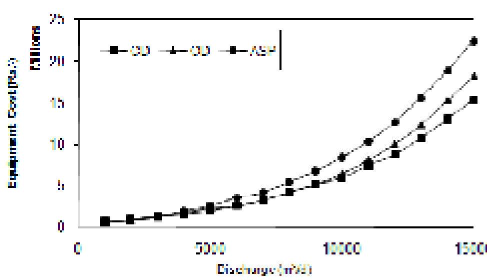

Figure 8. Variation of Equipment (Aerator+Pumps) Cost with Respect to Discharge

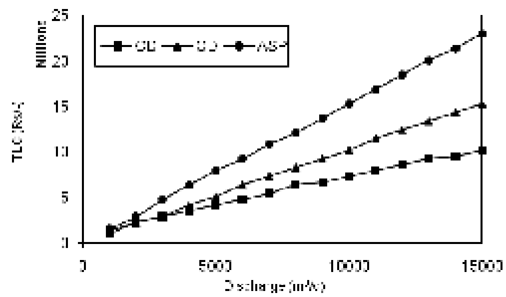

Figure 7. Variation of Land Cost with Respect to Discharge

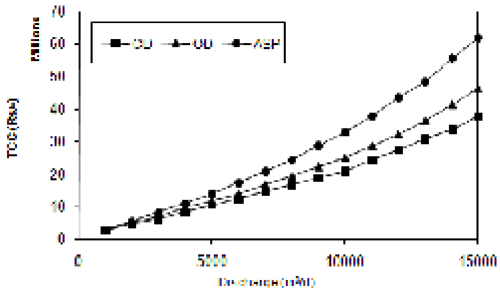

Figure 9. Variation of Total Capital Cost with Respect to Discharge

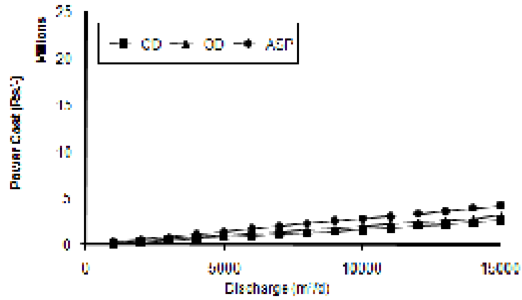

Figure 10. Variation of Power Cost with Respect to Discharge

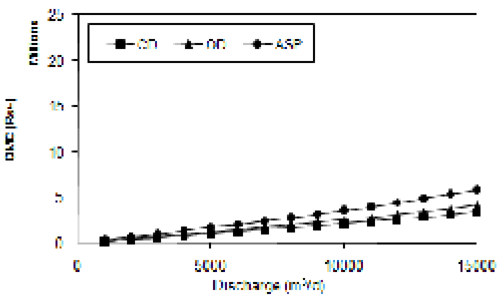

Figure 11. Variation of OMC with Respect to Discharge

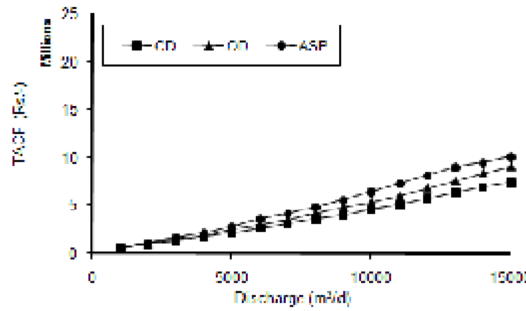

Figure 12. Variation of Total Annual Cash Flow with Respect to Discharge

Conclusions

The paper presents a laboratory treatability study on dairy wastewaters. The performance data on the lab scale has been scaled up for designing prototype system. A techno- economic study has been done to arrive at comparative feasibility of carrousel ditches vis-a-vis Pasveer oxidation ditch and activated sludge process. Carrousel system has been found to be better option than the other two. The results of the study can be extended to similar biodegradable wastewaters also which will go a long way in providing a prudent effluent treatment system for them.

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