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OPTIMIZATION OF THE PERFORMANCE OF HOPPERED PERIPHERAL-FEED CLARIFIERS

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ABSTRACT

The tide of "development" gathering pace in developing countries has resulted in the production of increasing quantities of wastewaters. This inevitably necessitates a reappraisal/reassessment of wastewater technologies. This study demonstrates the role of simple physical modelling approaches in evaluating/appraising the technical performance of hoppered peripheral-feed (spiral-flow) clarifiers – which clarifiers have enormous scope for use in small plants in developing countries. The study focuses on the optimization of local geometrics and hydrodynamics for the purposes of improving overall performance in hoppered spiral flow clarifiers. It is concluded that for a defined set of clarifier global geometry and loading conditions, an optimum race width and inlet nozzle diameter exist. The optimum values of these parameters for a defined conceptual prototype are presented. It is further concluded that the mere variation of either the race width or the inlet nozzle diameter significantly affects the hydraulic detention and solids removal interrelationships in hoppered spiral flow clarifiers. Under the conditions of this study, a 50% reduction in inlet nozzle diameter resulted in an incredible more than 50% loss in hydraulic efficiency. Overall, the possibility of significantly increasing clarifier capacity and/or overall performance by simply optimizing local geometrics and hydrodynamics has been demonstrated via a well tested and friendly methodology.

KEYWORDS

Circular tank; hoppered clarifier; hydraulic efficiency; peripheral feed clarifier.

INTRODUCTION

Some of the challenges that will confront environmental and sanitary engineers in the years ahead will have as much to do with developing new wastewater treatment technologies as with the judicious optimization and rationalization of existing ones. With regard to optimization, it is perhaps true that clarification, being one of the most widely used processes in wastewater treatment, will demand increased attention.

Whether improvement in the level of treatment will be best achieved by increasing clarifier capacity (constructing additional clarifiers) or among other things, by further optimizing the flow and solids fields in existing clarifiers (retrofitting) is a matter that will deserve serious consideration. To date, design and optimization have been based, in most cases, on two simple parameters: surface loading and detention time.

This practice has led to a pre-occupation with global geometry and hydraulics at the expense of optimizing local geometrics and hydrodynamics, which approach is likely to be more cost effective.

Recent attempts at transport modelling of clarifiers (Zhou *et al.*, 1992a,b; Samstang *et al.*, 1992) however, have generated interest in the need for a better understanding of the influences of local geometry and hydraulics on the overall performance of clarifiers. For instance, Bretscher *et al.* (1984) showed that the performance of conventionally designed final clarifiers can be improved by influencing their flow field. Lumley *et al.* (1988) concluded that the hydraulic performance of clarifiers has a great influence on effluent quality. Zhou *et al.* (1992c) studied the role of reaction baffle position in the performance of center-fed clarifiers with radial flow. Krebs *et al.* (1992) studied the effects of porous walls on the hydraulics as well as the flocculation of activated sludge in final clarifiers. In all these efforts, the ideal would be the use of transport models that would simulate clarifier behaviour under arbitrary geometry and variable solids and hydraulic loading rates. Such models however, are still under development and are not widely used for design and analysis. Furthermore, these models require very powerful computers to achieve acceptable simulation time, making them unsuitable for the engineer-analyst in many a developing country.

Fully cognizant of the above and in recognition of the fact that there is a dearth of information and data on hoppered pererally sufficient in small plants. This is more so for oxidation ditch plants where it is necessary to allow for sufficient depth in the clarifier and to handle the high concentrations of sludge carried in the ditch.

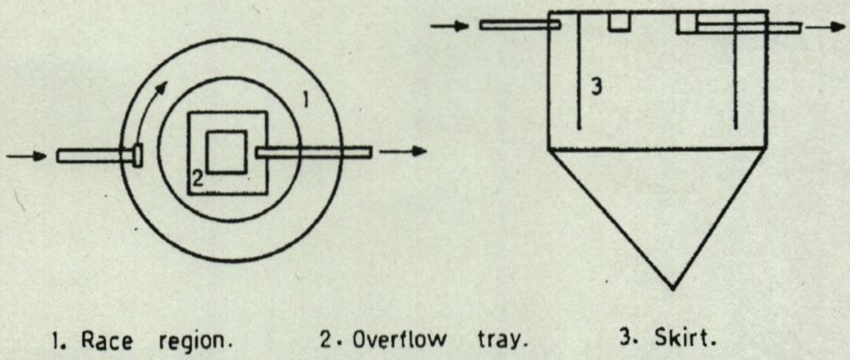


Figure 1. Schematic diagram of the model spiral flow (peripheral flow) clarifier.

METHODOLOGY

In this investigation, physical hydraulic scale models were used (refer to Figure 1). In line with other investigators (Kawamura, 1981), Froude law was used as the governing similarity law thus:

$$F = V^2/Lg$$

where
V is a characteristic velocity of the system;
L is a characteristic linear dimension; and
g is the acceleration due to gravity.

Suspended solids were modelled by using hydrous ferric oxide. This material was chosen because of its flocculent characteristics.

The hydraulic characteristics of the clarifiers were studied by using a tracer based stimulus-response technique. The generated residence-time-distribution curves were then analyzed for various hydraulic parameters in the usual manner. Rhodamine B was used as the dye-tracer and standard flourometry methods were used for its assay. Using this method, the clarifier mean flow through period is defined thus (Moreno, 1990):

$$T_m = \frac{\sum S(t_i)\, t_i\, \Delta t_i}{\sum S(t_i)\, \Delta t_i}$$

where
t = time elapsed since tracer was injected (minutes)
$S(t_i)$ = concentration of tracer in sample (mg/L)

The major criteria for hydraulic performance evaluation included stability of flow; degree of short-circuiting and hydraulic detention efficiency. Based on a scale factor of 1:20, the major model and prototype parameters are presented in Table 1. The major geometric variables in this optimization study were inlet nozzle diameter and race width.

Table 1. Model and prototype geometry

Parameter	Model	Prototype
Diameter	0.50 m	10 m
Straight Wall Depth	0.175 m	3.5 m
Hopper Depth	0.43 m	8.6 m
Surface Area	0.196 m^2	78.5 m^2
Inlet Nozzle Diameters	0.5,0.75,1 cm	10,15,20 cm
Race Widths	2.5,5.0,7.5 cm	50,100,150 cm

RESULTS AND DISCUSSION

General performance

Mean flocculent solids retention characteristics for various nozzle diameters and race widths are presented in Figure 2. In all cases, the influent suspended solids concentration was 1500 mg/L as hydrous ferric oxide. This value was chosen solely for the purpose of expediting the results. The model surface loading corresponded to conceptual prototype values of about 20 to 30 $m^3/m^2.d$.

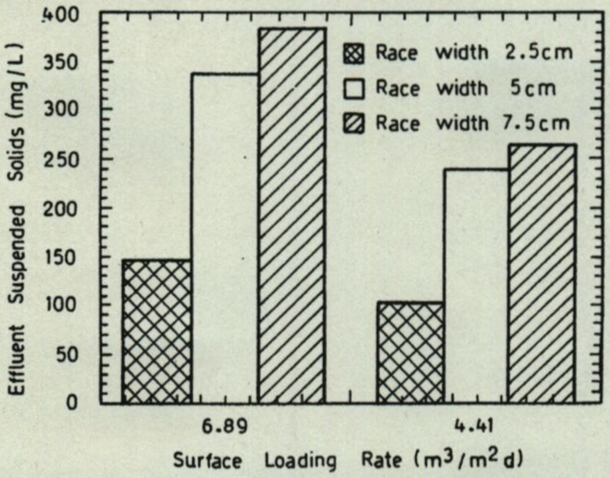
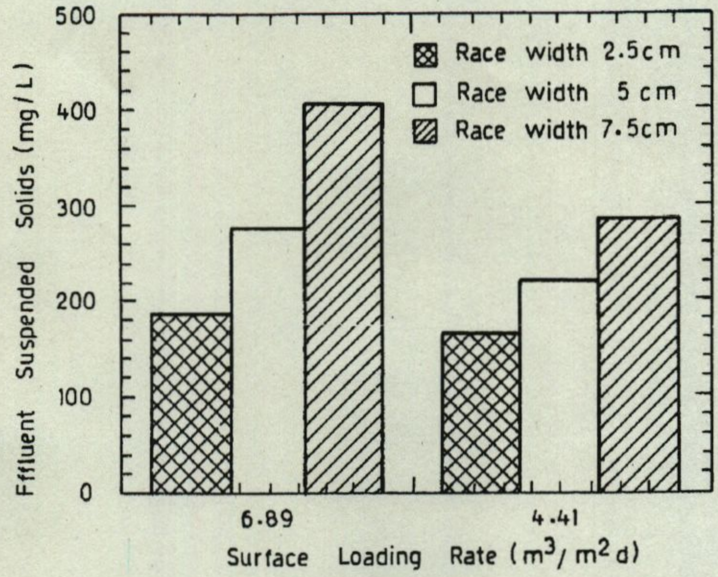
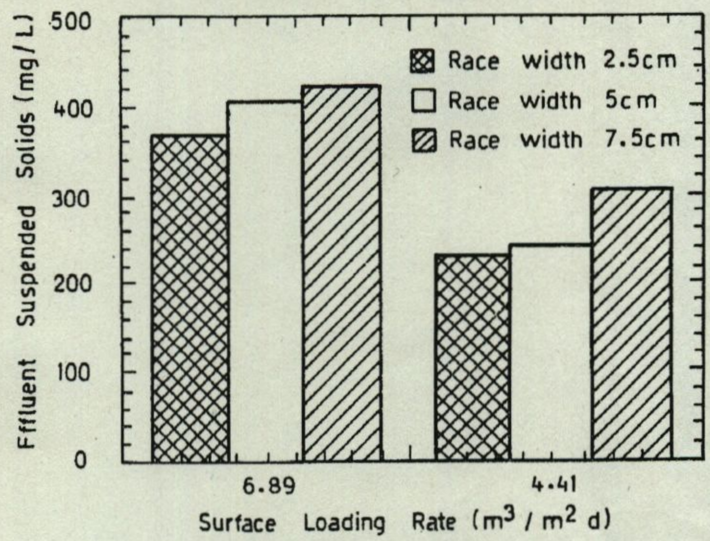


Figure 2. Comparative performance characteristics with respect to solids retention at various inlet nozzle diameters and race widths (continued on following page).



(a) Inlet nozzle diameter 0.5 cm.



(b) Inlet nozzle diameter 0.75 cm.

Figure 2 (continued from previous page). Comparative performance characteristics with respect to solids retention at various inlet nozzle diameters and race widths.

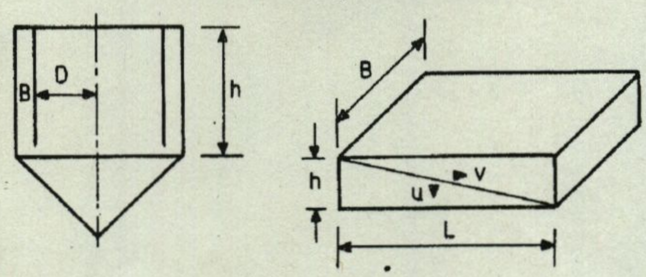


Figure 3. Transformation of spiral flow clarifier with central settling area $A_1 = (\pi D^2)$ into a hypothetical horizontal flow clarifier of width B and length L.

It is evident from the above data therefore, that for a given clarifier diameter, loading conditions and nozzle diameter, progressive increases in race width generally lead to poorer effluent quality. This trend finds explanation in classical sedimentation theory. For the purposes of analysis, consider a transformation of the spiral flow clarifier geometry into a hypothetical horizontal flow clarifier as presented in the Figure 3.

Referring to Figure 3 then, it is clear that for the case of a particle settling at the critical velocity u_o in the settling zone ($A_1 = \pi D^2$) of the spiral flow clarifier - and in the light of the above simplified hypothetical transformation - the following relationships hold:

$$u_o = Q/A1$$

Realizing that the particle takes the same time to cover the length L and depth h of the hypothetical tank, we have:

$$u_o = vh/L$$

Assuming plug flow conditions in the hypothetical tank, further algebraic manipulation yields:

$$u_o = Qh_o/Bh_oL = Q/BL$$

i.e. within reason, A_1 is equivalent to BL in a hypothetical horizontal flow tank.

Based on this hypothesis and the clarifier geometry under investigation in this study, the geometric variables of importance are summarized in Table 2.

Table 2. Clarifier geometric variables (actual and hypothetical)

Race width B(m)	D* (m)	L* (m)	1** $2\pi(D+B/2)$	L/1(β)	L/B(α)	$A_1(BL = \pi D^2)$ (m^2)
0.025	0.225	6.362	1.488	4.276	254.480	0.159
0.050	0.200	2.513	1.414	1.777	50.26	0.126
0.075	0.175	1.283	1.335	0.961	17.107	0.096

* as defined in Figure 3. ** mean circumference of race area.

α - Length:Width ratio of hypothetical horizontal flow tank

β - Ratio of hypothetical horizontal flow tank length to mean circumference of race area.

It therefore follows from Table 2 that with progressive reductions in race width, not only is the effective settling zone area increased but the L/B ratio(α) is also increased. As noted elsewhere (Shield *et al.*, 1991), the larger the L/B ratio, the greater the reduction in basin short-circuiting and dispersion. In other words, overall treatment efficiency is improved.

It stands to reason therefore, that for given loading conditions and clarifier and inlet nozzle diameters; an optimum race width exists which is such that clarifier short-circuiting and dispersion are reduced. This leads to improved solids removal as demonstrated by the model experimental data presented in Figure 2. For the clarifier geometry under investigation, it would appear that a race width of 2.5 cm is optimum. This corresponds to a race width of 50 cm in the conceptual prototype. The benefits that accrue to rational design and optimization in this regard are obvious. For instance, for a given clarifier diameter, it appears quite possible to operate at higher surface loading rates (and attain comparable effluent quality) by simply optimizing the race width.

A further trend that emerges from the data presented in Figure 2 is the one pertaining to the inlet nozzle diameter. In general it would appear that for a given clarifier diameter and race width, under given loading conditions; an optimum inlet nozzle diameter exists. It appears that the magnitude of this optimum nozzle diameter is determined by a complex interaction of inlet zone conditions and clarifier internal geometry. It is hypothesized that inlet velocity (inlet diameter) affects performance via the resulting surface drift velocities and secondary currents.

In this investigation, for a model race width of 2.5 cm, the optimum nozzle diameter is 1.0 cm. This corresponds to an inlet nozzle diameter of 20 cm in the conceptual prototype. It appears that the nature and manner in which the inlet nozzle diameter influences the resident flow field will depend to some measure on the choice of race width.

General residence-time-distributions

The results of the residence-time distribution analyses are presented in Figures 4 and 5. It is evident from Figure 4 that for a given clarifier diameter, nozzle diameter and loading conditions; varying the race width does affect the flow-through curve. In this investigation, it appears that for race widths of 2.5 and 5.0 cm, the respective flow-through curves almost coincide. The flow-through curve for the largest race width investigated (7.5 cm) does however, suggest a loss of hydraulic detention efficiency coupled with notably more short-circuiting.

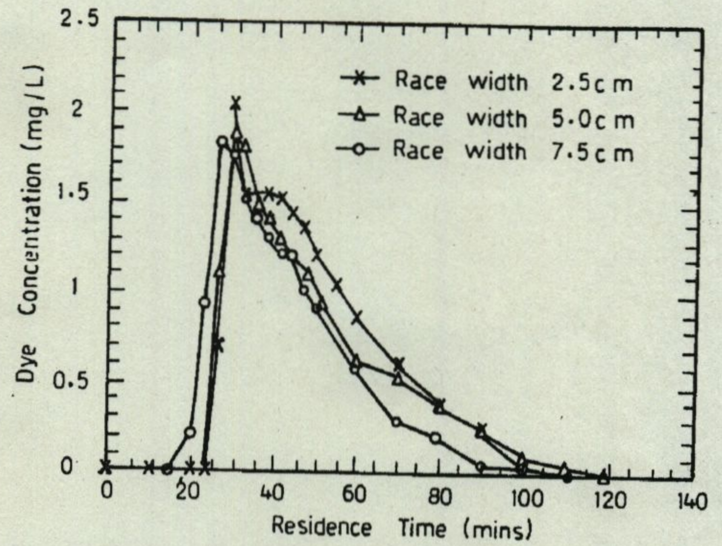


Figure 4. Residence-time-distribution curves for variable race widths.

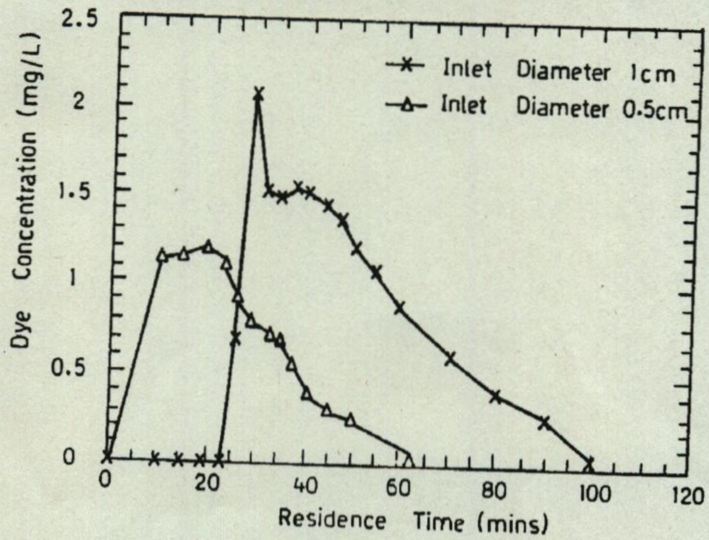


Figure 5. Residence-time-distribution curves for variable inlet nozzle diameters.

Trend of turbulent mixing/relative quiescence

One of the factors that affects solids removal is the trend of turbulent mixing or relative quiescence in clarifiers (2). Quantitatively, this is expressed by the coefficient of clarifier performance, n, which has a lower limit of zero and an upper limit of 1. A relatively higher value implies relatively more turbulent mixing (less quiescence). From a mathematical analysis of mixing in clarifiers (Fair *et al.*, 1968), n may be approximated by:

$$n = (T_m - T_{mo})/T_m$$

where
T_m = mean flow-through period (as determined from flow-through curves)
T_{mo} = modal flow-through period (as determined from flow-through curves)

The calculated values of n for variable clarifier geometries are given in Table 3.

Table 3. Variation of coefficient of clarifier performance (n) with clarifier race width for a fixed inlet nozzle diameter

Surface Loading ($m^3/m^2.d$)	Race Width (cm)	Inlet Nozzle Diameter (cm)	HE %
6.89	2.5	1.0	0.40
6.89	5.0	1.0	0.42
6.89	7.5	1.0	0.60
4.41	2.5	1.0	0.27
4.41	5.0	1.0	0.44
4.41	7.5	1.0	0.48

It is evident from the data in Table 3 that progressive increases in clarifier race width lead to relatively higher values of the coefficient of clarifier performance (n). On the other hand, it was discovered that a relatively smaller inlet nozzle diameter corresponded to a relatively larger value of n. For instance, at an overflow rate of 6.89 m^3/m^2.d, n was 0.56 for an inlet nozzle diameter of 0.5 cm and 0.40 for an inlet nozzle diameter of 1.0 cm. This implies a trend towards more turbulent mixing with consequent deterioration in clarifier performance as the race width is increased or as the inlet diameter is decreased. It is conceivable therefore that the optimization of both the race width and the inlet nozzle diameter are crucial in the performance of spiral flow clarifiers. This is confirmed by the solids retention data presented in Figure 2.

Trend of hydraulic detention efficiency

Apart from the trend of turbulent mixing, another factor that affects solids removal in clarifiers is the hydraulic efficiency (HE) of the clarifier. This is defined as the ratio of the actual detention time, T_m, to the theoretical detention time, T, as obtained from flow-through curves. This may be expressed symbolically thus:

$$HE = T_m/T = \frac{\sum S(t_i)\, t_i\, \Delta t_i}{\sum S(t_i)\, \Delta t_i}$$

where
t = time elapsed since dye/tracer was injected (minutes)
$S(t_i)$ = concentration of dye/tracer in sample (mg/l)

The calculated values of HE for variable clarifier geometries are presented in Table 4.

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Table 4. Variation of hydraulic efficiency (HE) with clarifier race width for a fixed inlet nozzle diameter

Surface loading ($m^3/m^2.d$)	Race Width (cm)	Inlet Nozzle Diameter (cm)	HE %
6.89	2.5	1.0	85
6.89	5.0	1.0	77
6.89	7.5	1.0	66
4.41	2.5	1.0	72
4.41	5.0	1.0	67
4.41	7.5	1.0	59

The results presented in Table 4 clearly demonstrate the dependence of hydraulic efficiency on clarifier internal geometry. In summary then, progressive increases in race width generally lead to a loss of hydraulic efficiency. On the other hand, increases in inlet nozzle diameter lead to a gain in hydraulic efficiency. It is hypothesized that this arises directly out of the influences of these geometrical variations on the flow/velocity fields, dispersion and short-circuiting as discussed earlier.

Overall then, this simple modelling approach has demonstrated that for the hoppered spiral flow clarifier geometry under investigation, increases in capacity and hydraulic efficiency can be had by instituting simple remedial measures such as changing the inlet nozzle diameter and/or race width. At a time when ever more stringent effluent quality requirements are being imposed and land area is becoming more and more scarce, the benefits that would accrue from a better understanding of local clarifier geometry and hydrodynamics cannot be overemphasized.

CONCLUSIONS

It is concluded that for a given hoppered spiral flow clarifier diameter, loading conditions and inlet nozzle diameter, progressive increases in race width generally lead to poorer effluent quality. This suggests the existence of an optimum race width. In this investigation the optimum was 2.5 cm in the model or 50 cm in the conceptual prototype.

Further, for a given clarifier diameter, loading conditions and race width, an optimum nozzle diameter exists; the magnitude of which is interactively linked with internal geometry and loading conditions. In this investigation, the optimum nozzle diameter for a model race width of 2.5 cm was 1.0 cm or 20 cm in the conceptual prototype.

It is concluded that the mere variation of either the race width or the inlet nozzle diameter significantly affects the hydraulic detention efficiency characteristics as well as the trend of turbulent mixing of spiral-flow clarifiers. In this study for instance, a 50% reduction in inlet nozzle diameter, resulted in an incredible more than 50% loss in hydraulic efficiency.

Finally, the possibility of increasing clarifier capacity and/or overall performance by simply optimizing local geometrics and hydrodynamics has been demonstrated and supporting hypotheses have been developed.

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