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PROCESS KINETICS OF SEPTIC TANKS

A 3-compartment septic tank located at the Federal University of Technology, Owerri, Nigeria, was examined for biochemical oxygen demand (BOD) removal efficiencies under various flow rates. The tank had a volume of 17.71 m^3 and was partitioned in proportions of 2:1:1 and had a depth of 1.72 m. The removal efficiencies of septic tanks in Sri-Lanka, Brazil, Zambia, the United States of America and Canada were evaluated from comprehensive septic tanks influent and effluent literature data. An equation for determining BOD removal efficiency was derived from process kinetics in septic tank. The rate constants for septic tank in different locations were evaluated from the equation. The BOD removal efficiency at other flow conditions outside those used in estimating rate constant was calculated from the process kinetic equation and compared with measured values.

Results showed that septic tank design can be based on the characteristics of the suspended solids and liquid medium, flow rate and the terminal velocity of the solid particles if known. Monitoring of septic tank performance can be done using the kinetic equation. The percentage of BOD removal measured for the experimental septic tank at Owerri at retention time of 2 days was 87% and the value calculated from the derived kinetic model was 83.4%.

NOTATIONS

V_s – terminal velocity (m/s),
d – average diameter of particles (m),
S_s – specific gravity of particles (kg/m^3),
Q – flow rate (m^3/s),
A – surface area of tank (m^2),
t – retention time (d),
BOD_t – BOD (mg/dm^3) removed after time t,
BOD_i – initial BOD (mg/dm^3) of influent,
E – BOD removal efficiency (%),
V – volume of tank (m^3),
k – rate constant (d^{-1}).

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1. BACKGROUND

A septic tank is a watertight chamber for disposal of sewage in an individual household or collection of households located in places that are not connected to a sewerage system. It is seen in temperate countries such as Canada that the use of a mere sedimentation tank according to BABBITT [1] and SHETTY [9] is not efficient because of its lower bioactivity in cold water. In the tropics, septic tanks can be seen as small works for digestion and storage of sewage over a period between cleaning intervals. The processes that occur in a septic tank can be put to advantage in its design and monitoring schemes.

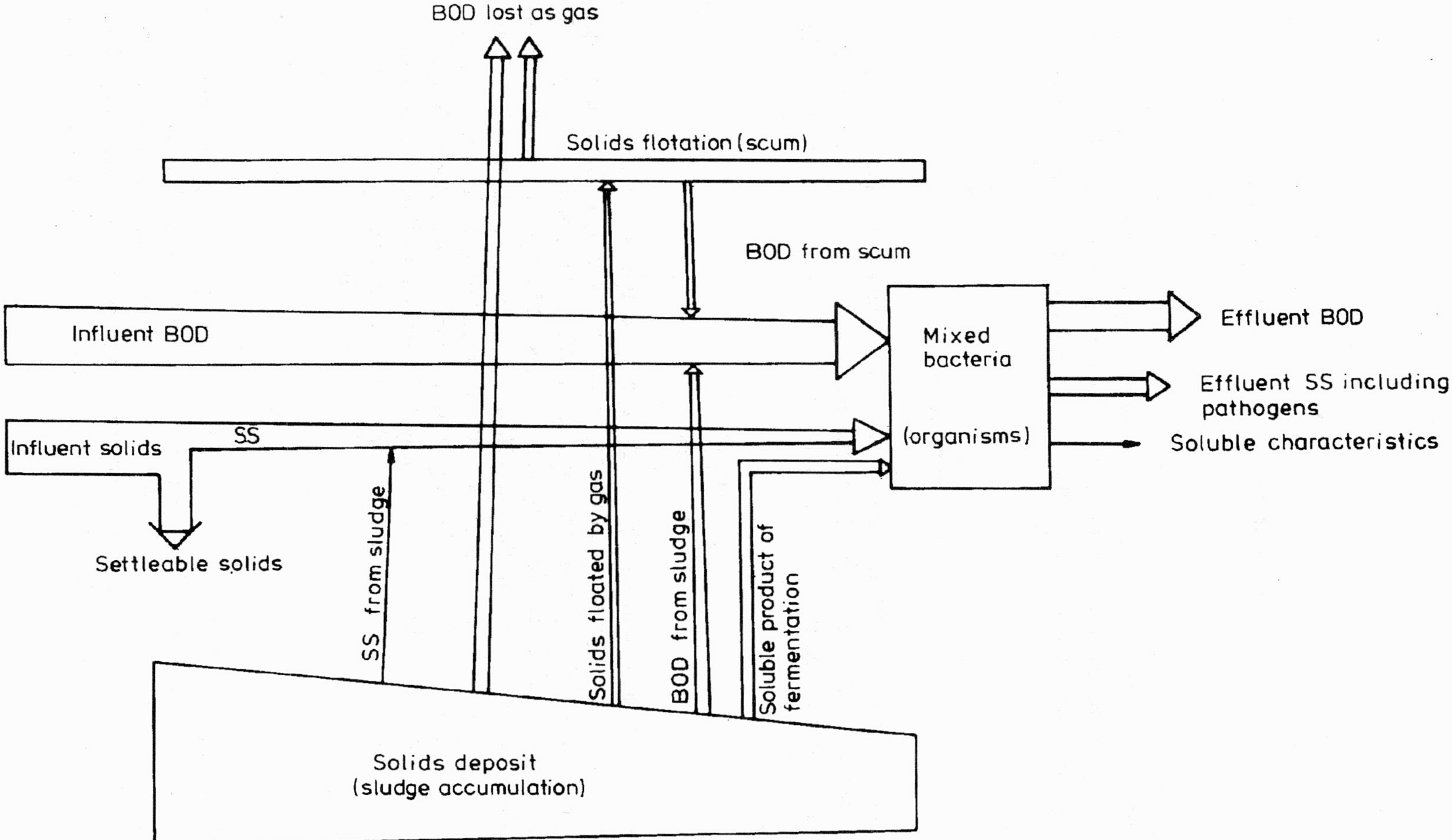
In this paper, the process kinetics of a septic tank that explains its behaviour and removal efficiency of biochemical oxygen demand is the main thrust presented for in depth appreciation of the function and for conceptual application in its design and performance monitoring.

2. PROCESS KINETICS

There are three zones of activity in the septic tank, essentially, the solids sedimentation (sludge) zone, the liquid zone directly above the sludge zone and the solids flotation zone directly above the liquid zone (figure). There are two major pathways involved in the purification of wastewater in septic tanks, namely, the BOD (biochemical oxygen demand) removal pathway and SS (suspended solids) removal pathway. The minor pathway involves removal of the soluble product of fermentation. Each of these pathways occurs in the three zones of activity in the tank. Solids accumulate in the sludge zone by gravity settlement, and removal is by desludging. The putrescible organic materials in the sludge are digested and the BOD is removed through anaerobic digestion. The gases produced cause resuspension and flotation of buoyant materials in the process of escaping. The floated materials appear as a scum layer. In the scum layer, digestion of organics takes place and BOD removal is also apparent and solids could return to the liquid medium as suspended solids or the sludge zone as settled solids. The removal of solids in suspension in the liquid zone is also achieved by the agglomeration of particles collision during hydraulic disturbance. The large particles or flocs arising from the agglomeration process settle by gravity and form part of the sludge. This results in the clarification of the effluent that is discharged. The soluble BOD in the liquid medium and the BOD in the solids in the tank are removed by the two-stage digestion reaction involving the actions of mixed bacteria as given in equations (1) and (2).

Stage 1

$$\underset{\text{(ultimate BOD)}}{\text{organic matter}} + \underset{\text{(acid-formers)}}{\text{bacteria}} \longrightarrow \text{new cells} + \underset{\text{organic acids}}{\overset{}{\text{alcohols}\ \&}} + H_2O \tag{1}$$



Pathways of BOD and SS removal in septic tanks

Stage 2

$$\begin{array}{llllll} \text{alcohols} & + \ \text{bacteria} & \longrightarrow \text{new cells} & + & \text{gases} & + \ H_2O \\ \quad \& & & & & & \\ \text{organic acids} & (\text{methane-formers}) & & & (CH_4, H_2S, CO_2, & \\ & & & & \quad NH_3, H_2) & \end{array} \quad (2)$$

In a normal septic tank, the mixed bacterial actions are almost simultaneous and there is little or no time lag between the reaction of acid-formers and methane-formers. Based on this background, the process kinetics in septic tanks should be seen from two perspectives, notably, the simple sedimentation scenario and the complex biological reaction.

3. SEDIMENTATION

If we assume that the settleable solids in the septic tank are made up of discrete particles, then we apply the theory of sedimentation leading to Stokes law which assumes that the discrete particles fall in the liquid medium with constant terminal velocity V_s

$$V_s = \frac{gd^2\left(S_s - 1\right)}{18\nu} \quad (3)$$

where g is acceleration due to gravity, d is the average diameter of the particles, S_s is the specific gravity of the particle and ν is the kinematic viscosity of the liquid. Equation (3) for terminal velocity V_s is presented by TEBBUTT [10] and it is adapted for septic tank solids' settling velocity in this study. This settling velocity is the velocity at which discrete particles fall in the tank. However, because solids found in septic tanks are nor largely discrete in nature, only those that attain the 'discrete' characteristics during settlement will fall to the bottom of the tank at this velocity. The putrescible organic solids probably will not fall at the same rate as the discrete particles because of the particulate decay and agglomeration processes that go on during sedimentation of solids. So, the velocity of fall will be of the form:

$$\frac{dh}{dt} = \pm mf\left(h\right) \quad (4)$$

where h is the depth of fall at time t, dh/dt is the velocity of fall and m is a coefficient which depends on the nature of the organic solids and temperature. The effect of temperature is reflected on the viscosity of the liquid medium of the tank and according to MARA et al. [4], its effect is minimal and may be ignored. An increase in temperature also increases the rate at which the particles change in size and shape due to decay or agglomeration. The solution of equation (4) is therefore complex. An approximate particle settling velocity can be obtained from equation (3). Thus,

$$\frac{dh}{dt} \approx \frac{gd^2 (S_s - 1)}{18V}, \tag{5}$$

$$h \approx \frac{gd^2 (S_s - 1)t}{18v} \tag{6}$$

where h is the depth of the tank, t is the retention time and the other notations bear their usual meaning.

The particles with settling velocity V_s greater than the surface overflow rate V_o ($V_s > V_o$), or at depth less than $V_s t$ ($h < V_s t$) will be removed in the tank. The surface overflow rate is Q/A. Thus,

$$\frac{gd^2 (S_s - 1)}{18v} > \frac{Q}{A} \tag{7}$$

where Q is the flow rate, A is the surface area of the tank required to remove the particles.

$$h < \frac{gd^2 (S_s - 1)t}{18v}. \tag{8}$$

where t is the retention time and h is the depth of the tank.

Digestion reaction. Digestion (purification) is the fermentation of organic matter (equations (1) and (2)) resulting in BOD removal. This is an important biological reaction in septic tanks requiring the action of the obligate anaerobes, namely, the acid forming bacteria and the methanogenic bacteria under the anaerobic conditions prevalent in septic tanks. This reaction reduces the biochemical oxygen demand (BOD) of wastewater and some level of microbial kill is achieved, too. The performance of septic tanks is assessed based on the degree of removal efficiency realised by these processes. The rate of digestion of organic matter (BOD removal) is proportional to the amount of organic matter (BOD) remaining in the septic tank. This approximates to a first order kinetics which can be represented mathematically as:

$$\frac{dB}{dt} = -K_1 B \tag{9}$$

where dB/dt is the rate of BOD removal, B is the remaining BOD and K_1 is a constant which depends on the temperature of the medium and the species of microbes.

Equation (9) can be rearranged to equation (10)

$$\frac{dB}{B} = -K_1 dt. \tag{10}$$

Integrating and putting the limits B_0 and B_t at the time $t = 0$ and $t = t$, equation (10) simplifies to:

$$B_0 - B_t = B_0\left(1 - 10^{-kt}\right) \tag{11}$$

where B_0 is ultimate BOD, B_t is BOD remaining after time t and k is the rate constant.

Or

$$\frac{\text{BOD}_t}{\text{BOD}_i} = 1 - 10^{-kt} \tag{12}$$

where BOD_t is the BOD removal measured from the difference in the influent and effluent values after retention time, t in days and BOD_i is the influent BOD measured at reference time $t = 0$ relative to time $t = t$; k is the rate constant (d^{-1}). Equation (12) can be expressed in terms of percentage BOD removal efficiency E, flow rate Q and effective volume of tank V.

Thus,

$$E = 100(1 - 10^{-kV/Q}). \tag{13}$$

4. EVALUATION OF k AND EXPERIMENTAL METHOD

In order to determine the rate constant k for septic tanks, sewage samples (influent and effluent wastewater) were collected from a 3-compartment septic tank (of volume of 17.71 m^3 partitioned in proportions of 2:1:1 and of a depth of 1.72 m located at the Federal University of Technology, Owerri, Nigeria, temporary campus at the Lake Nwaebere) on different occasions (daily for 2 months) in 1992. The BOD_5 of the influent and effluent samples were measured directly using the manometric BOD Apparatus HACH Model 2178B. The flow rate at each occasion was determined from a chart marked by septic tank users in which the number of toilet flushings and volume of water per flush are indicated. The retention time $t = V/Q$ (V – volume, Q – flow rate) was evaluated and equation (12) or (13) was used to determine the rate constant k at the prevailing temperature of the tank of 26 °C using influent BOD_i, effluent BOD_e and t average measures.

Example: On the date of May 4th, 1992 the average influent and effluent BOD_5 were measured to be 8000 mg O_2/dm^3 and 550 mg O_2/dm^3, respectively. The flow rate and the effective septic tank volume were 5965 dm^3/d and 17.71 m^3, respectively. We use equation (13) rearranged to:

$$k = -\frac{Q}{V}\log\left(1 - \frac{E}{100}\right).$$

Then

$$k = -\frac{1}{2.95}\log\left(1 - 0.94\right),$$

or

$$k = 0.39$$

for septic tank in Nigeria (typical).

k for other countries, namely, Brazil, Sri-Lanka, the USA and Canada were also calculated based on data of septic tank influent and effluent BOD and their corresponding flow rates and retention times obtained from a comprehensive literature search. Of all the works on septic tanks, those of OKEREKE and COTTON [7], OLIVEIRA [6], CHAMPIKA [2], OTIS et al. [8], HICKEY et al. [5], NOTHINGHAM and LUDWIG [5] and VIRARAGHAVAN [12] had records (data) of influent and effluent characteristics that could be used to calculate BOD removal efficiency and these were therefore used in this study for the respective countries involved. The BOD removal efficiencies were correspondingly calculated for the respective retention times excluding those used in estimation of k. Removal efficiencies determined by the measurement of percentage BOD removal from the relation

$$\frac{\left(\mathrm{BOD}_t\right)100}{\mathrm{BOD}_i}$$

and by calculation from kinetic process equation (13) were tabulated.

5. RESULTS AND DISCUSSION

The inequalities (7) and (8) can be applied to design septic tanks if the characteristics of the solids (specific gravity) and liquid (kinematic viscosity) in the tank as well as the retention time t and flow rate Q are known. The requisite variables of population (number of users), wastewater production per capita per day and peaking factor for septic tank design are used in the estimation of design flow rate Q to be applied in equation (7). The suspended solids (SS) removal efficiency can be obtained from experimental measurement of various suspended solids concentrations in the influent and effluent of the septic tank but not from the conceptual process kinetic equations. The biochemical oxygen demand (BOD) removal efficiency of septic tanks can be calculated from the derived kinetic process equations (12) and (13) for septic tanks whose rate constant k and retention time t or effective volume V and flow rate Q are known.

Typical rate constants k in countries of Nigeria, Sri-Lanka, Brazil, Zambia, the United States of America and Canada presented in table 1 show that k varies from country to country or place to place depending on environmental temperature differences. The process kinetic model should be applied with a k value for the localality and if this is done, equations (12) and (13) can become very useful in septic tank performance monitoring or evaluation in terms of BOD removal efficiency. If a regression equation between suspended solids (SS) and biochemical oxygen demand (BOD) for the septic tank is estimated by simple experimental data and analysis model, the SS corresponding to the calculated BOD value can be deduced and vice versa.

Table 1

Rate constants of septic tank in some locations

Country of location of septic tank	Typical k values (d^{-1})	Nature of study and researcher(s)
Nigeria	0.60	field studies at 26 °C
	0.39	field studies below 26 °C
		field studies OKEREKE [7]
Sri-Lanka	0.16	field studies CHAMPIKA [2]
Brazil	1.07	field studies OLIVEIRA [6]
	0.70	
Zambia	0.77	
	0.10	field studies VINCENT [11]
USA	0.07	laboratory studies at 17 °C
	0.24	field studies OTIS et al. [8]
Canada	0.07	laboratory studies at 15 °C
		VIRARAGHAVAN [12]

Table 2 shows the BOD removal efficiencies obtained by measurement and by calculation. From this table (using $k = 0.39$ for Nigeria), it can be seen that the percentage BOD removal obtained by calculation from the process kinetic equation is 83.4% at a retention time of 2 days and it is in close agreement with the measured value of 87%. The BOD removal efficiencies obtained by measurement and by calculation from the kinetic model for such countries as the USA and Sri-Lanka are also in close agreement. The difference in the USA values is 4% at a retention time of 3–6 days, whereas that of Sri-Lanka is 11% at a retention time of 3 days. For septic tanks, these are acceptable disparity and therefore the process kinetic equation (13): $E = 100(1 - 10^{-kV/Q})$ can be used to determine performance of a septic tank.

This kinetic process equation may be of paramount importance in computer coordinated septic tank performance monitoring schemes of integrated nature.

Table 2

Comparison of BOD removal efficiency obtained by measurement and calculation with kinetic model of septic tank

Country of location of septic tank	Retention time (d)	Percentage BOD removal		References
		By calculation from kinetic model	By experimental measurement	
Nigeria	2.0	97.4	84	OKEREKE
	3.6	83.4	87	COTTON [7]
Sri-Lanka	3.0	67.0	78.0	CHAMPIKA [2]
Brazil	0.45	67.0	67.0	OLIVEIRA [6]
	0.75	84.2	70.0	
Canada	4.6	52.4	52.0	VIRARAGHAVAN [12]
USA	1.5	56.3	56.0	OTIS et al. [8]
	3.6	44.0	40.0	
	4.1	48.3	47.0	HICKEY [3]
	4.5	51.6	52.0	NOTHINGHAM
	11.7	84.8	60	and LUDWIG [5]

6. CONCLUSION

In locations where equipment or chemicals for measuring BOD of wastewater are lacking, but the flow rate and effective volume of the septic tank can be estimated, the calculation of percentage BOD removal (efficiency) can be done based on the kinetically derived equation (13) using an appropriate k value. This equation will be useful in computer aided monitoring of the performance of septic tanks, particularly, an integrated program provided there are compact instruments in place to easily record the flow rate and effective volume of the septic tank. Whereas BOD removal efficiency can be derived and calculated from a kinetic process, experiments are required to determine SS (suspended solids) removal efficiency from the SS concentration in the influent and effluent or from the % SS and % BOD removals' regression relationship.

REFERENCES

[1] BABBITT H.E., *Sewerage and sewage treatment*, 3rd Ed., John Wiley and Sons, 1928, p. 387.

[2] CHAMPIKA K., *The performance of septic tanks*, M.Sc. Thesis, Department of Civil Eng. University of Moratuwa, Sri-Lanka, 1990.

[3] HICKEY J.L.S., DUNCAN D.L., *Performance of single family septic tank systems in Alaska*, J. Water Pollution Control Fed., 1966, 38 (8), pp. 1298–1309.

[4] MARA D.D., SINNATAMBY G.S., *Rational design of septic tanks in warm climates*, The Public Health Engr., 1986, 14 (4) pp. 49–54.

[5] NOTHINGHAM M.C., LUDWIG H.F., *Septic tank performance as related to tank length, width and depth*, Water and Sewage Works, 1948, pp. 460–464.

[6] OLIVEIRA R., *Contribuicao ao Estudo de Tanque Septicos*, M.Sc. Thesis, Federal University of Paraiba, Campina Grande, Brazil, 1982.

[7] OKEREKE C.D., COTTON A., *Performance of Multi-Compartment Septic Tanks in Nigeria*, A Conference Paper presented at Water Africa '94 Exhibition and Conference held in Accra, Ghana, May 2–5, 1994.

[8] OTTIS R.J., HUTZLER N.J., BOYLE W.C., *Onsite household wastewater treatment alternatives. Laboratory and field studies*, Water Research, 1974, 8, pp. 1099–1113.

[9] SHETTY M.S., *Septic tank design. Construction and maintenance practices*, A paper presented at a seminar on Water Supply and Sanitation Problems of Urban Areas, 1971, Vol. 11, The Inst. of Engrs (India), Roorke Sub-centre, Roorke pv.

[10] TEBBUTT T.H.Y., *Principles of water quality control*, Pergamon, 1983, pp. 87–88.

[11] VINCENT J.L., *A system of sanitation of low cost, high density housing*, Proc. of Symposium on Hygiene and Sanitation in Relation to Housing, Committee for Technical Cooperation in Africa South of Sahara, 1961, London, pp. 137–172.

[12] VIRARAGHAVAN T., *Septic tank efficiency*, J. Env. Eng. Div. Proc. of ASCE, 1976, Vol. 102 EE 2, pp. 505–509.

KINETYKA PROCESÓW PRZEBIEGAJĄCYCH W SZAMBACH

Badano, jak szybko maleje BOD w trójkomorowym szambie przy różnych prędkościach przepływu. Szambo znajdowało się w politechnice w Owerri w Nigerii. Zbiornik miał pojemność 17,71 m^3, głębokość 1,72 m i był podzielony w stosunku 2:1:1. Szybkość obniżania się BOD w szambach w Sri-Lance, Brazylii, Zambii, Stanach Zjednoczonych i Kanadzie oceniano na podstawie wyczerpujących danych literaturowych na temat wcieku i wycieku z szamb. Równanie określające szybkość obniżania się BOD wyprowadzono z kinetyki procesu zachodzącego w szambie. Stałe szybkości dla szamb z różnych miejsc obliczono z tego równania. Szybkość obniżania się BOD w przypadku innych warunków przepływu niż te, które wykorzystano do oszacowania stałej szybkości, obliczono z kinetycznego równania procesu i porównano ze zmierzonymi wartościami.

Otrzymane wyniki świadczą, że projekt szamba może opierać się na charakterystykach zawiesin ciała stałego i ciekłego środowiska, szybkości przepływu i końcowej szybkości stałych cząsteczek, jeśli jest ona znana. Monitorowanie wydajności szamb może opierać się na równaniu kinetycznym. Procent obniżania się BOD w doświadczalnym szambie w Owerri dla czasu retencji 2 dni wynosił 87%, a jego wartość obliczono na podstawie wyprowadzonego modelu kinetycznego była równa 83,4%.