Activated sludge settling Part II: Settling theory and application to design and optimisation

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Abstract

Activated sludge settlers perform both clarification and thickening. Depending on the operational conditions of a settler and sludge settleability characteristics, either one of these processes may limit the solids loading rate. Assuming the validity of Vesilind's (1968) equation, expressions are derived for the limiting sludge loading rates for clarification and for thickening. Based on settling theory an optimisation procedure for the design of the reactor-settler system was developed. For optimal design the mixed liquor concentration and recycle ration must be chosen such that these limiting loading rates are equal. For any specified sludge settleability the design procedure based on theory gives virtually the same results as empirical procedures suggested by Dutch and German research organisations (STORA, 1981; ATV, 1976)

Introduction

Activated sludge settlers have two simultaneous functions:

- clarification, i.e. the separation of the solid and liquid phases of mixed liquor, necessary to produce an effluent free of suspended solids; and
- thickening, i.e. the increase of total suspended solids (TSS) concentration from its value in the mixed liquor to that in the return sludge.

Depending on the settleability of the sludge and on the operational conditions in the settler (notably the incoming and outgoing flow rates and TSS concentrations), either one of these two functions may limit the solids handling capacity per unit area, which in turn determines the minimum surface area and hence the volume of the settler.

In this paper equations are derived for the maximum loading rate of final activated sludge settlers, both for clarification and for thickening. These equations are used for the optimisation of activated sludge process design. It is demonstrated that the design resulting from the developed theory is virtually identical to that of existing empirical models.

Sedimentation in a continuous settler

In the activated sludge process the final settler receives a flow of mixed liquor and discharges a clarified effluent, while a (more concentrated) return sludge is recirculated to the aeration tank. In order to describe the behaviour of a final settling tank the following suppositions and approximations will be made (see also Fig. 1):

- The flow rate of the mixed liquor entering the settler is the sum of the influent flow rate (which initially will be assumed to be constant) and the return sludge flow. Hence the mass flows in and out of the settler are:

$$F_{in} = X_t (Q_a + Q_r) \qquad (1a)$$

and

$$F_{out} = (X_r Q_r) \qquad (1b)$$

where :
F_{in} and F_{out} = incoming and outgoing mass flows (kg TSS/h)
X_t = mixed liquor concentration (kg TSS/m^3)
X_r = return sludge concentration (kg TSS/m^3)
Q_a = influent flow rate (m^3/h)
Q_r = return sludge flow rate (m^3/h)

If it is assumed that no accumulation of sludge takes place in the settler, then:

$$F_{in} = F_{out} \qquad (2a)$$

and

$$X_r = X_t (Q_a + Q_r) / Qr = X_t (s + 1) / s \qquad (2b)$$

where :
s = recirculation factor
= Q_r / Q_a

- The flow in the settler has a vertical direction. The incoming flow is uniformly distributed at a certain depth where an interface is formed between a supernatant with no suspended solids at the top part and settling sludge at the bottom part. In the top part there is an upflow velocity equal to the overflow rate:

$$T_s = Q_a/A \qquad (3)$$

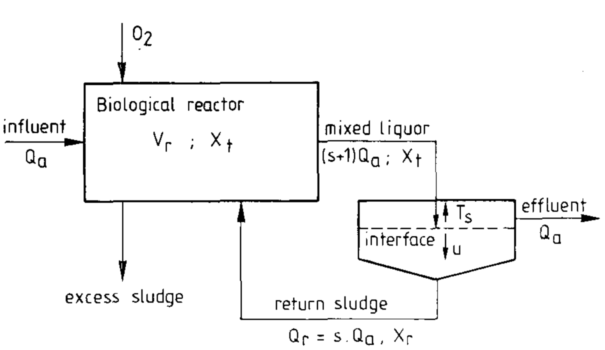

Figure 1
Schematic representation of an activated sludge process with a final settler

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where:

T_s = overflow rate (m/h)
= superficial upflow velocity of effluent in the settler
A = settler surface area (m^2)

In the bottom section there is a liquid downflow velocity due to abstraction of return sludge :

$$u = Q_r/A = sQ_a/A = s\,T_s \qquad (4)$$

where:

u = underflow velocity of the liquid phase (m/h)

- Superposed on the downflow velocity of the liquid there is a zone settling velocity (ZSV) of the flocs with respect to the liquid phase. It will be assumed that the influence of the TSS concentration on the ZSV can be described with the aid of Vesilind's equation (Vesilind, 1968):

$$v = v_0\exp(-kX_t) \qquad (5)$$

where:

v = zone settling velocity
k and v_0 are constants that characterise the sludge settleability

The validity of Vesilind's equation has been verified by several authors and estimates of values for the constants have been established in Part I of this series (Catunda and Van Haandel, 1992).

- The total sludge subsidence velocity in the settler is the sum of the velocities of the liquid and solid phases. Hence the mass flux at some level beneath the feeding level is given by:

$$F = X(v+u) = F_v+F_u \qquad (6)$$

where :

F = total solids flux or mass of solids passing per unit time and surface area (kg TSS/m^2·h)
F_v = mass flux due to sedimentation of the solids (ZSV)
F_u = mass flux due to return sludge abstraction

- The solids loading rate of the settler is the ratio between the mass flow of solids in the mixed liquor and the available settler surface area:

$$F_s = X_t(s+1)Q_a/A \qquad (7)$$

where:

F_s = solids loading rate.

- For proper functioning of the settler it is crucial that the solids loading rate does not exceed the mass flux of solids at any level in the settler. If this condition is satisfied, then all solids introduced into the settler will be transported to the abstraction point of return sludge, because the total solids flux will exceed the solids loading rate. However, if, at some level, the solids loading rate is greater than the mass flux of the solids, then, at that level, not all solids will pass. Therefore there will be an accumulation of solids in the settler and, eventually, solids will appear in the effluent. Hence the basic condition for the settler is:

$$F = F_v + F_u < F_s \quad \text{for } X_t < X < X_r \qquad (8)$$

Solids flux curve

Equation 8 is the basis for the design of final settlers. In order to evaluate the solids flux F it is convenient to consider separately its components F_v and F_u. Assuming that Vesilind's equation applies, F_v as a function of the TSS concentration, X is shown plotted in Fig. 2a . Figures 2b and 2c show plots of F_u and F respectively as functions of X. The curve of Fig. 2a reflects only the ZSV and is called the batch flux curve, while the curve in Fig. 2c is named the solids flux curve.

For the chosen values of the feed and bottom concentrations, the solids flux curve exhibits a relative minimum, F_l, for a concentration X_l intermediate between the values of feed (X_t) and bottom or return sludge concentration (X_r).This flux F_l limits the transport through the settler and is therefore called the limiting solids flux. Figure 2c also shows the geometric method, developed by Yoshioka et al. (1957) to determine the limiting solids flux if the shape of the batch flux curve is known. This method can be described as follows:

- Draw the straight line through the value of X_r on the abscissa and that is tangential to the batch flux curve.
- The limiting solids flux is given by the intersection point of this curve with ordinate.

It is clear from Fig. 2c that the limiting solids flux depends directly on the value of the return sludge concentration X_r. Hence under the circumstances chosen in Fig. 2, the solids flux that can be transported through the settler, depends upon the concentration of the thickened (return) sludge and therefore thickening is the limiting function. However, still in Fig. 2, it may be noted that the limiting solids flux is not an absolute minimum of the solid flux curve: When the feed concentration, X_t, is greater than the limiting concentration, X_l, the value of F increases continuously with increasing concentration from X_t to X_r. Therefore, in this case, the greatest flux that can be transported through the settler is equal to the flux relative to the feed concentration X_t and is independent of the return sludge concentration, X_r. Also when the feed concentration is smaller than a certain value X_m (Fig. 2c), the flux relative to the feed concentration will be smaller than the limiting flux and will therefore be the true limit of solids transport through the settler. It is concluded that when the feed solids concentration is greater than the limiting concentration X_l or smaller than a minimum concentration X_m, the solids flux relative to the feed concentration is the maximum solids flux that can be transported in the settler, and for that reason the feed solids concentration determines the maximum solids loading rate. Hence, under these circumstances, clarification and not thickening is the limiting function of the settler.

Figure 2c shows that Yoshioka's method is only applicable if it is possible to draw a line tangent to the concave part of the batch flux curve. There is a critical return sludge concentration, X_c, such that, for any concentration lower than the critical value, it is not possible to draw this line. The straight line for the critical concentration is tangent to the batch solids curve at its inflection point , i.e. where the inclination of this curve is maximum. If the return sludge concentration is lower

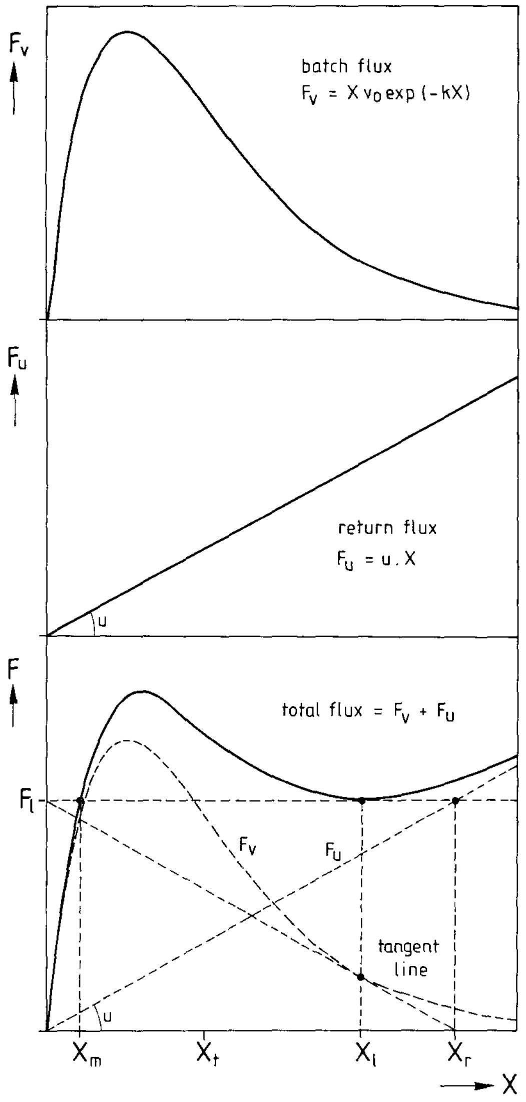

Figure 2
Flux of solids due to zone settling (batch flux curve in accordance with Vesilind's (1968) equation), F_v in Fig. 2a, due to return sludge abstraction, F_u in Fig. 2b and total solids flux, F, in Fig. 2c.

than the critical concentration, the limiting concentration does not exist and consequently the thickening function of the settler will not be limiting.

The conclusion from the analysis of Fig. 2 can be resumed as follows: If the feed concentration of a settler has a value between a minimum concentration, X_m, and a limiting concentration, X_l, and if the return sludge concentration has a value greater than the critical concentration, X_c, then the limit of the solids throughput in a settler is determined by the thickening function. In all other cases the limiting function is clarification.

In order to establish which function is limiting in a particular design situation the values of the concentrations X_m, X_l and X_c must be determined. A derivation of the values of these parameters is presented below for the case that Vesilind's equation is used to express the ZSV.

Determination of the limiting concentration X_l

The straight line tangential to the batch flux curve can be expressed as:

$$F = m(X-X_r) \qquad (9)$$

where:

$$\begin{aligned} m &= \text{inclination of the tangential line} \\ &= (dF_v/dX)_{x=xl} \\ &= v_0\,(1-kX_l)\exp(-kX_l) \end{aligned}$$

At the tangential point the ordinate values of the straight line and the curve F_v are equal, so that:

$$F = -(X_l-X_r)\,v_0\,(kX_l-1)\exp(-kX_l) = X_l v_0 \exp(-kX_l)$$

or

$$X_l = (X_r/2)\,(1+\sqrt{1-4/(kX_r)}) \qquad (10)$$

Now, the limiting flux can easily be determined as the ordinate value of the straight line for X=0 (Fig. 2c):

$$F_l = -mX_r = X_r v_o (kX_l - 1)\exp(-kX_l) \qquad (11)$$

The value of X_l in Eq.(11) can be calculated from Eq.(10). The liauid velocity in the lower part of the settler, due to sludge abstraction can also be calculated with the aid of Fig. 2c:

$$u = F_l/X_r = v_0\,(kX_l-1)\exp(-kX_l) \qquad (12)$$

Determination of the critical concentration X_c

The critical concentration, X_c, is given as the abscissa value at the intersection point of the X-axis with the line tangent to the batch settling curve, F_v, when the inclination of this line is maximum, i.e. when the line goes through the inflection point of the curve F_v. The co-ordinates of the inflection point (X_i, F_{Vi}) are given by the condition:

$$(d^2F_v/dX^2)_{x=xi} = 0$$

or

$$X_i = 2/k \text{ and } F_{vi} = 2v_0/(ke^2) \qquad (13)$$

Now the maximum inclination of the straight line is calculated as:

$$m_{max} = (dF_v/dX)_{x=xi} = -v_0/e^2 \qquad (14)$$

Thus, the straight line going through the inflection point of F_v, can be written as:

$$F-2v_0/(ke^2) = -v_0/e^2[X-2/k]$$

or

$$F = -(v_0/e^2)(X-4/k) \qquad (15)$$

The critical concentration is obtained from Eq. (15) by noting that $X=X_c$, when F=0, so that:

$$X_c = 4/k \qquad (16)$$

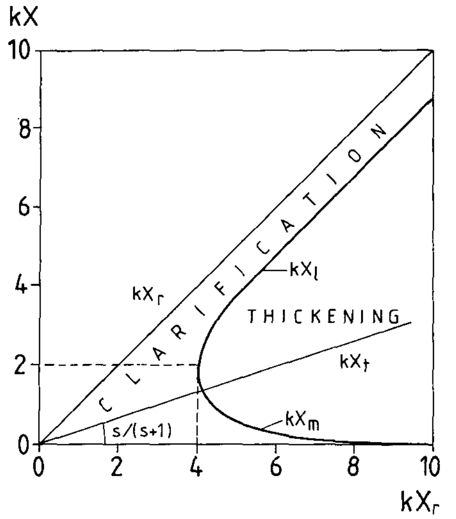

Figure 3
Values of the limiting and the minimum sludge concentrations as a function of the return sludge concentration. The critical concentration is also indicated.

Determination of the minimum concentration X_m

The minimum concentration X_m for thickening to be the limiting function is given by the condition that the incoming flux F is equal to the limiting flux F_l. This can be formulated as:

$$F_{x=xm} = (F_v+F_u)_{x=xm} = F_l \tag{17}$$

By substituting for F_v, F_u and F_l and rearranging one has:

$$X_m\exp(-kX_m) = (X_r-X_m)(kX_l-1)\exp(-kX_l) \tag{18}$$

Equation (18) does not have an analytical solution but its value can be determined as a function of X_r by trial and error.

In order to represent graphically the values of X_l and X_m it is convenient to use an adimensional diagram with kX_r on the abscissa and kX_l or kX_m on the ordinate axis, as shown in Fig. 3. The critical concentration $kX_c = 4$ is also indicated in the diagram. Figure 3 is of great practical use: It allows to determine for any "pair" of feed and return sludge concentrations, X_t and X_r, which of the two processes is limiting: clarification or thickening. Once this has been established it is a relatively simple matter to determine the overflow velocity that can be used and hence the settler surface and volume, as will be shown in the next section.

Determination of the overflow rate

The most important parameter for settler design is the overflow rate: the allowable flow rate per unit surface area. The maximum overflow rate can be determined for both clarification and thickening from the basic condition for proper performance of a settler: the solids loading rate must not exceed the maximum flux that can pass through the settler (Eq.(8)). This equation can be applied for clarification and for thickening as follows:

Clarification

In the case of clarification the basic equation (Eq.(8)) can be written as:

$$F_s < F = (F_v+F_u)_{x=xt}$$
or
$$X_t(s+1)Q_a/A_{min} = X_tv_o\exp(-kX_t) + sQ_a/A_{min}$$
or
$$\ln (T_{sm}/v_0) = \ln [(Q_a/A_{min})/v_o] = -kX_t \tag{19}$$

where:
A_{min} = minimum settler surface area
T_{sm} = maximum overflow rate

Equation (19) shows that in the case of clarification the maximum overflow rate depends only on the sedimentation constants v_0 and k and on the feed sludge concentration X_t.

Thickening

In the case of thickening the solids loading rate cannot exceed the limiting flux, so that:

$$F_l = X_rv_o (kX_l-1)\exp(-kX_l) < F_s = X_t (s+l) Q_a/A_{min}$$
or
$$\ln (T_{sm}/V_0) = \ln [(kX_l-1) /s] - kX_l \tag{20}$$

Equation (20) shows that in the case of thickening, the maximum overflow rate does not depend on the feed concentration and is a complex function of the return sludge concentration, the recirculation factor and the sedimentation constants of Vesilind's equation.

Equations (19) and (20), in combination with Fig. 3, allow an easy determination of the maximum overflow rate, if the sedimentation constants v_0 and k are known. This can be done as follows:

- Using the values of kX_t and kX_r, determine in Fig. 3 if clarification or thickening is the limiting function for solids throughput in the settler.
- Calculate the maximum overflow rate from Eq. (19) in the case of clarification or from Eq. (20) in the case of thickening.

The operational overflow rate will always be smaller than the maximum value calculated with the procedure above. In practice a safety factor of about 2 is used to compensate for non-ideal behaviour of the settler (Anderson, 1981). For a particular safety factor s, the surface area, A_s, of the settler can be calculated as:

$$A_s = s_fQ_a/T_{sm} \tag{21}$$

Now, to calculate the volume of the settler, the depth must be known. In practice the depth is usually chosen between 3 and 5 m (average depth). The criteria for selection of the optimal depth are hydraulic stability and the possibility to accumulate sludge during a temporary overload of the settler. If the value is known the hydraulic and actual retention times in the settler can also be calculated:

$$v_s = V_s/Q_a = A_sH_s/Q_a = s_fH_s/T_{sm} = s_f(H_s/v_o)/(T_{sm}/v_o) \tag{22}$$

$= (s+1)\, R_{set}$

where:

v_s = volume of the settler per unit flow rate
= hydraulic retention time in the settler
V_s = volume of the settler
A_s = surface area of the settler
H_s = (average) depth of the settler
s_f = safety factor (generally about 2)
R_{set} = actual retention time in the settler = $V_s/((s+1)Q_a)$

There are practical constraints for the value of the actual retention time: If the value is very small (e.g. < 1h), there is a probability of inefficient solid-liquid separation in the settler due to excessive turbulence. On the other hand if the retention time is too long (e.g. > 3h), there is a possibility of deterioration of the mechanical and biological properties of the sludge. Hence in practice one has:

$$1\ \text{h} = 1/24\ \text{d} < v_s/(s+1) < 3/24\ \text{d} = 3\ \text{h}$$

or

$$(s+1)/24 < v_s < 3(s+1)/24 \quad (V_s \text{ in h}) \qquad (23)$$

If the calculated value of V_s falls outside the range indicated in Eq. (23), other values of X_t and/or X_r must be chosen.

Determination of the critical recirculation factor

Equation (19) shows that in case of clarification, the overflow rate is independent of the recirculation factor. Hence, in principle, it is convenient to operate at the minimum recirculation factor before thickening becomes the limiting function of the settler. A further reduction of the recirculation factor is counter-productive: Thickening would then become the limiting function and probably, the advantage of having a lower recirculation factor would not compensate the necessity for a larger settler volume. Hence, if the hydraulic retention time is adequate, it is convenient to operate the settler with the lowest possible recirculation for clarification i.e. the recirculation factor for which the overflow rate for clarification and thickening are equal. This recirculation factor will be denominated the critical recirculation factor, s_c.

In order to determine the critical recirculation factor, Fig. 3 can be used. In this diagram the relationship between the feed and the return sludge concentration can be drawn as a straight line. In accordance with Eq. (2) the slope of this straight line is s/(s+l). It can be noted in Fig. 3 that this straight line has an intersection with X_m for s<1 and with X_l for s>1. Hence, these intersection points are defined as:

$$X_t = s_c/(s_c+1)X_r = X_l \quad (s_c>1) \qquad (24a)$$

or

$$X_t = s_c/(s_c+1)X_r = X_m \quad (s_c<1) \qquad (24b)$$

Equation (24a) can be solved analytically by substituting for X_l from Eq. (10):

$$kX_r = (s_c+1)^2/s_c \text{ and } kX_t = s_c+1 \qquad (25)$$

Equation (24b) has no analytical solution, but the values of kX_r and kX_t can be calculated as a function of s_c by trial and error. Figure 4 shows the critical recirculation factor as a function of kX_t and of kX_r. Figure 4 is extremely useful for design optimisation as will be shown in the next section.

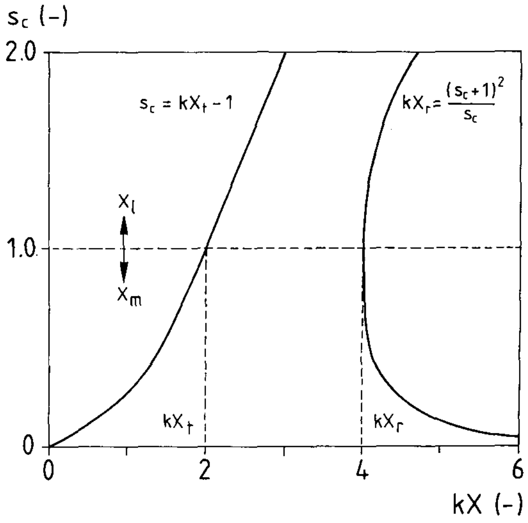

Figure 4
The critical recirculation factor as a function of the feed and of the return sludge concentrations

Optimisation

The optimisation of the system biological reactor/settler consists of selecting values of X_t and X_r, so that the resulting treatment system will function properly and that construction and operational costs are kept to a minimum. The construction costs are reflected in the volumes needed for the biological reactor and the settler, i.e. by the hydraulic retention times in the reactor and in the settler. In this context it is interesting to note that in an activated sludge process a sludge mass will build up compatible with the organic load and with the operational conditions of the system (notably the sludge age). The reactor volume is inversely proportional to the sludge concentration in it. On the other hand, the higher the sludge concentration in the reactor, the larger the final settler must be. This means that there is an optimal sludge concentration that requires a reactor and a settler volume so that the construction costs of these are as low as possible. The operational costs are defined by the pumping costs of the return sludge, i.e. by the magnitude of the recir-culation factor. For the optimisation procedure, the objective function to be minimised is the total cost, when the recirculation factor has its critical value, s_c. The optimisation procedure comprises the following steps:

- From Eq. (24b) or (25) determine the critical recirculation factor as a function of the feed concentration X_t.
- Assuming that the critical recirculation factor will be used (which means that clarification is still the limiting factor) from Eq. (22) calculate the nominal retention time in the settler as a function of the feed concentration.
- Determine the hydraulic retention time in the reactor as a function of the reactor sludge (=feed) concentration.
- Plot the retention times v_s and v_r and the sum of these two, v_t, as a function of the feed sludge concentration.
- Determine the optimal sludge concentration by identifying the

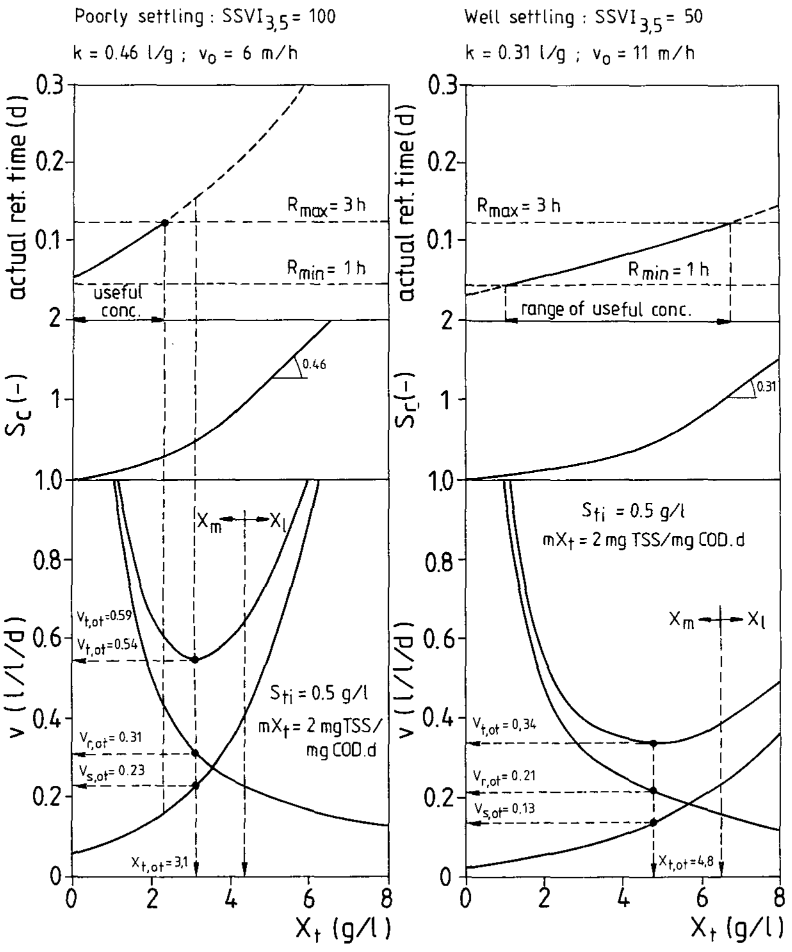

Figure 5
Design optimisation procedure for sludge with poor (5a) and good (5b) settleability

minimum value of the total hydraulic retention time v_t.

- Verify if for the optimal concentration and the corresponding critical recirculation factor, the actual retention time in the settler is within the desired range of 1 to 3 h approximately. If this is so, select the optimal concentration and the critical recirculation factor for design.
- If the retention time is too long, consider two possibilities:
  - increase the recirculation factor beyond its critical value until the hydraulic retention time is within the desired range; or
  - decrease the feed concentration to below the optimal value until the consequent reduction of the retention time in the settler is sufficient. A combination of these two options is also possible.

The design procedure is demonstrated in Figs. 5a and 5b. To be able to carry out the optimisation procedure, it was assumed that the sludge mass in the system (kg TSS) is equal to twice the daily organic load (kg COD/d) i.e. mX_t = 2 kg TSS/(kg COD·d) and that the influent COD is S_{ti} = 0,5 g/ℓ (the value of mX_t represents a sludge age of about 8 d; the influent COD is "normal" for sewage).

In Fig. 5a the volumes per unit influent flow of the reactor and the settler (v_r and v_s in $m^3/(m^3 \cdot d)$ as well as the sum of these (v_t) are shown plotted as a function of the sludge concentration in the reactor. It is assumed that the critical recirculation factor is used and that the sludge settling characteristics are "bad": k =0,46 ℓ/g and v_0 = 6 m/h (In a previous paper, Catunda and Van Haandel, 1992, it was shown that these values characterise badly settling active sludge). The corresponding critical recirculation factor and the actual retention time in the settler are also shown plotted. For the given conditions, the concentration for the lowest total volume is 3,1 g/ℓ. For this optimal concentration the recirculation factor is 0,5 and the actual retention time in the settler is about 0,15 d or 3,6 h. If these values are acceptable, then the optimal (minimum) reactor and settler volumes are 0,31 and 0,23 $m^3/m^3 \cdot d$) of influent flow, leading to a total optimal volume of 0,54 $m^3/m^3 \cdot d$). If the actual retention time in the settler is considered excessively long, the sludge concentration may be reduced: If the sludge concentration is 2,3 gTSS/ℓ, the critical recirculation ratio is 0,3 and the actual retention time in the settler is 3 h. However, while the settler volume is reduced (V_s=0,16 d and R_{set}= 3 h, Fig. 5a), the reactor volume is bigger: V_r=0,44 d, so that the total volume now is given by V_t= 0,16+0,44=0,60 d, an increase of some 10 per cent with respect to the total volume, calculated for a sludge concentration of 3,1 g/ℓ.

Figure 5b is a similar plot but "good" settling characteristics

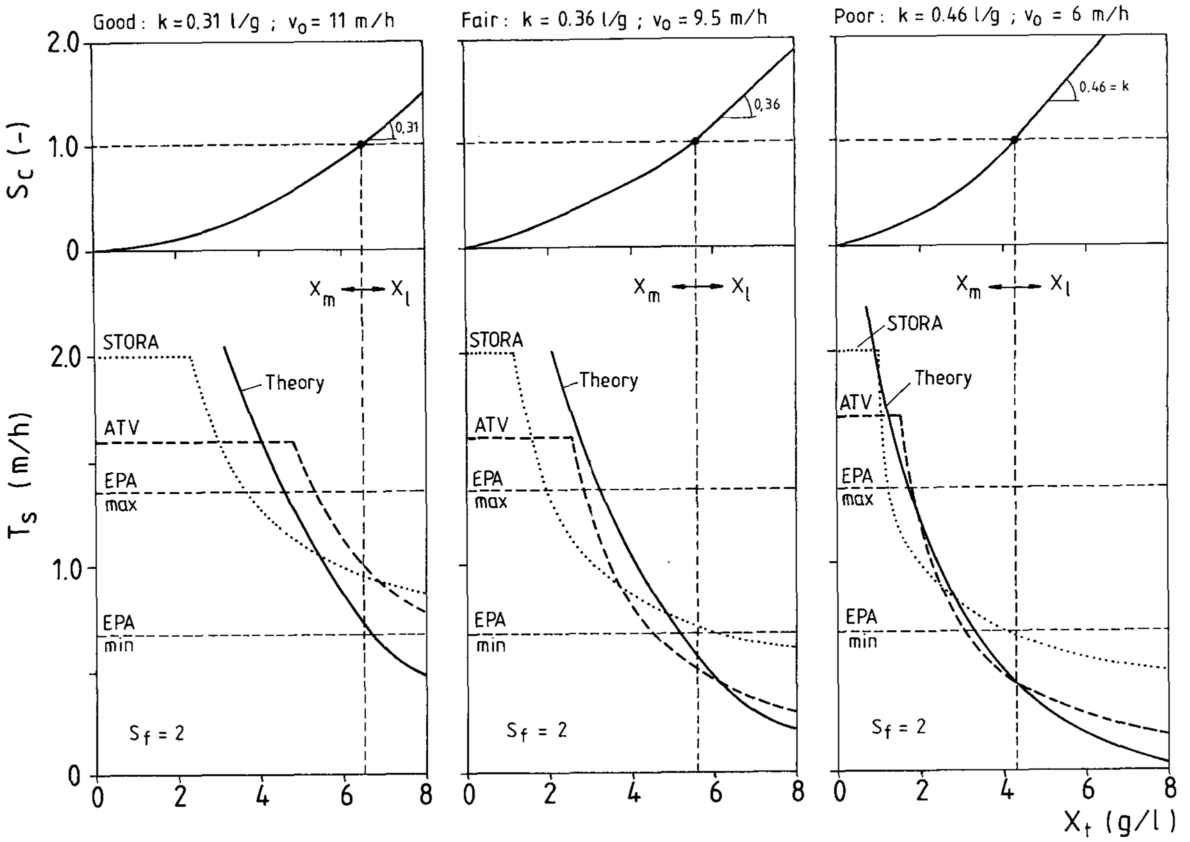

Figure 6

Comparison of theoretically calculated overflow rates and experimental values, obtained from the empirical criteria by EPA, ATV and STORA

have been assumed: k= 0,31 ℓ/g and v_0 = 11 m/h. Comparing Figs. 5a and 5b, it can be seen that the numerical values of the settling constants k and v_0 have a very marked influence on the optimal design values of reactor and settler volumes. For conservative design it is good practice to assume that the settling characteristics are bad (as these indeed will be, at least occasionally) and optimise the design for this situation. When the real settling characteristics are better than the assumed values, the recirculation factor may be reduced and/or the sludge concentration increased.

Applicability of settling theory in practice

Several research organisations have given design criteria for final settlers in the activated sludge process. All these criteria are based on empirical correlations established from experimental observations of full-scale settlers. In order to evaluate the applicability of the settling theory described in this paper it is interesting to compare the results of the theory with the empirical criteria established by research organisations. The best known criteria are issued by EPA (Environmental Protection Agency, USA ; ATV (Technical Federation for Waste Water, Germany) and STORA (Research Foundation for Waste Water Pollution Control, Netherlands). The essence of the criteria is the rule to be used for the design overflow rate of the settler. The following criteria are given:

EPA: T_s must be between 0,68 and 1,36 m/h.

ATV: T_s is correlated to the sludge concentration and sludge settleability:

$T_s = 2400/(X_t.DSVI)^{1,34}$ subject to: $T_s<1,6$ m/h

STORA: T_s is correlated to the sludge concentration and sludge settleability:

$T_s = 1/3 + 200/(X_t{\cdot}DSVI)$ subject to: $T_s < 2$ m/h

In the ATV and STORA equations, the value of T_s represents the experimentally identified highest value that can be applied at a sewage works without having problems of settler failure and sludge carry-over.

A problem which arises when comparing the theoretical model

TABLE 1
VALUES OF THE SETTLEABILITY CONSTANT PARAMETERS FOR BAD, FAIR AND GOOD SETTLEABILITY OF ACTIVATED SLUDGE

Parameter	Sludge settleability		
	Bad	Fair	Good
K (ℓ/g)	0,46	0,36	0,31
V_o (m/h)	11	9,5	6
DSVI	150	100	75
$SSVI_{3,5}$	100	65	50

with the empirical models is that the parameters which characterise sludge stability are not the same: in this paper the constants of Vesilind's (1968) equation (k and v_0) are used, while ATV and STORA use the diluted sludge volume index (DSVI) to assess sludge settleability. However, in a previous paper (Catunda and Van Haandel, 1992), it was shown that these parameters to express the sludge settleability are interrelated and that the values of k and v_0 can be found if the value of DSVI is known. The values of the constants for "bad", "fair" and "good" settleability are shown in Table 1.

In Fig. 6 the maximum overflow rate of an activated sludge settler is shown plotted as a function of the sludge concentration for bad (a), fair (b) and good(c) settling characteristics. Both the values from the empirical models (EPA, ATV and STORA) and the theoretical model are shown. The theoretical overflow rate has been calculated presupposing that the critical recirculation factor was used. The value of S_c is also indicated in Fig. 6. It can be noted that there is a very good correlation between the theoretical model presented in this paper and the empirical models by ATV and STORA, particularly for the range of sludge concentrations generally used in practice: 2 to 6 g/ℓ. It can be concluded that the theoretical model presented in this paper describes activated sludge settling adequately and can be used for design and optimisation of final settlers. To use the model in practice, the minimum sludge settleability, the influent COD concentration and the sludge mass in the activated sludge system must be known or estimated. The following values are suggested as estimates of sludge settleability constants: k = 0,46 ℓ/g; v_0 = 6 m/h; $SSVI_{3,5}$ = 100 and DSVI = 150 mℓ/g.

When the empirical models are compared it is seen that the EPA model does not take into consideration the sludge concentration, nor the sludge settleability. The ATV and STORA models are superior in that the influence of these two important parameters is incorporated in the equations of the allowable overflow rate. The theoretical model also recognises the influence of sludge concentration and settleability on the overflow rate but is superior in one point: It quantifies yet another parameter that is of influence on the settling behaviour, viz. the recirculation factor.

Conclusions

- A rational design method for the design and optimisation of final settlers can be developed from batch settling theory, using Vesilind's (1968) equation to describe the zone settling velocity:

  $$v = v_0 \exp(-kX)$$

- The maximum solids loading rate of a final settler is limited by either the clarification or the thickening function. Thickening is limiting when the influent concentration is within the range between the minimum, X_m, and the limiting concentration, X_l, and the return sludge concentration is greater than the critical concentration, X_c. In all other cases clarification is limiting.

- The values of the minimum , limiting and critical sludge concentrations depend on the sludge settling concentrations and on the return sludge concentration X_r and can be expressed as follows:

  $$X_c = 4/k$$
  $$X_l = [1+\sqrt{(1 - 4/(kX_r)}\ ].(X_r/2)$$
  $$X_m \exp(-kX_m) = (X_r-X_m)(kX_l-1)\exp(-kX_l)$$

- The critical recirculation factor is the lowest value of this parameter, still making clarification the limiting function for solids transport in the settler. Its value is given by:

  $$S_c = kX_t - 1 \quad \text{for } kX_t > 2$$
  or
  $$kX_t = s_c/(s_c+1) \cdot kX_r = kX_m \text{ for } kX_t < 2$$

  The critical recirculation factor is to be used for design and optimisation, unless the resulting retention time is too short or too long.

- Zone settling theory can be used for optimisation of the system activated sludge reactor/final settler. The optimisation procedure involves minimisation of construction costs (reactor and settler volume) and operational costs (pumping of return sludge).

- There is an excellent correlation between the design criteria derived from settling theory and empirical criteria by ATV and STORA, obtained from experiments using full-scale activated sludge settlers.

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