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High Capacity Depth Filter

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Abstract

To incease the capacity of a depth filter with a high performance, the authors have proposed a dual-floor depth filter with an upper Raschig ring bed and a lower sand bed. The Effectiveness of the high capacity filter was proved by pilot plant studies. Mechanism of the upper Raschig ring bed was analysed and a kinetic model of the removal process was proposed.

1. Introduction

Colloid suspensions coagulated by metal coagulants and precipitated metal hydroxides are the typical major substances to be removed in water and wastewater treatment. These are typical bulky and fragile flocculated particles which are not removed effectively by conventional filters. To overcome this difficulty, the authors attempted to propose a new dual-floor filter which has a much higher capacity and performance than conventional depth filters[1].

The upper floor of the proposed filter is a packed bed of Raschig rings with a few millimeter diameter and is placed in overlaid water above backwash-troughs of conventional gravity depth filter as shown in Fig. 1. The Major parts of suspended matters in a coagulated water can be removed in the upper packed bed of high porosity with very little head loss. Therefore, an ample head to drive depth filtration in the lower granular bed which ensured that low turbidity effluent can be held at the outlet of the upper bed.

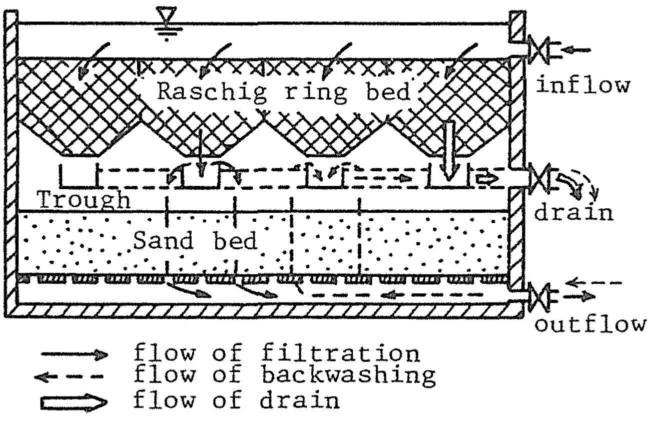

Fig.1 Schematic diagram of high capacity depth filter

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This combination of a high capacity rough filtration in the upper bed and an accurate removal in a lower sand bed makes depth filtration much more effective.

Reclamation of filter beds after the removing capacity reaches saturation is another important design and operation item to be discussed. A suitable washing method with economy of washwater and power should be discussed.

2. Experimental Apparatus and Method

Experimental studies are carried out by a pilot plant as shown in Fig. 2.

Kaolinite suspensions are coagulated by aluminium under optimal conditions, i.e. pH=

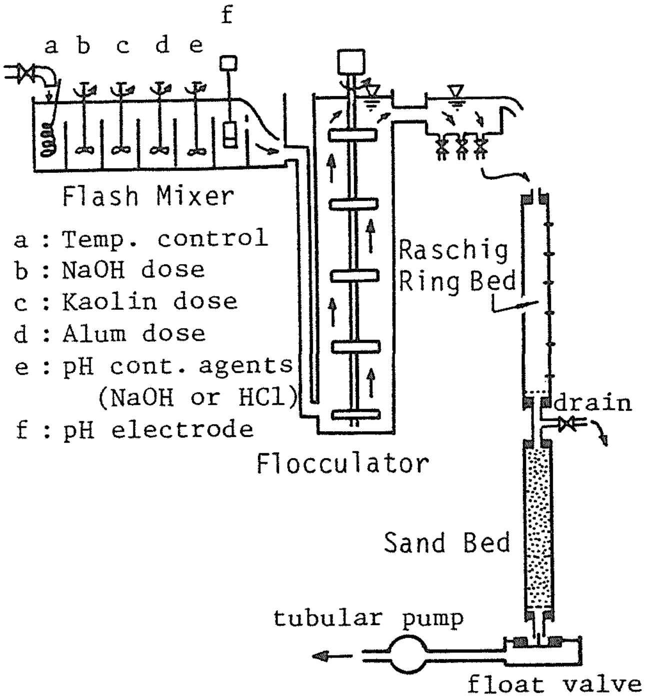

Fig. 2 Schematic diagram of experimental apparatus

7.0, Aluminium dosage/Kaolinite concentration=ALT Ratio=0.01. The temperature and pH are controlled automatically. 2ℓ/min of the coagulated suspession is flocculated in an upflow flocculator for 20 minutes and is introduced into a Raschig ring filter. Raschig rings of 3, 6 or 9 mm diameter which has 1: 2 diameter vs. length ratio are packed in a 5 cm diameter glass tube with 90 cm bed height. The Raschig ring is made from hard nylon tube. Porosity of the packed bed is about 0.7 at the beginning of a filter run.

A sand bed of 50 cm depth with 0.84-1.00 mm diameter grains follows the Raschig ring bed. In between these two beds a wash water exit valve is fixed. Through the valve, water in the upper Raschig ring bed is discharged by gravity for bed washing and backwash water for the sand bed cleaning is allowed to overflow.

The rate of filtration was changed at five levels namely 120, 160, 200, 300 and 400 m/day.

The rate of filtration is controlled with accuracy by a tube pump connected with a floated needle valve in a contstant level tank.

3. Effectiveness of The Dual-bed Filter

Fig. 3 shows variation of turbidity and head loss at the Raschig ring bed inlet and outlet, and the sand bed outlet with filtration time. The figure shows the case of an

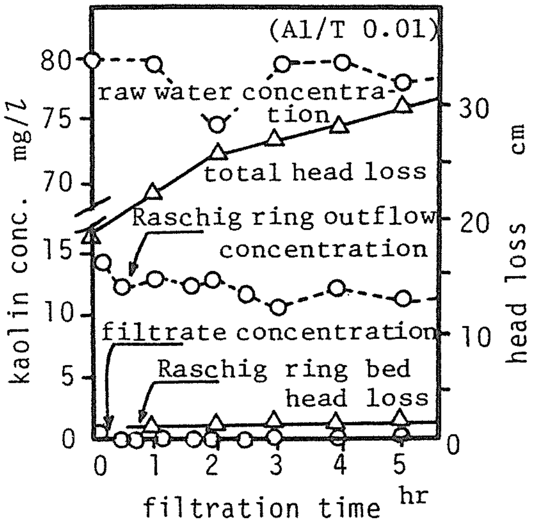

Fig.3 Progress of the dual-floor filtration

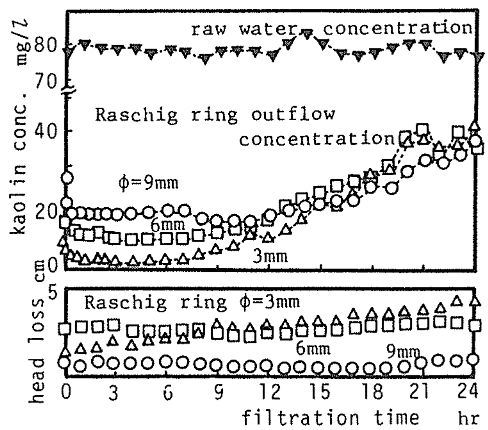

Fig.4 Variation of effluent concentration and head loss with filtration time (v=200m/d, Al/T=0.01)

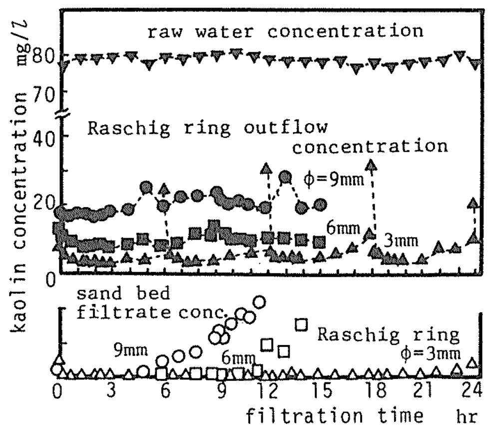

Fig.5 Variation of effluent concentration of Raschig ring and sand layers (V=200m/d, Al/T=0.01. Raschig ring bed drain : every 6 hrs)

optimum alum dosage for the Kaolinite suspension with 0.01 ALT-Ratio. The rate of filtration is 200 m/day. This figure shows the effectiveness of the dual filter bed for a high turbidity suspension.

The performance of the upper floor Raschig ring bed is examined with three size media for their effectiveness of turbidity removal and head loss variation with time as shown in Fig. 4. These data show that an ample removal efficiency as a preliminary first stage filter is maintained for six to ten hours with a very small head loss. Fig. 5 shows the performance of filter operations with packed bed washing of every six hours. The wash of the Raschig ring bed is carried out with good results only by draining out water in the bed pore through the wash water exit placed between the upper and the lower beds.

These data show the effectiveness of the dual-bed filter for high turbidity water.

Possible combinations of the Raschig ring size and the rate of filtration are examined and the results are shown in Figs. 6,7 and 8. From these data, the filtration rate of 200 m/day or less and the Raschig ring size of 3 mm or 6 mm are considered to be practical combinations.

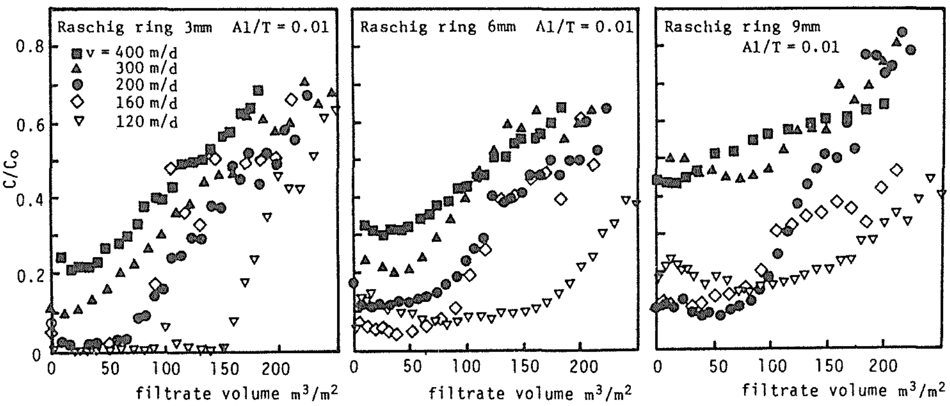

Fig.6 Fig.7 Fig.8

Variation of Raschig ring outflow concentration with filtration time

4. Filter Coefficient of The Raschig Ring Bed

The rate of removal per unit depth of filter is described to be proportional to the local concentration of suspedded solids, C, as originally shown by Iwasaki.

$$\partial C/\partial L = -\lambda C \qquad (1)$$

The first order reaction coefficient, λ, which is usually noted as filter coefficient is not constant but varies with time and depth in the filter. The variation of the filter coefficient, λ, can be described as a function of initial filter coefficient, λ_0, and the specific deposit, σ, as shown in Eq. 2.

$$\lambda = f_1(\lambda_0, \sigma) \text{ or } \lambda_0 f_2(\sigma) \qquad (2)$$

As the first step to discuss the nature of the Raschig ring bed filter coefficient, specific characteristics of the initial filter coefficient, λ_0, are discussed.

Based upon close-up observations by using a video recorder system, the following removal patterns in the Raschig ring bed are noted.

i) Flow is laminar, ii) The deposition of floc particles is only observed on the upper planes of the Raschig rings with a uniform depth. It is quite probable from these observations that gravitational sedimentation is the main mechanism of separation among those involved in the removal of suspended solids in the depth filter.

Therefore, a hypothetical filter, which is composed of a series of micro settling tanks as shown in Fig. 9, is proposed as a conceptual model of the Raschig ring bed. In between the micro sedimentation tanks, suspension is uniformly redistributed by mixing. Flow

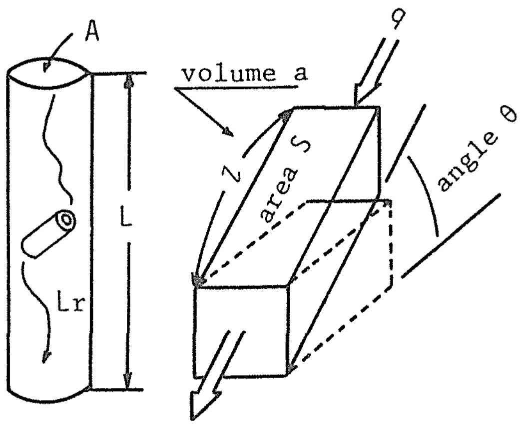

Fig.9 Conceptual model of the Raschig ring bed

direction is assumed to be in parallel with the longitudinal direction of a Raschig ring. Removal of the suspended solids is performed only by way of gravitational settling in the micro sedimentation tanks and is evaluated by the overflow rate theory.

Flow of suspension passes through average m chambers of the micro sedimentation tanks in the Raschig ring bed of a depth L. Therefore, the ratio of the total real distance of travel, Lr, vs. filter depth, L, which is denoted as the turtuosity of a filter bed, can be shown as Eq. 3 when inclination of a hypothetical sedimentation tank of the length l is assumed to be θ_i, and the average of the values θ_i is denoted as $\bar{\theta}$.

$$\frac{Lr}{L} = \frac{lm}{\sum_{i=1}^{m} l \sin\theta_i} = \frac{1}{\sin\theta_i} = \frac{1}{\sin\bar{\theta}} \tag{3}$$

The average number m in a series of the micro sedimentation tanks in a filter bed of the depth L is given by Eq. 4.

$$m = \beta\frac{L}{l} = \beta\left(\frac{L}{l}\right)\left(\frac{Lr}{L}\right) = \frac{\beta L}{l\sin\overline{\theta}} \tag{4}$$

The average settling area, S, of a Raschig ring which has an external diameter d_o, internal diameter d_i and length l is given by Eq. 5.

$$S = (d_0 + d_i)\, l \cos\overline{\theta} \tag{5}$$

The average volume, a, of the hypothetical micro sedimentation tank in a filter bed with a horizontal cross section A, the depth L and the porosity ε is given by Eq. 6.

$$a = \frac{\varepsilon AL}{AL(1-\varepsilon)/[(\pi/4)(d_0^2 - d_i^2)\, l]} = \frac{\pi}{4}\,\frac{\varepsilon}{1-\varepsilon}(d_0^2 - d_i^2)\, l \tag{6}$$

The rate of flow, q, which passes through a micro sedimentation tank can be calculated as follows when the superficial velocity of the filtration is v.

$$q = \left(\frac{v}{\varepsilon}\right)\left(\frac{L_r}{L}\right)\left(\frac{a}{l}\right) = \frac{\pi v(d_0^2 - d_i^2)}{4(1-\varepsilon)\sin\overline{\theta}} \tag{7}$$

From Eqs. 5 and 7, the overflow rate, w_0, of a hypothetical micro sedimentation tank is derived as Eq. 8.

$$w_0 = \frac{q}{S} = \frac{\pi v(d_0 - d_i)}{2l(1-\varepsilon)\sin 2\overline{\theta}} \tag{8}$$

The total removal rate, R, of suspended solids, which have the settling velocity w, by a filter of the depth L can be derived as Eq. 9 when it is assumed that the filter in composed of m chambers of the hypothetical micro sedimentation tanks in series.

$$R = 1 - (1-r)^m = 1 - (1 - W/W_0)^m = 1 - \exp(-\lambda_0 L) \tag{9}$$

Therefore, the initial filter coefficient, λ_0, can be derived from Eqs. 4, 8 and 9 as Eq. 10 when the removal efficiency r of an individual micro sedimentation tank is small.

$$\lambda_0 = \left(\frac{m}{L}\right) ln(1-r) = \frac{m}{L}\left(r + \frac{r^2}{2!} + \frac{r^3}{3!} + \cdots\cdots\right) \fallingdotseq \frac{m}{L}r = \alpha\beta\frac{4(1-\varepsilon)\cos\theta}{\pi(d_0 - d_i)}\,\frac{w}{v} \tag{10}$$

The Validity of the above equations are examined against experimental data as follows. Fig. 10 shows that the relationship of Eq. 1 is held at the beginning of a filter run. The initial filter coefficient, λ_0, is calculated from the inclination of the plot.

Fig. 11 shows the relationship between the initial filter cefficient and the superficial velocity of filtration. Straight line relationship with -1 inclination are shown with respect to optimum coagulant dosages. This shows the existence of a suggested relationship between λ_0 and v in Eq. 10. However, the above mentioned relationship is not held with respect to higher dosage flocs, i.e. weak flocs.

Fig. 12 shows the relationship between the product of the coefficients $\alpha\beta$ and filtration rate v. For this calculation the mean settling velocity of flocs $\bar{w}$ is measured and put into

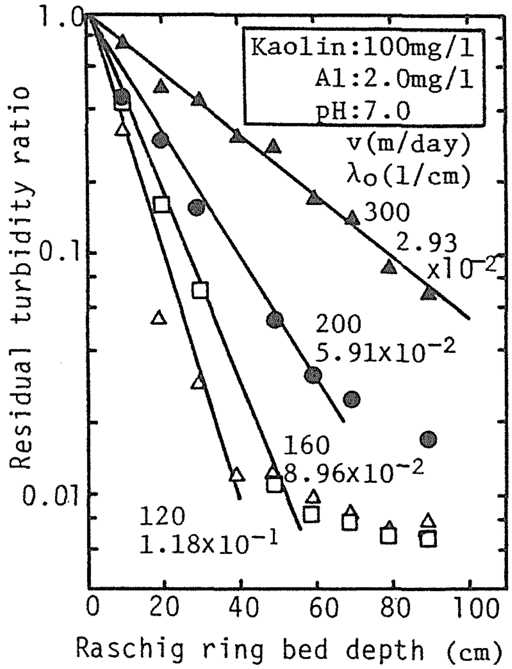

Fig. 10 Decrease of concentration with Raschig ring bed depth

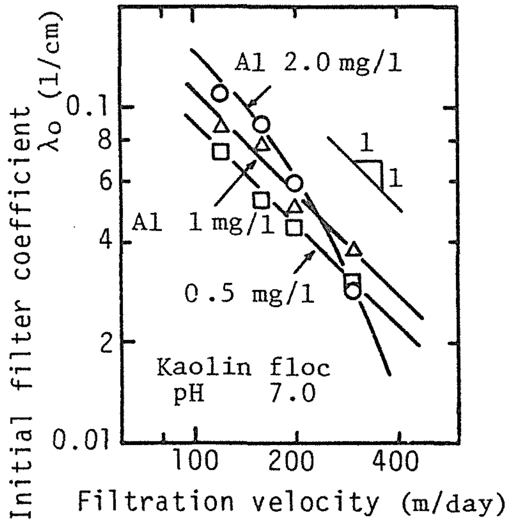

Fig. 11 Relationship between initial filter coefficient and filtration velocity (case of non-linear)

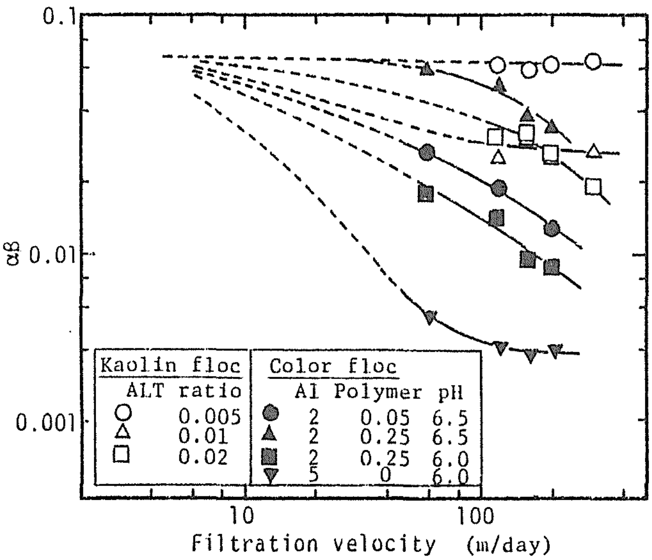

Fig. 12 Relationship between constants, $\alpha\beta$, of filter coefficient and filtration velocity

Eq. 10. Fig. 12 shows the intial coefficient λ_0 depends not only on filter composition and filtration rate but also depends on floc nature which is characterized by the coefficient α. The value α shows an increase of floc detachment by fluid shear. Therefore it will approach to $\alpha \fallingdotseq 1$ when the filtration rate approaches zero. By the assumption and converging tendendency of curves in Fig. 12, at low filtration rate region to the value of $\alpha\beta \fallingdotseq 0.09$, the coefficient β can be assumed to be about 0.09.

Eq. 10 shows that the thinner the thickness of a Raschig ring, (d_0-d_i), the higher the value of initial filter coefficient becomes. Therefore, a muck thinner packing materials are required to improve the efficiency of a packed bed as well as the capacity.

5. Progress of Filtration

The removal of suspension in the filter results in an accumulation of deposit on the upper faces of Raschig rings. The deposits increase the interstitial velocity and tend to decrease the filtration efficiency. The relationship is discussed in this section.

A material balance of a suspension and deposit through a filter layer of a thickness ΔL in a period Δt is given as Eq. 11 by taking a specific scouring rate, $Z(\sigma)$, of the deposit, σ, into account (Fig. 13). The specific scouring rate is assumed to be a function of the specific deposit.

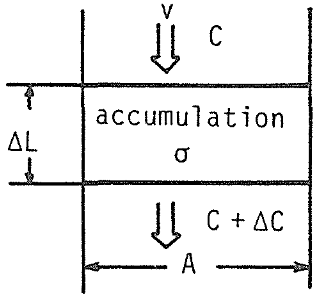

Fig. 13 Element of Raschig ring filter

$$Cv\Delta t-(C+\Delta C)v\Delta t=\lambda_0\Delta LCv\Delta t-Z(\sigma)\Delta L\Delta t \tag{11}$$

$$\partial C/\partial L=-\lambda_0 C+Z(\sigma)/v \tag{12}$$

If the removal and scour are independent from each other, Eq. 12 can be used. However, as Ives revealed,[2] the scour of deposits in filter pores are closely connected with the process of deposition. Therefore, Eq. 13 which is a modification of Eq. 12 is used as a basic equation for the discussion in this paper. By the equation, the observed phenomenon where $\partial C/\partial L=0$ when the incoming suspension concentration C_0 is zero can be described without contradiction.

$$\frac{\partial C}{\partial L}=-\lambda_0\left(1-\frac{Z(\sigma)/C}{v\lambda_0}\right)C \tag{13}$$

Calculation of the amount of specific scour in a unit time, $Z(\sigma)$, is performed by the Eq. 14 by using experimental data.

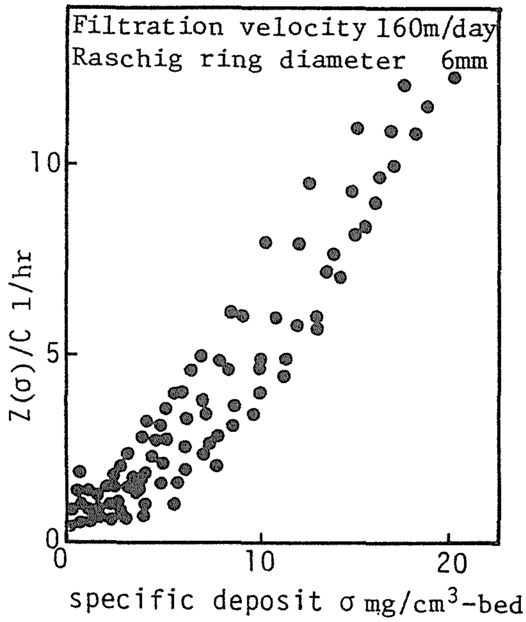

Fig. 14 Relationship between specific scouring and deposit

$$Z(\sigma) = (C_{out} - C_{in} \exp(-\lambda \Delta L))(v/\Delta L) \tag{14}$$

Fig. 14 shows that there is a straight line relationship between specific deposit, σ, and the modified specific scour function $Z(\sigma)/C$. Therefore, the relationship as shown in Eq. 15 hold.

$$Z(\sigma)/C = k\sigma \tag{15}$$

The value of k is evaluated by the inclination of the straight line in Fig. 14. Therefore, Eq. 13 can be rewritten as Eq. 16.

$$\partial C/\partial L = -\lambda_0(1 - k\sigma/v\lambda_0)C \tag{16}$$

At some time during a filter run, the amount of specific deposit reaches an ultimate value, $\sigma = \sigma_u$, at a point of filter bed, when the filter becomes ineffective, $dC/dL = 0$, at that point. From Eq. 16, the above mentioned phenomenon gives a relationship as shown in Eq. 17. By the equation, an ultimate specific deposit can be calculated when the values of λ_0 and k are known for the filter run.

$$\sigma_u = v\lambda_0/k \tag{17}$$

By way of Eq. 17, Eq. 16 is rewritten as Eq. 18 of Mintz type equation.

$$\partial C/\partial L = -\lambda_0(1 - \sigma/\sigma_u)C \tag{18}$$

The analytical solution of this type of equation is given as Eq. 19 for a steady state input for the filter[2]. An initial condition of $C = C_0 \exp(-\lambda_0 L)$ at $t = o$ and a boundary condition of $C=C_0$ at $L=0$ are used for the solution.

$$\frac{C}{C_0}=\frac{\exp(\lambda_0 v C_0 t/\sigma_u)}{\exp(\lambda_0 L)+\exp(\lambda_0 v C_0 t/\sigma_u)-1} \tag{19}$$

6. Notation

A :filter bed area (cm^2)
C :suspension concentration (mg/cm^3)
C_0 :raw water concentration (mg/cm^3)
L :filter depth (cm)
Lr :real distance of travel (cm)
R :total removal ratio (−)
S :settling area of a micro sedimentation tank (cm^2)
$Z(\sigma)$:specific scouring rate ($mg/cm^3/sec$)
a :volume of a micro sedimentation tank (cm^3)
d_0, d_i :outer and inner diameter of a Raschig ring (cm)
k :a coefficient ($cm^3/sec/mg$)
l :length of a Raschig ring (cm)
m :average number of micro sedimentation tanks in series (−)
q :rate of flow through a micro sedimentation tank (cm^3/sec)
r :removal efficiency of a micro sedimentation tank (−)
t :filtration time (sec)
v :superficial filtration velocity (cm/sec)
w :settling velocity of suspended particles (cm/sec)
w_0 :overflow rate of a micro sedimentation tank (cm/sec)
α :coefficient with respect to floc nature (−)
β :coefficient with respect to effective volume of filter bed (−)
ε :bed porosity (−)
θ :inclination of Raschig ring (−)
λ :filter coefficient (1/cm)
λ_0 :initial filter coefficient (1/cm)
σ :specific deposit (mg/cm^3)
σ_u :ultimate specific deposit (mg/cm^3)

7. Acknowledgement

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