활성슬러지 하수처리장의 주요 Process Control Variable 인 Sludge Age 와 Sludge Recycle 의 상호관계 규명

A Theoretical Relationship between Sludge Age and Sludge Recycle based on Mass Balances of Total Suspended Solids Contents in Conventional Activated Sludge Processes

고 광 백*
Ko, Kwang Baik
정 연 규**
Choung, Youn Kyoo

Abstract

Two rational formulae depicting the relationships between sludge ages and recycle flow rates have been developed to determine sludge wasting volumes at a particular sludge age.

A sensitivity analysis shows that the recycle ratio is the most important variable to be measured as accurately as possible in determining the sludge wasting volume to maintain a particular sludge age when the system is controlled by wasting recycled sludge. On the other hand, the final clarifier solids capturing capacity is the most important variable to be measured when the system is operated by wasting mixed liquor.

요 지

활성 슬러지 하수처리장의 주요 Process Control Variables 인 Sludge age 와 Sludge recycle 을 고려하여 폐슬러지의 유량(Q_w)을 효과적으로 결정하기 위한 두가지의 식이 개발되었다. 아울러 반송 슬러지의 일부를 폐슬러지로 배출할 경우에는 우선 순환비(R)를, 포기조내의 활성 슬러지의 일부를 폐슬러지로 배출할 경우에는 2 차침전지의 슬러지 침전효율(S_f)을 정확히 측정하여 개발된 식을 이용하면 폐슬러지의 유량을 용이하게 산정할 수 있다는 사실이 Sensitivity analysis 의 결과로 밝혀졌다.

1. Introduction

There are three major process control variables for a conventional activated sludge process: (1) sludge wasing rates, (2) return sludge flow rates, and (3) aeration rates. By evaluating the process and adjusting these rates, the wastewater treatment plant operator can control the process.

The sludge wasting rate and return slu-

---

* 정회원 · 충북대학교 공과대학 조교수, 환경공학과

** 정회원 · 연세대학교 공과대학 조교수, 토목공학과

dge flow rate are of special interest since these rates appear to be coupled for the purpose of process control. Provided that the influent wastewater does not contain toxic materials, the treatment plant is adequately designed and that the facility is maintained in a reasonable manner, the activated sludge process can and should produce an effluent low in BOD and suspended solids using a wide variety of designs and equipment.

The principal purpose of this study is to develop a rational relationship between sludge wasting volumes and recycle flow rates at a particular sludge age. The relationship will be formulated based on mass balances of total suspended solids contents in a conventional activated sludge treatment system. A sensitivity analysis will be conducted to delineate the most important variables to be measured in determining the wasting sludge flow rate.

2. Process Evaluation

Two conventional activated sludge treatment systems have been chosen. Each of them has a single aeration basin. The one is the system where the waste sludge is withdrawn from recycle lines. The other is the system where the mixed liquor is discharged to a thickener and the overflow(or underflow in the case of a flotation thickener) is returned to the aeration basin.

Both of the systems are assumed to be well-opperated at steady state conditions. The mixed liquor in the aeration basin is completely mixed with the sludge recycled. The schematic configurations of theactivated sludge systems used in this study are shown in Figure 1 and 2, respectively. The notation is also shown. Primary treatment and disinfection are not included in this research.

Notation

The following symbols are defined as shown below. The rest of the symbols which do not appear here are explained in the text where they first appear.

Q=flow rate, L/day

X=concentration of total suspended solids, mg of TSS/L

A, F and T denote the aeration basin, final clarifier and thickener in Figure 1 or 2, respectively.

Indices

The following indices are used exclusively throughout the text.

i=effluent from primary clarifier to aeration basin

a=effluent from aeration basin to final clarifier

r=recycle flow

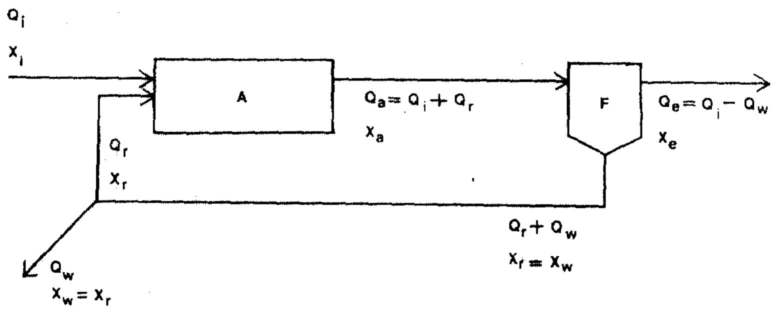

Fig. 1. A Conventional Activated Sludge Treatment System Controlled by Wasting Recycled Sludge

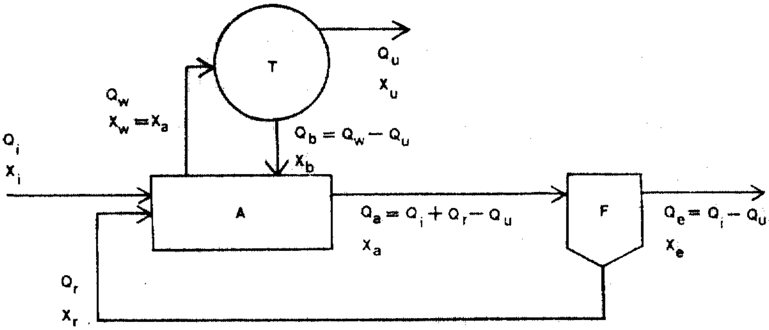

Fig. 2. A Conventional Activated Sludge Treatment System Operated by Wasting Mixed Liquor

w=waste sludge flow from returned sludge line or from aeration basin
e=final clarifier effluent
b=overflow from gravity thickener(or underfolw in the case of a flotaion thickener)
u=thickened sludge flow

The completely mixed continuous flow biological reactor with the sludge recycled is assumed to be operated with a fixed constant ratio maintained between the rate at which nutrients are utilized and the rate of bacterial growth. The theory and operation of continuous systems has been reviewed by many publications and is not discussed here.

2.1 Wasting of Return Sludge

For the system and notation of Figure 1, a portion of the returned sludge must be wasted in order to maintain a particular sludge age. The mean solids residence time or sludge age, θ°, can be defined as

$$\theta_c = \frac{VX_m}{Q_w X_w + Q_m X_m} \qquad \text{Eq. 1}$$

where V is the volume of the aeration basin in liters. The mass of solids in a final clarifier may not be taken into account if it does not represent a significant fraction of the total suspended solids in the system.

Define that S_f is the fraction of the total suspended solids settled and consequently returned into the recycle line. S_f is then expressed as

$$S_f = \frac{Q_r X_r + Q_w X_w}{Q_m X_m} \qquad \text{Eq. 2}$$

Considering the relation of Q_m $X_m = (1 - S_f) Q_m X_m$, substitute it for $Q_m X_m$ in Eq. 1. θ_c is then

$$\theta_c = \frac{VX_m}{Q_w X_w + (1 - S_f) Q_m X_m} \qquad \text{Eq. 3}$$

From the definition of S_f in Eq. 2,

$$Q_m X_m = \frac{Q_r X_r + Q_w X_w}{S_f} \qquad \text{Eq. 4}$$

Substituting Eq. 4 for $Q_m X_m$ in Eq. 3 under the assumption of $X_w = X_r$, Eq. 3 is modified to

$$\frac{Q_w}{V} = \frac{X_m S_r}{\theta^{\circ} X_r} - \frac{(1 - S_f) Q_r}{V} \qquad \text{Eq. 5}$$

The mass balance for total suspended solids in the aeration basin can be written as

$$Q_i X_i + Q_r X_r = Q_m X_m \qquad \text{Eq. 6}$$

Using the definition of $R = Q_r / Q_i$ and assuming that X_i can be negligible, X_r can be expressed as

$$X_r = \frac{(1 + R) X_m}{R} \qquad \text{Eq. 7}$$

Substituting Eq. 7 for X_m in Eq. 5, Q_w / V can be formulated as

$$\frac{Q_w}{V} = R\left(\frac{S_f}{(1 + R)} \frac{1}{\theta_c} - \frac{(1 - S_f)}{t_o}\right) \text{Eq. 8}$$

where $t_o (= V / Q_i)$ is the hydraulic retention time of wastewater in the aeration basin in days(based on the primary effluent flow only). As shown in Eq. 8, the daily volume of the recycled sludge to be wasted can be set once the values for recycle ratio, R, final clarifer solids capturing capacity, S_f, and hydraulic retention time, t_0, are chosen.

2.2 Wasting of Mixed Liquor

For the system shown in Figure 2, a portion of the mixed liquor should be discharged into a thickener to maintain a particular sludge age. The mean solids retention time, θ_c, may be defined as

$$\theta' = \frac{VX_m}{Q_w X_w + Q_m X_m - Q_b X_b} \qquad \text{Eq. 9}$$

Define that S_c is the thickener solids capturing capacity. S_c then expressed as

$$S_c = \frac{Q_u X_u}{Q_w X_w} \qquad \text{Eq. 10}$$

Considering the relation of $Q_b X_b = (1-S_c) Q_w X_w$ and substituting it for $Q_b X_b$ in Eq. 9, θ_c is then reduced to

$$\theta_c = \frac{VX_m}{S_c Q_w X_w + Q_m X_m} \qquad \text{Eq. 11}$$

The equation above is the identical one with the formula proposed by Hartley (1985). He has also developed another formula to determine the daily wasting volume of mixed liquor at a particular sludge age with effluent loss of suspended solids and thickener capturing capacity. However, he did not try to express θ_c in terms of recycle flow rates.

Define that S_f is the fraction of the total suspended solids returned into the aeration basin. It may then be given as

$$S_f = \frac{Q_r X_r}{Q_m X_m} \qquad \text{Eq. 12}$$

Regarding the mass balance of total suspended solids in the final clarifier, $Q_m X_m$ in Eq. 11 can be expressed as

$$Q_m X_m = \frac{(1-S_f) Q_r X_r}{S_f} \qquad \text{Eq. 13}$$

Substituting Eq. 13 for $Q_m X_m$ in Eq. 11 with the relation of $Q_r = RQ_i$,

$$\frac{Q_w}{V} = \frac{X_m}{\theta_c S_c X_m} - \frac{(1-S_f) RQ_i X_r}{V S_f S_c X_w} \qquad \text{Eq. 14}$$

Since the waste sludge is directly withdrawn from the aeration basin, X_w is equal to X_m. Q_w/V in Eq. 14 is finally ended up to

$$\frac{Q_w}{V} = \frac{1}{S_c}\left(\frac{1}{\theta'} - \frac{(1-S_f)}{S_f} \frac{RQ_i X_r}{VX_m}\right) \qquad \text{Eq. 15}$$

3. Discussion of Results

3.1 Wasting of Return Sludge

A sensitivity analysis has been performed by simulating the proposed formula, Eq. 8, to investigate how the response, Q_w/V, is affected by a given set of solids retention times over some specified range of interest. 4 and 8 hour hydraulic retention times of wastewater in the aeration basin were chosen, which are fallen within a typical range for a conventional activated sludge process (Metcalf and Eddy, Inc., 1979). The recycle ratios ranged from 0.25 to 0.5(Metcalf and Eddy, Inc., 1979). The typical solids capturing capacity was assumed to be between 0.992 and 0.995 in the final clarifier.

As shown in Figure 3, the portion of the recycled sludge to be wasted should be reduced as the sludge age increases. At a particullar sludge age, the sludge wasting volume must be increased as the recycle ratio increases. The sensitivity analysis shows that small changes in the recycle ratio caused relatively large changes in the daily volume of the recycled sludge to be wasted. Thus, the recycle ratio, in addition to total suspended solids contents in wastewaster, is the most important variable to be obtained as accurately as possible in determining the sludge wasting volume to maintain a particular sludge age.

The effect of the solids capturing capacity and hydraulic retention time on the response, Q_w/V, is relatively minor in determining the sludge wasting volume in this system.

3.2 Wasting of Mixed Liquor

The oter sensitivity analysis has been conducted with Eq. 15 to see how the response, Q_w/V, is affected by a given set of solids retention times over the specifed region of final clarifier solids capturing capacity, thickener solids capturing capacity and daily volume of recyled flow. As used in the previous analysis, the solids capturing capacity in the final clarifier was assumed to be between 0.992 and 0.995. A well-operated gravity thickener has typically a solids recovery of about 95%(Vesilind, 1980). The solids recovery in a flotation thickener could be increased from 85% to 98 or 99% with polyelectrolytes as flotation aids(Metcal and Eddy, Inc., 1979).

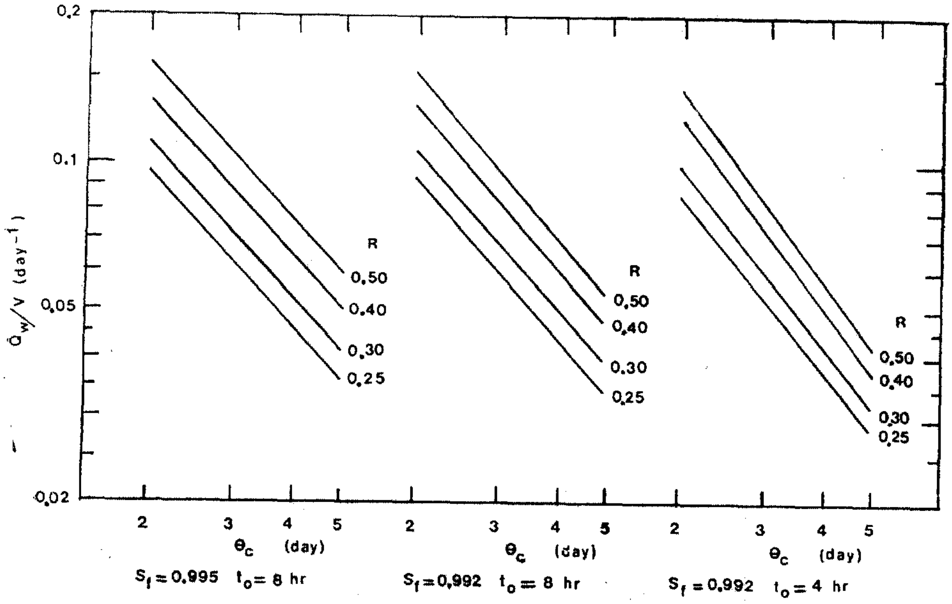

Fig. 3. Determination of Recycled Sludge Wasting Volume

The results are shown in Figure 4. The fraction of the mixed liquor to be wasted should be reduced as the sludge age increases. At a particular sludge age, the sludge wasting must be increased as the recycled mass rate per a unit mass of total suspended solids in the aeration basin decreases. The sensitivity analysis indicates that the final clarifier solids capturing capacity is the most important variable to be measured as precisely as possible in determining the sludge wasting volume.

To maintain a particular sludge age, the same mass of solids must be wasted whether the system is controlled on the basis of mixed liquor or return sludge. An interesting comparison can be made between those two systems shown in Figure 1 and 2. When the return sludge is wasted, the wasting volume is less by a factor of about 3 or 4 because of higher total suspended solids contents in the recycle line.

When the sludge age is preset, the daily volume to be wasted can be determined

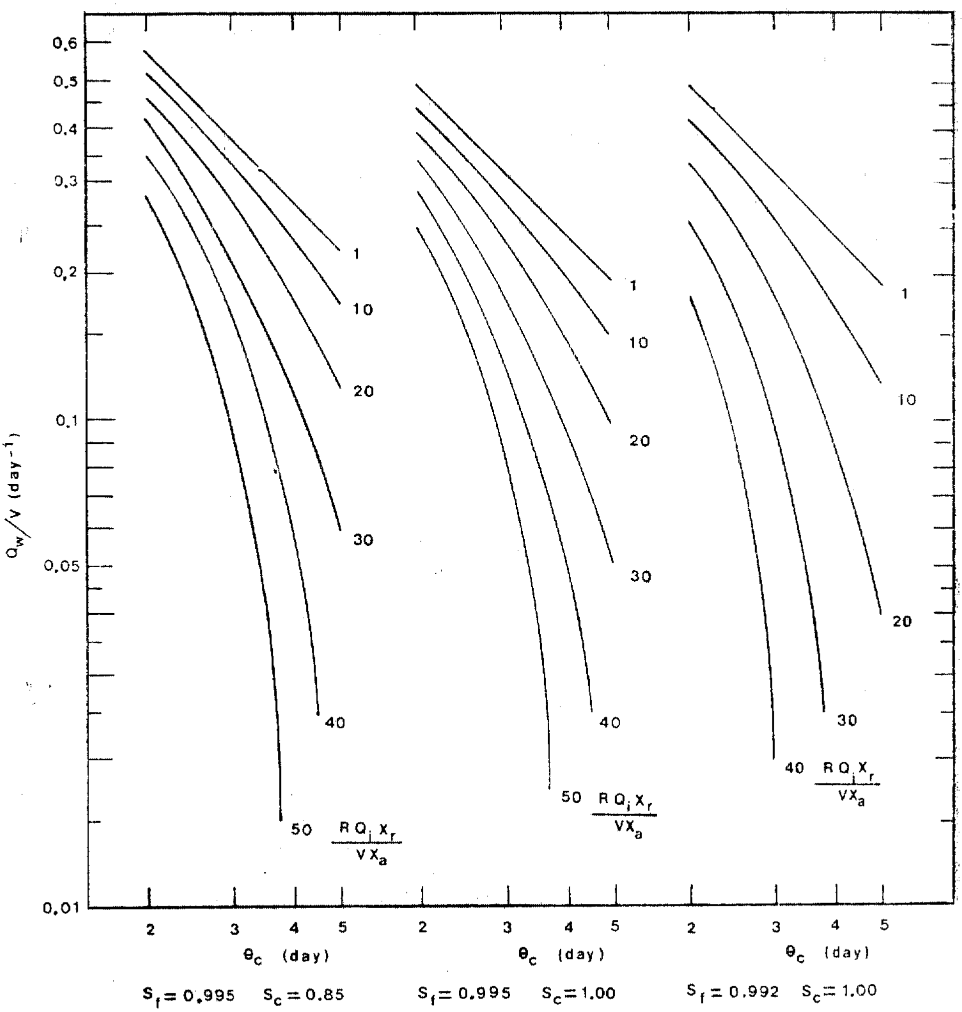

Fig. 4. Determination of Mixed Liquor Wasting Volume

using Figure 3 or 4. In other words, the precise sludge age over a period can be checked, if desired, using those two figures. The relevant data to the suspended solids concentrations are also needed to follow this procedure.

4. Conclusions

The following conclusions can be drawn:

(1) The sludge wasting volume at a particular sludge age can be accurately determined using the proposed formulae shown in Eq. 8 or 15, whether a conventional activated sludge system is consrolled on the basis of wasting recycled sludge or mixed liquor.

(2) The recycle ratio is the most important variable to be measured as accurately

as possible in determining the sludge wasting volume, when the system is controlled by wasting recycled sludge.

(3) The final clarifier solids capturing capacity is the most important variable to be measured as accurately as possible in presetting the sludge wasting volume, when the system is operated by wasting mixed liquor.

(4) When the return sludge is wasted, the wasting volume is less by a factor of about 3 or 4 due to higher solids contents in the recycle line over the specifieed range of variebles investigated in this study. The facror indicates a coincidence with the common agreement that wasting volume can be significantly reduced when the waste sludge is withdrawn from recycle lines rather than directly from aeration basin.

Experimental verification of the proposed formulae is now carried out at a conventional activated sludge wastewater treatment plant, and the results will be also presented in the upcoming issue.

References

1. Hartley, K.J., *Operating the Activated Sludge Process*, Gutteridge Haskins and Davey, Pty, Ltd., Brisbane, Australia (1985).
2. Metcalf and Eddy, Inc., *Wastewater Engineering: Treatment, Disposal and Reuse*, McGraw-Hill, New York, N,Y, (1979).
3. Vesilind, P.A., *Treatment and Disposal of Wastewater Sludge*, Ann Arbor Science, Ann Arbor, Michigan (1980).

(接受：1988. 1. 8)