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Technical note

Parameters to characterize the internal recirculation of an oxidation ditch

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Mixed liquor circulates ceaselessly in the closed-loop corridor in an oxidation ditch (OD), which is significantly different from other wastewater treatment processes. The internal recirculation ratio (IRR), i.e., the ratio between circulation flow rate (Q_{CC}) and influent flow rate (Q_{In}), and the circulatory period (T), i.e. the time consumed for the mixed liquor to complete one lap in the circular corridor, was used to quantify the internal recirculation characteristics of the OD system. In order to elucidate the characteristics and applicability of IRR and T, this study obtained the numerical relationship between IRR and T by formula derivation. It also discusses the factors influencing IRR and analyses the applications of IRR and T. The results showed that IRR = Q_{CC}/Q_{In} = HRT/T = HRT • IRF (HRT = hydraulic retention time of the mixed liquor in the circular corridor; IRF = internal recirculation frequency). Moreover, three kinds of parameters had an effect on IRR: Q_{In}; reactor dimensions, i.e., length (L_{mid}), width (B), and height (H) of the circular corridor; and horizontal velocity of the mixed liquor in the circular corridor (v). Q_{In} changed IRR by altering HRT. However, B, H, L_{mid}, and v changed IRR by altering IRF and T. Furthermore, the same IRR corresponded to many different HRT and IRF. Therefore, when Q_{In} and Q_{CC} varied in the OD system, using HRT and IRF to evaluate the variation of Q_{In} and Q_{CC}, respectively, was better than using IRR to evaluate their synthetical variation. IRF and T were useful for directly and precisely characterizing the circulation speed and circulation flow rate in the circular corridor, while IRR was more useful for evaluating the dilution effect of reflux on influent.

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INTRODUCTION

The oxidation ditch (OD) is a kind of sewage treatment technology widely used worldwide in wastewater treatment plants (WWTPs) (Wang et al., 2019a). The mixed liquor circulates ceaselessly in closed-loop corridors of the OD (Izadi et al. 2020), which is significantly different from other wastewater treatment processes. However, as the initial OD is only used for organic matter removal (Izadi et al., 2020), without consideration for nitrogen and phosphorus removal, dissolved oxygen (DO) is always uniformly and sufficiently supplied, so internal recirculation characteristics are never mentioned or used at the beginning of an OD application.

As stricter environmental protection requirements emerge, simultaneous nitrogen, phosphorus, and organic matter removal is required. Therefore, the OD technology is being developed continuously. By setting an anaerobic zone upstream from the circular corridor, biological phosphorus removal can be accomplished (Insel et al., 2005). Adjusting aeration devices in the circular corridor, spatial interval distribution of the aerobic and the anoxic zone can be performed, organic matter oxidation and nitrification can be achieved in the aerobic zone, and denitrification can be fulfilled in the anoxic zone. Optimization of the aerator operation (Insel et al., 2005; Alaya et al., 2010; Wei et al., 2016) and aeration mode (Chen et al., 2012; Guo et al., 2013; Zhou et al., 2015; Ratanatamskul and Kongwong, 2017) have been widely studied to improve nutrient removal efficiencies in the OD system.

A few researchers also began to study the internal recirculation characteristics of the OD system. The internal recirculation ratio (IRR), namely the ratio of circulation flow rate to influent flow rate in the circular corridor (Insel et al., 2005; Tang and Huang, 2006; Guo et al., 2013; Cakirgöz et al., 2021), is usually mentioned or used to study the influence of internal recirculation characteristics on nutrient removal performance of OD systems. For instance, Insel et al. (2005) mentioned that IRR was adjusted to 100, characterizing a high internal flow rate in an OD system. Guo et al. (2013) considered that a large IRR caused lower substrate concentration and denitrification rates. Tang and Huang (2006) calculated the required IRR for the effluent COD concentration to reach the expected results. Abusam et al. (2002) mentioned that the variation of horizontal velocity in the range of 0.25 to 0.60 m/s led the IRR to change from 60 to 120. Abusam et al. (2002) also considered that a high IRR affected the DO profile along the circular corridor, which consequently affected nutrient removal performance. According to the influent ammonia concentration and the expected effluent nitrate concentration, Argaman (1984) obtained a simplified formula of IRR in OD based on the requirement of nitrified mixed liquor needed to return to the anoxic zone during a traditional denitrification process. The internal recirculation period (T), i.e., the time taken for the mixed liquor to complete one lap in the circular corridor (Wang et al., 2019b), is another parameter that can characterize the internal recirculation of an OD system, and was occasionally used. For instance, based on the oxygen supply and demand balance and the invariable number of aerators, Chen et al. (2012) studied the effectiveness of a dual DO control technology in OD systems when T varies with the recirculation speed.

However, the numerical relationship between IRR and *T* has not been studied, and the characteristics and applications of IRR and *T* have not been considered either.

Therefore, in order to elucidate the characteristics and applicability of IRR and *T*, the numerical relationship between IRR and *T*, and the physical meanings of those parameters, were obtained by formula derivation in this study. Moreover, the influencing factors which could change IRR and *T* are discussed. Finally, the unfitness of IRR use was illustrated by an example.

Numerical relationship between IRR and T

As shown in Fig. 1, the arc part, at both ends of the circular corridor, was assumed to be a semicircle with a radius of *B*. Therefore, Eq. 1 was obtained:

$$\begin{aligned} V &= L_{mid\_line}\cdot B\cdot H+\pi\cdot B^2\cdot H = L_{mid\_line}\cdot B\cdot H+2\cdot\pi\cdot 0.5B\cdot B\cdot H \\ &= L_{mid\_line}\cdot B\cdot H+L_{mid\_circle}\cdot B\cdot H = L_{mid}\cdot B\cdot H \end{aligned} \tag{1}$$

where *V* is the effective volume of the circular corridor (m^3); *B* is the width of the circular corridor (m); *H* is the effective water depth of the circular corridor (m); L_{mid} is the midline perimeter of the circular corridor, namely the length of the broken line shown in Fig. 1 (m); $L_{\text{mid\_line}}$ is the straight-line segments of the midline perimeter (m); and $L_{\text{mid\_circle}}$ is the round segments of the midline perimeter (m).

The original definition of IRR in an oxidation ditch is the ratio of circulation flow rate to influent flow rate (Insel et al., 2005; Tang and Huang, 2006; Guo et al., 2013; Cakirgöz et al., 2021), so IRR could be described as Eq. 2:

$$\text{IRR}=\frac{Q_{\text{cc}}}{Q_{\text{In}}}=\frac{B\cdot H\cdot v}{Q_{\text{In}}} \tag{2}$$

where Q_{CC} is the circulation flow rate in the circular corridor (m^3/d); Q_{In} is the inflow rate of the OD system (m^3/d); and *v* is the horizontal velocity of the mixed liquor in the circular corridor (m/s).

Considering Eq. 3:

$$\text{HRT}=\frac{V}{Q_{\text{In}}}=\frac{L_{mid}\cdot B\cdot H}{Q_{\text{In}}} \tag{3}$$

where HRT is the hydraulic retention time of the mixed liquor in the circular corridor (Tchobanoglous et al., 2003) (h); Eq. 3 could be rewritten as:

$$\frac{B\cdot H}{Q_{\text{In}}}=\frac{\text{HRT}}{L_{\text{mid}}} \tag{4}$$

Placing Eq. 4 into Eq. 2:

$$\text{IRR}=\frac{\text{HRT}\cdot v}{L_{\text{mid}}} \tag{5}$$

Because:

$$T=\frac{V}{Q_{\text{cc}}}=\frac{L_{mid}}{v} \tag{6}$$

where *T* is the circulation period, namely the time consumed for the mixed liquor to complete one lap in the circular corridor (h) (Wang et al., 2019b).

According to Wang et al. (2019b):

$$\text{IRF}=\frac{1}{T} \tag{7}$$

where IRF is the internal recirculation frequency, namely the laps performed by the mixed liquor in the circular corridor during 1 h (h^{-1}) (Wang et al., 2019b).

Inserting Eq. 6 and Eq. 7 into Eq. 5:

$$\text{IRR}=\frac{\text{HRT}}{T}=\text{HRT}\cdot\text{IRF} \tag{8}$$

Therefore, another physical meaning for IRR was obtained, namely the number of laps performed by the mixed liquor in the circular corridor during the hydraulic retention time.

V and L_{mid} were always fixed, and Q_{In} and Q_{CC} usually changed in the established full-scale OD system. So it can be known, from Eqs 6 and 7, that IRF and *T* directly and precisely characterized the circulation speed and circulation flow rate in the circular corridor. It can be concluded, from Eq. 2, that IRR didn't realize the role of IRF and *T* because of the simultaneous variation of Q_{In}. Nevertheless, IRR was still more useful for evaluating the dilution effect of reflux on influent.

Analysis of influencing factors

According to the formulas deduced above, the physical aspects of IRR, IRF, and *T*, and their influencing factors, are summarized in Fig. 2.

It could be summarized from Fig. 2 that three kinds of parameters have an effect on IRR. One is the influent flow rate (Q_{In}); the other is the dimensions of the circular corridor (*B*, *H*, and L_{mid}); and the third is the horizontal velocity of the mixed liquor in the circular corridor (*v*). The independent effects of the above influencing factors on HRT, IRF, *T*, and IRR under different conditions are listed in Table 1.

As shown in Table 1, for the established OD system, with variation of Q_{In}, IRF and *T* do not change – only HRT and IRR change. Moreover, the numerical change of IRR was actually caused by the change of HRT, according to Eq. 8. Therefore, when Q_{In} varies, HRT is enough to evaluate the variation in nutrient removal performance of an OD system.

During the design of the OD system, the dimensions of the circular corridor (*B*, *H*, and L_{mid}) influenced the internal recirculation characteristics, which affected IRF, *T* and IRR. For the established OD system, the cross-sectional area (*B*•*H*) and the horizontal velocity of the mixed liquor in the circular corridor (*v*) also affected the internal recirculation characteristics, which influenced IRF, *T* and IRR as well. Under these circumstances, the quantitative change in IRR was actually caused by the change in IRF and *T*, according to Eq. 8, so IRF or *T* were enough to evaluate the variation in internal recirculation characteristics and nutrient removal performance in the OD system.

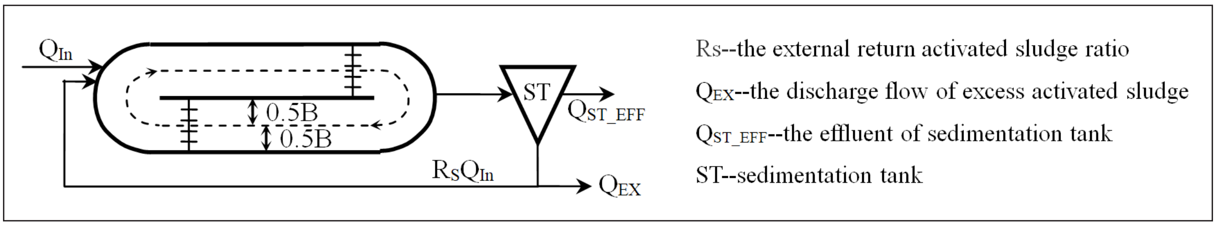

Figure 1. Diagram of an oxidation ditch (OD) for formula derivation

Table 1. Independent effects of influencing factors on HRT, IRF, *T* and IRR

Influencing factors and possible applications		HRT	IRF, *T*	IRR
For the established OD system, variation of inflow rate	Q_{In}	√	×	√
For the established OD system, the change of cross-sectional area in the circular corridor can improve the flow of the mixed liquor by adding or rebuilding a diversion wall. Alternatively, an intra-channel clarifier can be made by setting up a sedimentation zone. At that point, **a change in the cross-sectional area would not change L_{mid}.**	$B \cdot H$	×	√	√
During the design of the OD system, according to the inflow rate and raw wastewater quality, the loading rate and HRT are usually determined first, then *V* can be confirmed. According to the fixed *V*, L_{mid} can be selected first, and then *B* and *H* are obtained. Or, according to the fixed *V*, *B* and *H* are selected first, then L_{mid} is obtained. When *V* is fixed, **each L_{mid} value corresponds to a different *B* and *H*.**	*B*, *H*, L_{mid}	×	√	√
For the established OD system, variation of horizontal velocity of mixed liquor in the circular corridor	*v*	×	√	√

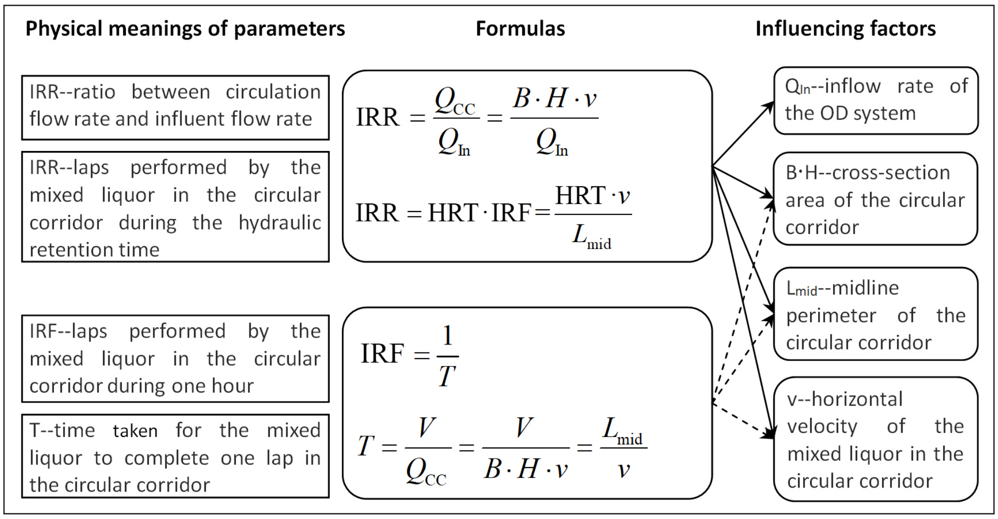

Figure 2. Physical meanings and influencing factors of IRR, IRF, and *T*

Illustration of IRR's unfitness

In a full-scale WWTP with an OD system, Q_{In} and Q_{CC} always change. However, for the established OD system in which $B \cdot H$ and L_{mid} are fixed, the variation of Q_{CC} is only caused by the change of *v*. That is, even if Q_{In} remains fixed, Q_{CC} still changes if *v* varies. When Q_{In} varies, Q_{CC} remains constant if *v* remains fixed. Therefore, the following three situations were considered: Q_{In} and Q_{CC} varied at the same time; only Q_{In} changed; and only Q_{CC} changed.

Simultaneous variation of Q_{In} and Q_{CC}

The horizontal velocity in the OD system varies between 0.20 and 0.70 m/s, and the typical values are between 0.25 and 0.35 m/s (Liu et al., 2013). Therefore, it could be assumed that Q_{In} fluctuated to $1.5Q_{In}$ and $2Q_{In}$, at the same time that Q_{CC} changed to $1.5Q_{CC}$ and $2Q_{CC}$. Therefore, IRR did not change because: IRR $= Q_{In}/Q_{CC} = 1.5Q_{In}/1.5Q_{CC} = 2Q_{In}/2Q_{CC}$. Nevertheless, HRT varied to 0.67 HRT and 0.5 HRT, and IRF varied to 1.5 IRF and 2 IRF. Thus, under these circumstances, it could not be easily concluded that the nutrient removal performance of the OD did not change, similarly to the IRR.

Single variation of Q_{In}

With a single change of Q_{In}, both HRT and IRR varied. Therefore, HRT was enough to evaluate the variation of nutrient removal performance of the OD system.

Single variation of Q_{CC}

With a single change of Q_{CC}, both IRF and IRR varied. Therefore, IRF or *T* were enough to evaluate the variation of internal recirculation characteristics and nutrient removal performance of the OD system.

It can be concluded that the same IRR could correspond to many different HRT and IRF. So, when Q_{In} and Q_{CC} varied at the same time, using HRT and IRF to evaluate the Q_{In} and Q_{CC} variation, respectively, was better than using IRR to evaluate their synthetical variation. For the same reason, when Q_{In} or Q_{CC} varied separately, using HRT or IRF to evaluate Q_{In} and Q_{CC} variation, respectively, was better than using IRR.

CONCLUSION

The original definition of IRR in an oxidation ditch is the ratio of circulation flow rate to influent flow rate. By formulaic deduction, IRR $= Q_{CC}/Q_{In} =$ HRT/*T* = HRT•IRF. Based on this, a second physical meaning of IRR was obtained, which was the number of laps performed by the mixed liquor in the circular corridor during the hydraulic retention time.

Three kinds of parameters had an effect on IRR. The influent flow rate (Q_{In}), the dimensions of the circular corridor (*B*, *H* and L_{mid}), and the horizontal velocity of the mixed liquor in the circular corridor (*v*). Q_{In} changed IRR by altering HRT, but *B*, *H*, L_{mid}, and *v* changed IRR by altering IRF and *T*. Moreover, the same IRR could correspond to many different HRT and IRF. Therefore, when Q_{In} and Q_{CC} varied in the OD system, using HRT and IRF to evaluate the variation of Q_{In} and Q_{CC}, respectively, was better than using IRR to evaluate their synthetical variation.

IRF and *T* were useful for directly and precisely characterizing the circulation speed and circulation flow rate in the circular corridor. However, IRR didn't realize the role of IRF and *T*. Nevertheless, IRR was more useful for evaluating the dilution effect of reflux on influent.

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