DRAINAGE SERVICES DEPARTMENT

FINAL REPORT

PROTOTYPE STUDY TO ASSESS THE PERFORMANCE OF USING HYBRID REACTOR TO TREAT CEPT EFFLUENT

(Contract No.: DEMP10/04)

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EXECUTIVE SUMMARY

1. Background

1.1 This is the final report for the "Prototype Study to Assess the Performance of Using Hybrid Reactor to Treat CEPT[1] Effluent" conducted by the Environmental Management Division of Hong Kong Productivity Council (HKPC) for the Research & Development Team of Electrical & Mechanical Projects Division, the Drainage Services Department (DSD) of the Government of the HKSAR.

1.2 The objectives of the study are:

(a) To conduct a systematic bench-scale study to assess the cost effectiveness of using hybrid reactor and Moving Bed Bioreactor (MBBR) to treat the CEPT effluent and raw sewage at the Stonecutters Island Sewage Treatment Works (SCISTW);

(b) To assess the maximum organic loading rate (OLR) that can be accepted by the hybrid reactor and MBBR reactor to meet generic effluent criteria (BOD_5[2] $\leq$ 20 mg/L, TSS[3] $\leq$ 30 mg/L, ammonia-nitrogen $\leq$ 5 mg/L for winter temperature) for both raw sewage and CEPT effluent;

(c) To assess the denitrification performance of the Integrated Fixed-film Activated Sludge (IFAS) system and MBBR system in MLE[4] configuration and to compare it with the reference criterion of total nitrogen (TN) $\leq$ 20 mg/L which will be considered in future;

(d) To estimate the overall sizes of the hybrid and MBBR reactor systems for SCISTW for illustration.

1.3 Hybrid bioreactor system (also known as Integrated Fixed-film Activated Sludge, IFAS) is a modified activated sludge process and it consists of both suspended and attached biomass (on carriers) in a reactor. It has been reported that such hybrid bioreactor systems have superior capability over the ordinary activated sludge process such as high volumetric loading, stable treatment performance, short sludge age (SRT), short hydraulic retention time (HRT) and less space requirement.

1.4 As land is scarce in Hong Kong, it is desirable to investigate compact biological methods other than the activated sludge process. Furthermore, it is understood that the CEPT effluent from SCISTW may need further treatment in order to meet the Water Quality Objectives (WQO) in the future. DSD therefore commissioned HKPC to evaluate the applicability and performance of hybrid bioreactor system treating CEPT effluent through a pilot trial at SCISTW. The trial was conducted from 12 October 2010 to 28 June 2012.

[1] CEPT stands for Chemically Enhanced Primary Treatment.
[2] BOD_5 stands for 5-day Biochemical Oxygen Demand
[3] TSS stands for Total Suspended Solids
[4] MLE stands for Modified Ludzack-Ettinger

2. Study Programme

2.1 Originally, a 6-phase prototype study program was designed to understand and compare the capability of two hybrid treatment processes, the MLE system and the fully aerated reactor (FA) system on CEPT effluent. After completing Phases 1 and 2 of this study, it was found that FA process was not suitable to treat CEPT effluent due to the low effluent pH as a result of nitrification. Subsequently, an extended prototype study was introduced. An MBBR system with MLE configuration replaced the hybrid FA system, the original hybrid MLE system was renamed as IFAS (MLE) system for clarity. The study programme was thus revised to Phase 1, Phase 2, Phase A and Phase B so as to assess the performance of FA, IFAS and MBBR systems on treating raw sewage and CEPT effluent.

2.2 The hybrid systems contained both suspended biomass and carriers for attached-growth micro-organisms, but there was no carrier in the anoxic zone of the IFAS reactor. The denitrification was carried out by MLSS[5] only. On the other hand, there was no sludge return in the MBBR reactor and the denitrification was accomplished by the carriers in the anoxic zone. The anoxic zones occupied 30% and 40% of the total volume of the IFAS and MBBR biological reactors respectively.

2.3 The media fill ratio in the FA reactor and the aerobic zone of the IFAS reactor was 60% by volume. The media fill ratio was further increased to 65% in the aerobic zone of the MBBR reactor. All the above configurations required good supply of coarse air bubbles for mixing and had no operational problems. The media fill ratio was 50% in the anoxic zone of the MBBR reactor as recommended by the media supplier (AnoxKalnes) and complete mechanical mixing of the carriers was easily achieved.

3. Comparison between Hybrid FA and Hybrid MLE systems

3.1 The biomass on the carriers in both hybrid reactors was cultivated under the most favorable operating conditions in Phase 1. The COD and ammonia removal performance was satisfactory. Then the effect of reducing sludge age on the treatment performance of CEPT effluent was evaluated in Phase 2 Part 1−3 at 23ºC. All the generic effluent criteria were fulfilled in both reactors, despite sludge age as short as 2 days and at very low MLSS. However, it was found that effluent pH was usually below 6.0 in the FA system. The results of ammonia oxidation rate tests demonstrated that the majority of nitrification was contributed by attached biomass on carriers.

3.2 Operation parameters in Phase 2 are summarized:

Study Phase		Phase 2 Part 1	Phase 2 Part 2	Phase 2 Part 3	Phase 2 Part 4
Influent		CEPT Effluent			Raw Sewage
Water Temperature (ºC)		23			
Designated SRT (day)		10	5	2	N/A
HRT (hr)	FA	6.0 – 7.4	6.2 – 6.6	6.2 – 7.2	6.1 – 6.7
	IFAS	6.0 – 6.7	6.2 – 6.8	6.1 – 6.9	6.1 – 6.8

5 MLSS stands for Mixed Liquor Suspended Solids

3.3 The treatment performance on raw sewage was then evaluated in Phase 2 Part 4 with MLSS controlled at about 900 mg/L. The 'MLSS-controlled' approach was used in the subsequent phases for the reactor systems. Since the raw sewage has a higher alkalinity than CEPT effluent, the pH of both reactors were higher than those in Phase 2 Part 1−3.

3.4 After completion of Phases 1 and 2, some important issues revealed:

(i) Hybrid FA system without pre-denitrification was considered *not suitable* to treat CEPT effluent due to the low effluent pH after nitrification;

(ii) Hybrid MLE (also called IFAS in later study) system with pre-denitrification had advantages over FA process in terms of effective total nitrogen removal, supplementation in alkalinity consumption and oxygen requirement;

(iii) The treatment performance of hybrid MLE process on treating *raw sewage* was satisfactory and worth more study;

(iv) Shortcoming of hybrid MLE process − it is expected that when the reactor MLSS is further reduced at shorter sludge age, pre-denitrification performance may deteriorate.

4. Comparison between IFAS and MBBR systems in MLE configuration

4.1 An extended prototype study was introduced. A pure attached-growth system with pre-denitrification and nitrification using the MBBR technology has replaced FA. MBBR system would be compared with the IFAS system in the subsequent Phases A and B. Both IFAS and MBBR systems are in MLE configuration with anoxic and aerobic zones, and internal recycle. Unlike IFAS, denitrification in MBBR would rely on attached biomass on carriers in the anoxic zone.

4.2 Operating parameters in Phases A and B are summarized:

Study Phase	A1	A2	A3	A4	B1	B2	B3 (Trial 1)	B3 (Trial 2)	B4 (Trial 1)	B4 (Trial 2)
Influent	Raw Sewage				CEPT Effluent					
Water Temp. (ºC)	23			18	23				18	
MBBR HRT (hr)	6.2 – 6.8	4.0 – 4.7	4.6 – 6.0	7.2 – 7.8	6.0 – 6.3	4.2 – 5.6	3.8– 4.1	3.5 – 3.6	4.5 – 4.9	4.2 – 4.4
IFAS HRT (hr)	6.3 – 6.7	4.2 – 4.5	3.7 – 4.1	5.1 – 5.6	4.0 – 4.2	2.9 – 3.6	2.4 – 2.8	2.2	2.9 – 3.0	3.1 – 3.2

4.3 The treatment performance on *raw sewage* by the IFAS and MBBR reactors was evaluated at different short HRTs in Phase A1 − A3 at 23°C. Although the BOD met the limit of ≤ 20 mg/L in all phases, NH_3-N and TN criteria could not be met at HRT shorter than 6.2 hr and 4.2 hr in the MBBR and IFAS reactor respectively. That means the ammonia removal was the governing factor in determining the minimum HRT for raw sewage.

4.4 At a temperature of 18°C in Phase A4, the performance of the MBBR and IFAS was evaluated at HRT ranges of 7.2 – 7.8 and 5.1 – 5.6 hr, respectively, for a relatively short period. Effluent NH_3-N dropped to below 5 mg/L after one week when the micro-organisms acclimatized at the low temperature. Due to the time limit, a range of minimal HRT at 18°C is reported. Nevertheless, it is expected that the performance would be stabilized if the trial was extended and the more aggressive values of 7.2 and 5.1 hr were adopted in the HATS 2B full-scale plant design in Chapter 5.

4.5 In Phase B, the minimum HRT for the IFAS and MBBR reactors to treat *CEPT effluent* at 23°C were determined. Again, the BOD limit could be met even at very short HRT in the MBBR reactor. Despite a transient non-compliance of effluent BOD at the beginning of Phase B2 and B3 in the IFAS reactor, effluent BOD_5 still met the effluent criteria after the biomass had acclimatized itself. The ammonia removal was still the governing factor in determining the minimum HRT for CEPT effluent.

4.6 At a temperature of 18°C, the performance of the MBBR and IFAS was evaluated at two HRT ranges for a relatively short period. Nevertheless, more than one week was allowed for the micro-organisms to acclimatize to 18°C. The minimum HRT of MBBR and IFAS system on treating CEPT effluent at 18°C was determined to be 4.5 – 4.9 and 3.1 – 3.2 hr respectively. The more aggressive values of 4.5 and 3.1 hr were adopted in the HATS 2B full plant design in Chapter 5.

4.7 The minimum HRTs achieved by IFAS and MBBR are summarized.

	MBBR		IFAS	
Operating Temp. (°C)	23	18	23	18
Raw Sewage	6.2	7.2 – 7.8	4.2	5.1 – 5.6
CEPT Effluent	3.8	4.5 – 4.9	2.4	3.1 – 3.2

5. Comparison between Treating Raw Sewage and CEPT Effluent

5.1 From the observation of the carriers in the MBBR and IFAS aerobic zones in Phase A while treating raw sewage, it was found that there was flourishing growth and so a thick layer of biomass inside the mobile carriers, especially in the MBBR reactor system. This might hinder oxygen from penetrating into the biofilm of nitrifiers on mobile carriers and suppressed the growth of nitrifiers. This also led to poor ammonia removal performance despite good mixing and high dissolved oxygen (DO) in the bulk solution. This can be related to poor ammonia removal performance at high organic loading as a result of "biomass overgrowth" that suppressed the nitrification activity.

5.2 In Phase B treating *CEPT effluent*, the "biomass overgrowth" problem was not as serious. As a result of lower organic loading rate (OLR) despite a higher sewage flow, the competition from the heterotrophs was not as severe as in Phase A and the allowable nitrogen loading rate (NLR) was *even higher* than that of Phase A. The reactors could be operated at a much shorter HRT when treating CEPT effluent.

5.3 Concerning the denitrification performance, although the effluent TN levels from the IFAS and MBBR systems were higher in Phase B when treating CEPT effluent, effluent TN levels in Phase B were still well below the criteria of 20 mg/L. Therefore, raw sewage and CEPT effluent are both suitable as the feed into either MBBR or IFAS system in terms of total nitrogen removal.

6. Comparison between IFAS and MBBR

6.1 The minimum HRT for MBBR to treat either raw sewage or CEPT effluent are longer than that for IFAS at both 23°C and 18°C. Effluent data confirmed ammonia removal was the governing factor in determining the minimum HRT. There is a difference between the nitrification efficiencies in MBBR and IFAS. The lower nitrification efficiency in MBBR than IFAS can be attributed to:

(i) For MBBR under high OLR, heterotrophic biomass grew excessively on top of the autotrophic biomass on the mobile carriers, the biomass overgrowth could have affected DO penetration and substrate diffusion to the nitrifiers and impaired the nitrification activity;

(ii) For IFAS, the influent COD was first removed by the suspended growth biomass in both anoxic zone and aerobic zone of the IFAS reactor, so the adverse effect of “biomass overgrowth” on the nitrification was less severe.

6.2 Therefore, it is highly probable that, if the carbonaceous removal process can be separated from the nitrification process in aerobic zone so that COD and BOD_5 can be first reduced before the NH_3-N is removed, the treatment efficiency of MBBR may be further improved.

6.3 Occasional sludge bulking and deflocculated MLSS in IFAS system were observed. That could be a result of intense aeration to keep carriers moving, the SV_{30} and SVI in the IFAS system was observed to be higher than those in conventional activated sludge process. The effluent TSS of the IFAS system was always higher than that of the MBBR system during Phases A and B of the study. It is therefore opined that final clarification for IFAS was more difficult than MBBR.

7. Potential Application in Harbour Area Treatment Scheme (HATS) Stage 2B

7.1 Based on the minimum HRT for the IFAS and MBBR to treat raw sewage and CEPT effluent at 18°C, four design options were developed. One more ‘MBBR improved’ option was proposed for the MBBR treating CEPT effluent, in which the biological reactor is modified to shorten the HRT. This study focused on biological treatment processes, and final clarification is considered only to estimate land use of final clarification facilities for illustrative purpose.

7.2 All five options were considered together with their final clarification facilities and compared with the available land area in the designated site near the exiting SCISTW. A two-level basement, each level with a maximum floor area of about 130,000 m^2, will be designed for the additional secondary treatment for the HATS 2B. Only the areas for the biological reactors and final clarifiers are considered in this report. The space requirement of other auxiliary equipment, like pumps, air blowers, sludge handling, odor control system and other facilities, has not yet been taken into account in this exercise. Circular DAF (dissolved air flotation) is assumed for clarification with MBBR options treating CEPT effluent for illustration purpose only. Other clarification facilities such as lamella clarifier, chemical enhanced clarifier, or Actiflo™ which is a very high-rate clarifier by Veolia, shall also be considered in HATS 2B.

HATS 2B treating CEPT effluent

7.3 Among the 3 design options of treating CEPT effluent, the IFAS option has the smallest estimated floor area of 65,200 m^2 for the bioreactors (at Basement 1). However, the space requirement of the secondary clarifiers is about 129,600 m^2 which makes the IFAS option for CEPT effluent rather difficult to fit into Basement 2. Careful layout design and floor space planning is required to decide whether this IFAS option is feasible.

7.4 The MBBR basic option for treating CEPT effluent requires a floor area of 94,200 m^2 for bioreactors and 60,000 m^2 for DAF units as final clarification, which should be able to fit into the allocated space.

7.5 In the MBBR improved option for treating CEPT effluent, it is expected that through increasing the media fill ratio to a maximum of 67%, proper staging of C and N removal, and increasing the NH_3-N loading in the nitrification reactor by raising the DO to 5 mg/L, the floor area for bioreactors can be reduced to 70,200 m^2 and a floor area of about 60,000 m^2 for DAF units is needed. It is expected that this option can be fit into the basement very comfortably and it is considered to be the most promising option. Further studies will be proposed to verify the feasibility of this option.

HATS 2B treating raw sewage

7.6 For treating raw sewage in the IFAS option, the estimated floor areas of 107,100 m^2 for bioreactors and 129,600 m^2 for the secondary clarifiers as final clarification are extremely marginal to be fit into the two-level basement with the maximum floor area of 130,000 m^2 on each level.

7.7 For the MBBR option for treating raw sewage, the raw sewage will enter the biological treatment plant in HATS 2B directly and so the existing CEPT plants in HATS 1 and 2A can be spared for the final clarification. No extra space will be required for final clarification in the designated site. A floor area of 151,000 m^2 is required for the bioreactors which will be comfortably and evenly fit into the two-level basement. Therefore, this option would be a promising option for the future biological treatment plant (BTP) in HATS Stage 2B. The drawbacks of this option are higher operating cost and energy consumption for aeration of raw sewage, and vulnerability to shock loads such as organic loading surge due to the large COD fluctuation in raw sewage.

8. Proposed Further Studies

8.1 Due to the limitations on the original design of the study, the configuration and the volume of the anoxic and aerobic zones could not be adjusted and optimized. After analyzing the results from the prototype study and considering the space constraints in the HATS 2B Scheme, there are two targets worthy of further studies.

(a) To optimize the MBBR reactor by:
   (i) separating the aerobic process into two stages of BOD removal and nitrification;
   (ii) raising the DO to 5 mg/L in the nitrification reactor and so increasing the nitrification rate;
   (iii) increasing the media fill ratio to 67% or higher, in all bioreactors;
   (iv) optimizing the volume-fractions and HRT proportions of the anoxic, BOD removal, and nitrification reactors so that the overall system can attain a shorter minimum HRT.

(b) To improve the MBBR option treating raw sewage by pre-treatment using compact solid removal technology such as fine mesh sieve filter to removing particulate material.