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BIOLOGICAL PHOSPHORUS AND NITROGEN REMOVAL IN A FULL SCALE SEQUENCING BATCH REACTOR TREATING PIGGERY WASTEWATER

A. Tilche*, E. Bacilieri**, G. Bortone***,
F. Malaspina***, S. Piccinini† and L. Stante***

* *European Commission, JRC, Environment Institute, 21020 Ispra, Italy*
** *Ing. Elio Bacilieri s.r.l., Via A. di Vincenzo 33, 40129 Bologna, Italy*
*** *ENEA, Section of Wastewater Treatment and Water Cycle, Via Martiri di Monte Sole 4, 40129 Bologna, Italy*
† *CRPA S.p.A., C.so Garibaldi 42, 42100 Reggio Emilia, Italy*

ABSTRACT

Research activities carried out at ENEA during the last few years allowed the development of a Sequencing Batch Reactor (SBR) that is able to remove biologically organic waste, nitrogen and phosphorus and that was shown to be particularly suited to obtaining low effluent nutrient concentrations even starting from concentrated wastes. Research on optimisation of time cycles and on process modelling, allowed an advanced comprehension of reactor behaviour and the development of a process able to obtain more than 98% removal of nitrogen, phosphorus and COD, and therefore almost capable of matching effluent standards with a sole biological process.

On the basis of laboratory results and process modelling, a full scale SBR plant has been designed and realised. This plant, in ten months of operation, is achieving even better results compared to the laboratory ones. © 1999 IAWQ Published by Elsevier Science. All rights reserved

KEYWORDS

Biological nitrogen removal; biological phosphorus removal; piggery wastewater; sequencing batch reactor.

INTRODUCTION

In Italy, pig farming is concentrated in few areas, mainly located in the Po valley and in the Umbria Region. The high concentration and the industrial typology of piggery farms, often not connected with land cultivation, lead to an excessive generation of animal wastes, frequently higher than their recycling potential on land as a fertiliser. Restrictions on landspreading, today stated by regional, national and European regulations for the protection of surface and groundwater from pollution, cause the necessity - in areas of high animal density - of local use as a fertiliser of only a fraction of the produced wastes. There are different options with respect to environmental rules, from moving farms in more receptive areas, to modifying barn structures to produce only solid wastes (farming on straw bedding) and then "export" wastes towards receptive areas, or to the choice of treating wastewater for discharge into surface waters. The last option was experienced in the past with rare success, due to both economic-management and to technical causes.

Traditional nutrient removal processes, based on pre-denitrification configurations, do not allow discharge standards for nitrogen to be reached. In fact, with removal efficiency linked to the recycle rate of the nitrified mixed liquor (maximum applicable recycle rate around 5, corresponding to N-removal efficiency of about 85-90%), it is impossible, starting from wastewater containing 1,500 mg/l TKN, to meet the discharge standards for nitrate-nitrogen (in Italy around 20 mg/l). The only chance for continuous flow processes is to apply a post-denitrification stage with addition of an external carbon source; this means a large increase in plant complexity, in management difficulties and in operating costs.

Research carried out at ENEA (Tilche *et al.*, 1994) with an upgraded pilot scale (continuous flow) nutrient removal treatment plant treating piggery wastewater with an initial average concentration of 27,000 mg/l COD, 1,550 mg/l TKN and 725 mg/l P_{tot} obtained removal efficiencies of 96% for COD and 92% for nitrogen and phosphorus, still resulting in concentrations far higher than discharge standards.

Other laboratory research (Bortone *et al.*, 1992, 1994), using Sequencing Batch Reactors, demonstrated the possibility of driving the use of the carbon source towards biological nitrogen and phosphorus removal through the correct design of the time cycle, in order to obtain low levels of nutrients in the final effluent.

The process has been modelled (Andreottola *et al.*, 1997) modifying the Activated Sludge Model I (ASM1), by splitting into two reactions the nitrification process and by adding a switch function that simulates the toxic effect of ammonia on the nitratation step, obtaining a very close correspondence between experimental and simulated data. The model was used for designing a full scale plant at the S. Anna farm in Magreta (Modena, Italy), a full cycle piggery with an animal population of about 800 tons of live weight, bred on partially slotted floors, with an estimated wastewater production of about 150-190 l/(d·ton of live weight). The plant, designed for a minimum wastewater temperature of 12°C, applying a safety factor of 1.5, resulted in a total working volume of 2,500 m^3, with a maximum daily need of 1,500 kg O_2 and a design sludge age of 15 days.

The objective of the present research was to demonstrate in full scale the possibility of obtaining biological nutrient removal down to the limits set by Italian regulations using the SBR process, starting from undiluted piggery wastewater.

MATERIALS AND METHODS

Plant description

The plant, schematically represented in Fig. 1, is composed of two parallel SBRs (25(L) x 10(L) x 5(H_{max})m. The wastewater is collected in a mixing and pumping tank from where it is pumped into a PIERALISI FP600.2RS centrifuge working at a flow rate of about 12 m^3/h. The liquid fraction is sent to the equalisation tank, where it is mixed with other supernatants deriving from the sludge settling and dewatering. Submerged pumps load alternately the two Sequencing Batch Reactors at the beginning of each denitrification phase, during which only the mixer is operating. Each SBR is equipped also with two ABS 1200 TAK submerged aerators, each one of 35 kW power. The clarified effluent is discharged by means of a submerged pump installed about 1 m below the minimum liquid level. Excess sludge is withdrawn before the end of each oxidation phase and is transferred to a gravity settler. The supernatant returns to the equalisation tank, while the settled sludge is transferred to a gravity thickener. The thickened sludge is dosed to a second centrifuge (equal to the previous) after addition of cationic polyelectrolyte; the thickener supernatant and the liquid fraction from the centrifuge return to the equalisation tank.

SBR cycle description

The cycle has been conceived after a deep simulation study (Tilche and Bortone, 1996) showed that the higher was the number of denitrification/oxidation-nitrification phases per day, the lower was the effluent concentration of nitrate-nitrogen. The limit to the number of phases in one cycle is only due to nitrification kinetics. Figure 2 shows the behaviour of effluent nitrate concentration by varying the number of denitrification/oxidation-nitrification phases per daily cycle from 1 to 5. The evidence is that, in the case of

1 phase/cycle, supposing a designed SBR of 10 days HRT and an influent of 1,000 mg/l TKN, after denitrification, if the influent COD is sufficient to denitrify completely all the nitrate present, ammonia nitrogen concentration will be close to 100 mg/l. During the following oxidation-nitrification phase, ammonia nitrogen is converted in about 100 mg/l of nitrate nitrogen. When the cycle is fragmented in two phases, and the loading is divided in two parts, each one supplied to the reactor at the beginning of denitrification, ammonia nitrogen will reach about 50 mg/l at the end of denitrification, and about 50 mg/l will be nitrate nitrogen in the effluent.

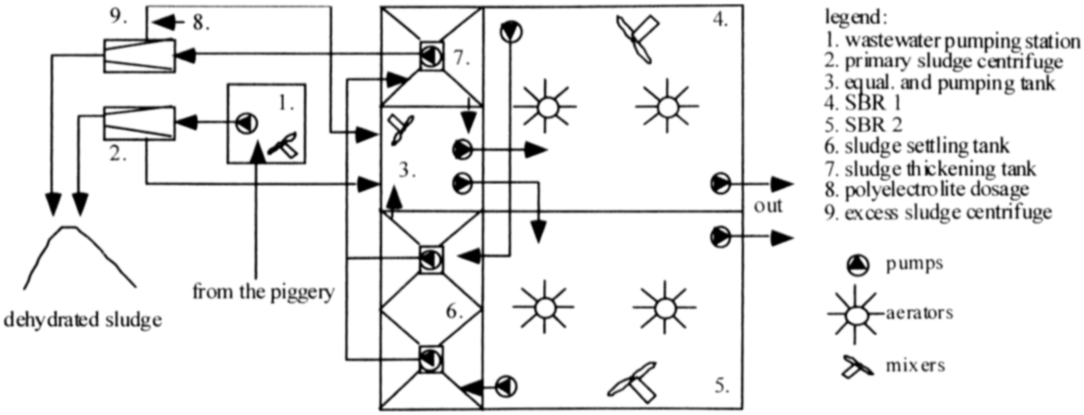

Figure 1. Schematic drawing of the full scale SBR plant.

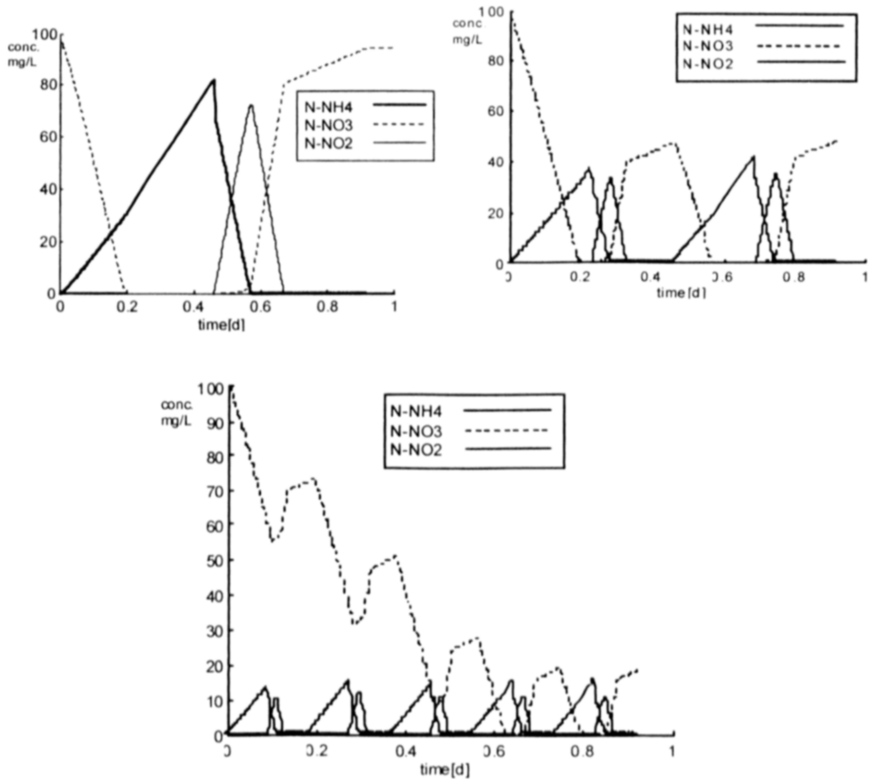

Figure 2. Upper left: simulation of SBR cycle with one denitrification/oxidation-nitrification phase per day; upper right: simulation with two phases per day; lower: simulation with five phases per day.

Therefore, in order to obtain effluent nitrate-nitrogen concentration lower than 20 mg/l, an SBR cycle composed of 5 denitrification/oxidation-nitrification phases per day, and only one settling/discharge/idle phase at the end, has been designed. Each denitrification and each oxidation-nitrification phase had a duration of 2 hours. The settling/discharge/idle phase lasts 4 hours; effluent discharge begins after 1.5 h of settling, ending when the lower level, fixed by a buoyant switch, is reached. In order to contain the power demand of the plant, the two SBRs are never together in oxidation mode. The cycle is governed by a PLC; the programme is highly flexible and can be easily modified by the plant manager in order to meet the needs of higher or lower loadings, and to control sludge growth. A series of level signals in the equalisation tank inform the PLC about the amount of load to be pumped in each SBR at the beginning of each denitrification phase. As already said, the PLC activates the sludge withdrawal pumps that go into operation for a given (adjustable) time period before the end of each oxidation phase.

Sampling and analyses

Sampling was carried out for a period of three months, every 10-15 days. Each sampling consisted of a series of samples in various parts of the plant (raw influent, centrifuged solids, equalisation tank, mixed liquor, liquid effluent) and of a "track" sampling carried out on SBR 1 for a period of 4 hours, starting at the beginning of a denitrification phase and ending at the end of the following oxidation-nitrification phase. For the characterisation of the equalisation tank content, automatic sampling was carried out every 6 h for a period of one week using a refrigerated autosampler.

Analyses of samples were carried out according to the procedures described in Standard Methods (APHA, 1989). NH_4-N, NO_3-N, NO_2-N and PO_4-P were analysed by a High Performance Ion Chromatograph (Dionex 4000i). PHB was determined with GC using the method reported in Stante *et al.* (1997).

RESULTS AND DISCUSSION

Analyses of raw wastewater gave highly dispersed results; therefore, the average data reported in Table 1 are only indicative, being raw waste composition dependent on barn cleaning operations.

The first centrifuge produced a solid fraction at about 30% TS that remove a variable fraction of total COD (30-40%), a similar fraction of total phosphorus and a slightly lower fraction of total nitrogen. The correct evaluation is quite difficult due to the high error in sampling. Primary sludge represents in terms of weight about 6% of the influent. A better evaluation has been done on the characteristics of the equalisation tank, from where the two SBRs are loaded. In Table 2 the average results of one full week of sampling are reported.

In Figures 3, 4 and 5 the trends of COD, N and P in the equalisation tank are reported; it can be noticed that the fluctuations of concentration are not directly linked with cleaning operations. During cleaning, however, the flow rate increases.

The plant was started up on September 1997, partially filling the SBR tanks with water and adding to each tank about 30 m^3 of activated sludge from a nearby treatment plant treating piggery wastewater. With a gradual increase in loading, the plant reached the full treatment capacity after about three weeks. Data that follow were obtained from April to June 1998, but the periodical monitoring carried out during winter and spring always gave similar results. In Table 3, the general plant performance is presented. Removal efficiencies are for the main parameters always higher than 98%. If efficiency is calculated for the sole biological process, values are only slightly lower.

Values of effluent ammonia nitrogen are always higher with respect to those obtained at the end of the oxidation phases during "track" monitoring, that averaged 1.78 mg/l. It is possible that the difference is due to the long settling period before discharge that allows for some ammonification of organic nitrogen in the settled sludge.

Moreover, despite the very low concentration of suspended solids, the presence of colloidal suspended material gives relatively high effluent values of COD and TKN. Laboratory jar tests, dosing $FeCl_3$ as a coagulant at 90 mg/l, removed more than 50% of the COD in the clarified effluent. A coagulant dosing station is present in the full scale plant, but it was never put into operation, because the effluent concentrations were always well inside the required limits.

Table 1. Raw wastewater characteristics

Parameters	Units	Values
Wastewater flow	m^3/d	150
COD_{tot}	mg/l	28760
TKN	mg/l	2153
NH_4-N	mg/l	1414
P_{tot}	mg/l	450

Table 2. Average characteristics of the content of the equalisation tank during one week of sampling

Parameters	Average conc. ($mg\ l^{-1}$)	RSD (%)	No. of samples
tot. COD	4600	34	29
sol. COD	1988	42	29
TSS	2130	22.2	29
VSS	1702	24.2	29
TKN	594	14.6	29
NH_3-N	435	18	29
tot. P	81.9	29.6	29
PO_4-P	12.4	38.5	29

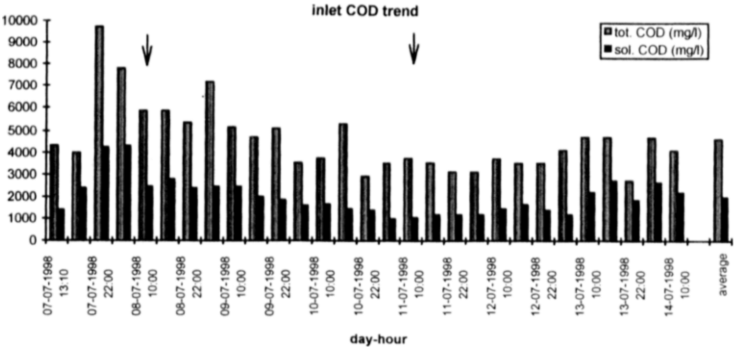

Figure 3. Trends of COD in the equalisation tank; arrows indicate cleaning operations

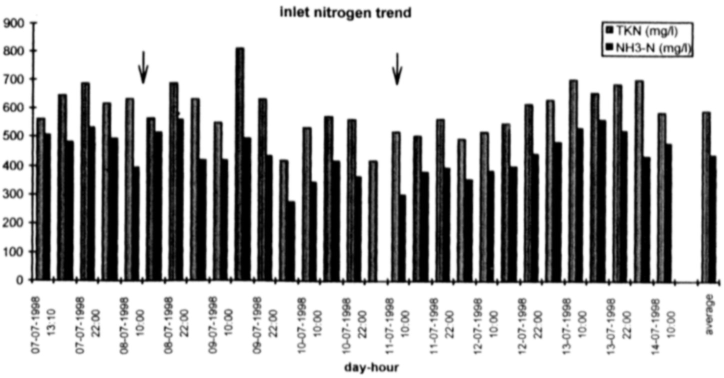

Figure 4. Trends of TKN and NH_4-N in the equalisation tank; arrows indicate cleaning operations.

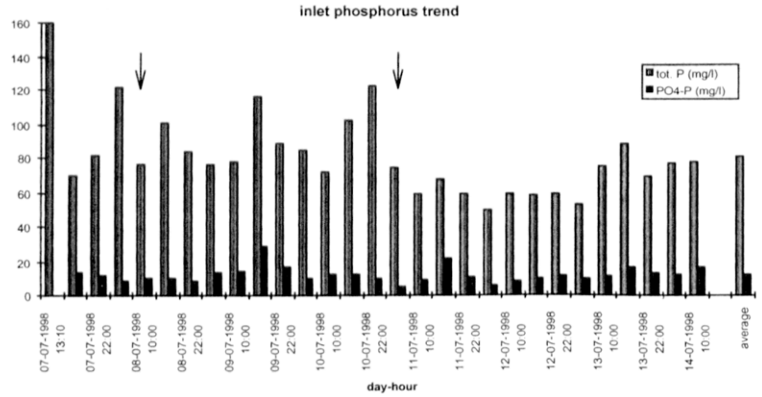

Figure 5. Trends of P_{tot} and PO_4-P in the equalisation tank; arrows indicate cleaning operations.

Table 3. Comparison among influent, equalisation and plant effluent

Parameter	Unit	Raw wastewater	Equalisation tank	Outlet
Flow	m^3/d	150	440	138
TSS	$mg \cdot l^{-1}$	n.d.	2130	35.3
COD_{tot}	$mg \cdot l^{-1}$	28760	6456	336
TKN	$mg \cdot l^{-1}$	2153	695	18.36
NH_3-N	$mg \cdot l^{-1}$	1414	500	5.48
NO_3-N	$mg \cdot l^{-1}$	0	0	11.9
N_{tot}	$mg \cdot l^{-1}$	2153	695	30.26
P_{tot}	$mg \cdot l^{-1}$	450	91.8	8.75

Track studies

Six track studies were carried out. Except in one case, when due to hydraulic and organic overloading nitrification was not complete at the end of the second hour, leaving a residue of about 4.5 mg/l NH_4-N, during all the other tracks both nitrification and denitrification were completed after about 50% of the reaction time. To show the typical trend of various parameters, the track of June 2nd has been chosen. In Fig. 5a and b trends of soluble COD, NH_4-N, NO_3-N, DO and ORP are showed. No nitrite transient peak during nitrification was detected.

The COD decrease during denitrification correlates well with denitrification. However, the COD growth at the beginning of the aeration step can be also due to the poor mixing provided by a single mixer in a 1,250 m^3 volume tank; when aerators are switched on, they resuspend or desorb a considerable amount of fines. For the first hour of the anoxic phase, raw wastewater was pumped into the SBR. This is well in accordance with the trend of ammonia nitrogen; however, COD should also increase, but it is simultaneously removed by denitrifiers and it is used by phosphorus accumulating microorganisms to build up storage products. The long anaerobic time in fact stimulates the growth of PAOs. Biological phosphorus removal, usually witnessed by ortho-phosphate release in anaerobic conditions, is not evident under the reactor conditions. This is well known after previous studies (Bortone *et al.*, 1992) demonstrated that phosphorus release in piggery wastewater treatment is masked by chemical precipitation. However, as can be seen from Fig. 6, PHB is accumulated under anoxic-anaerobic conditions and is subsequently consumed under oxic conditions. The dissolved oxygen curve shows that nitrification could have been stopped well before the time set. ORP shows promise for use as a control parameter both for denitrification and nitrification. However, a reliable oxygen controller would be the most advisable solution to avoid excess oxygen delivery.

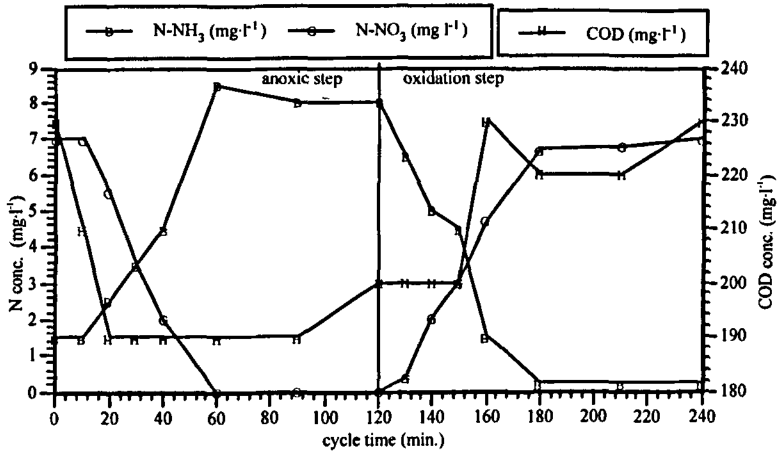

Figure 5a. Ammonia, nitrate and COD behaviour during the track of June 2nd, 1998.

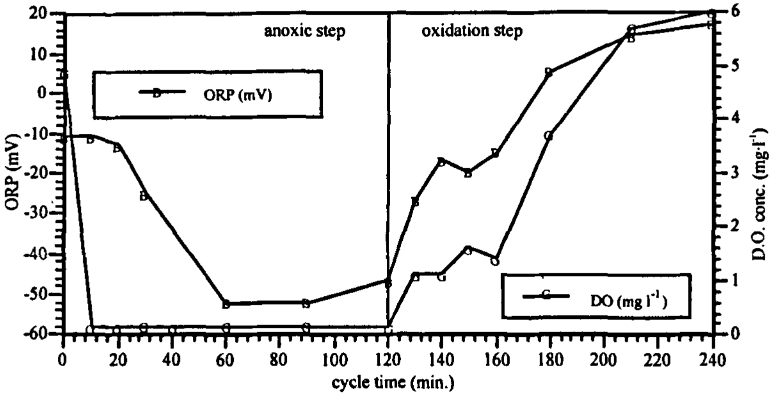

Figure 5b. Dissolved Oxygen (DO) and Oxidation/Reduction Potential (ORP) during the track of June 2nd, 1998.

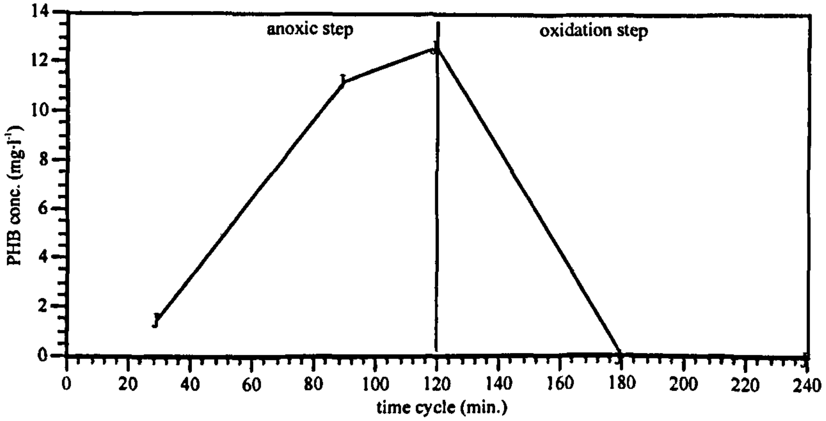

Figure 6. Trend of Poly-β-hydroxybutirate (PHB) under anoxic-anaerobic and oxic conditions.

CONCLUSIONS

The Sequencing Batch Reactor has been demonstrated to be an extremely efficient biological process, capable of obtaining very low nitrogen and phosphorus concentrations from highly concentrated wastewaters - like piggery wastewater - with COD, nitrogen and phosphorus removals higher than 98%. A proper design of the time cycle is therefore necessary, and modelling capacity is needed to optimise the duration of the single phases.

The proposed process, implemented in full scale, can represent a new chance for solving environmental problems generated by large industrial piggeries. Draft economic evaluations, not reported here, indicate that the operative costs can be tolerated by pig farmers, with minor effect on meat prices. Electric energy costs, that represent the main cost item, can greatly be reduced if the separated solids are anaerobically digested to produce biogas for co-generation. Laboratory experiences are now being carried out to evaluate the potential of energy recovering.

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