**Characterization of the retained sludge in a down-flow hanging sponge (DHS)
reactor with emphasis on its low excess sludge production**

Takashi Onodera^{1,2,†*}, Kengo Matsunaga^{1,3,†}, Kengo Kubota³, Ryoko Taniguchi³,
Hideki Harada³, Kazuaki Syutsubo², Tsutomu Okubo⁴, Shigeki Uemura⁴, Nobuo Araki⁵,
Masayoshi Yamada⁶, Masahito Yamauchi⁶, Takashi Yamaguchi^{1*}

¹ *Department of Civil and Environmental Engineering, Nagaoka University of
Technology, 1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan*

² *Center for Regional Environmental Research, National Institute for Environmental
Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan*

³ *Department of Civil and Environmental Engineering, Tohoku University, 6-6-06 Aoba,
Aramakiaza, Aoba-ku, Sendai 980-8579, Japan*

⁴ *Department of Civil Engineering, Kisarazu National College of Technology, 2-11-1
Kiyomidaihigashi, Kisarazu 292-2188, Japan*

⁵ *Department of Civil Engineering, Nagaoka National College of Technology, 888,
Nishi Katagai, Nagaoka, Niigata 940-8532, Japan*

⁶ *Department of Urban Environmental Design and Engineering, Kagoshima National
College of Technology, 1460-1 Shinkou Hayato, Kirishima, Kagoshima 899-5193,
Japan*

† Two authors contributed equally to this work.

***Corresponding authors**

T. Onodera (E-mail: onodera.takashi@nies.go.jp; Tel: +81-29-850-2412; Fax:
+81-29-850-2569)

T. Yamaguchi (E-mail: ecoya@vos.nagaokaut.ac.jp; Tel/Fax: +81-258-47-9612)

Abstract

Experiments to characterize retained sludge in a down-flow hanging sponge (DHS) reactor fed with upflow anaerobic sludge blanket (UASB) treated sewage under moderate conditions were conducted. Plenty of oxygen was supplied through the DHS reactor without aeration and the effluent qualities after the reactor were comparable to activated sludge processes. The average excess sludge production rate was 0.09 g SS g⁻¹ COD removed. The DHS reactor maintained a high sludge concentration of 26.9 g VSS L⁻¹ sponge, resulting in a low loading rate of 0.032 g COD g⁻¹ VSS day⁻¹. The endogenous respiration rate of DHS sludge was comparable to previously reported aerobic sludges. The numbers of microfauna were one order of magnitude greater than those in activated sludge. The results indicated that low excess sludge production was attributable to the high sludge concentration, sufficient oxygen supply, adequate endogenous respiration rate, and a high density and diversity of microfauna.

Keywords: Sewage, low excess sludge, down-flow hanging sponge (DHS), microfauna

1. Introduction

The activated sludge process is one of the most widely applied biological sewage treatment processes, despite the production of a large amount of excess sludge. Disposal of the excess sludge is an important issue in wastewater treatment plants because of the huge treatment cost, limitation of disposal fields, and public perception. To save costs in excess sludge management, it is preferred to reduce sludge production during wastewater treatment processes rather than using additional sludge treatment processes.

Considering metabolic mechanisms, anaerobic treatment processes have great potential to reduce the excess sludge production compared with aerobic treatment processes (McCarty, 1964). Recently, upflow anaerobic sludge blanket (UASB) reactors have been used for sewage treatment, especially in tropical and sub-tropical regions, as a simple and low cost process (Sato et al., 2006; Kassab et al., 2010). Smaller amounts of well-stabilized sludge are produced by the UASB process compared with the activated sludge process (Lettinga et al., 1983; Takahashi et al., 2011). However, UASB treated sewage needs post-treatment because its water quality usually does not satisfy regulations for discharge into environments (Sato et al., 2006).

Many processes have been applied as post-treatment processes for UASB treated municipal sewage (Kassab et al., 2010). An attractive process is the down-flow hanging sponge (DHS) process (Machdar et al., 2000; Tawfik et al., 2006; Tandukar et al., 2006; Tandukar et al., 2007). The configuration of the DHS process is similar to that of the trickling filter. The wastewater is trickled from the top of the vessel filled with polyurethane sponge media and is treated by sludge retained in the sponge media. The sewage flows vertically down each sponge in the reactor by gravity. Oxygen is

1 naturally supplied to the sewage from the atmosphere because the sponge media are
2 exposed to the air. The DHS process shows high organic removal efficiency and high
3 nitrification efficiency. Its effluent water is similar to an activated sludge process and
4 satisfies adequate levels for discharge (Tandukar et al., 2007). The retained sludge
5 concentration of the DHS process is 5–10 times greater than that in activated sludge
6 (Tandukar et al., 2005). Moreover, pilot scale experiments have shown much lower
7 amounts of excess sludge during long experimental periods (Tandukar et al., 2005;
8 Tandukar et al., 2007). However, the retained sludge characteristics in the DHS process
9 have not been comprehensively evaluated so far.

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11 The aim of this study is to evaluate the sludge characteristics of a DHS
12 reactor, from which very low excess sludge is produced. The DHS reactor was fed with
13 UASB treated municipal sewage for more than 2 years under moderate climate
14 conditions and the process performance and excess sludge production were
15 continuously monitored. The retained sludge concentrations, endogenous respiration
16 rates, and microfauna populations were investigated and the changes in the water
17 quality and sludge characteristics along the height of the DHS reactor were also
18 evaluated.

19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 **2. Methods**

47 48 *2.1. Reactor configurations*

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52 A UASB and DHS combined system (UASB-DHS system) was operated under
53 ambient temperatures ranging from 10 to 32°C at a municipal sewage treatment plant
54 in Nagaoka, Japan (Fig. S1). A cylindrical UASB reactor with a height of 4.0 m and a
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working volume of 1,148 L, including a gas solid separator (GSS), was employed as an anaerobic pre-treatment process. The DHS reactor consisted of 10 segments connected vertically, and was randomly filled with sponge media as the packing material. A distributor was set at the top of the DHS reactor to feed UASB effluent in. The DHS reactor volume (vessel volume) and the sponge media volume were 857 L and 454 L, respectively, which corresponds to a sponge media occupancy of 53%. The sponge media was a polyurethane sponge cube (33 mm) packed inside a cylindrical plastic net ring (33 mm diameter, 33 mm length). The void ratio of the sponge was more than 97% and the average pore size of the sponge was 0.63 mm. The sponge media volume was calculated based on a cylindrical shape. A clarifier was set at the bottom of the DHS reactor with a working volume of 32.5 L.

2.2. Operating conditions

The settled sewage obtained from the sewage treatment plant was fed to the UASB reactor by using a peristaltic pump. The UASB effluent was distributed from the top of the DHS reactor and flowed down through the sponge media by gravity. The DHS effluent was discharged from the clarifier. The hydraulic retention time (HRT) of the UASB reactor and the DHS reactor based on the sponge media volume were 8.0 h and 3.2 h, respectively. The UASB reactor was started up with inoculation of the digested sewage sludge 76 days before the DHS reactor operation started. The DHS reactor was started up using sponge media without inoculation and operated without sponge replacement or sponge washing during the entire operational period of approximately 850 days.

2.3. Water quality analysis

The routine analysis was continuously performed twice a week. The sewage and the UASB effluent were obtained by 24 h composite sampling (5 min every h) and samples were stored in tanks at 4°C. The DHS effluent was obtained by grab sampling. Temperature, pH, oxidation-reduction potential (ORP), and dissolved oxygen (DO) in the samples were obtained by grab sampling and measured on site. The pH and ORP were analyzed using a pH meter (HM-12P, TOA DKK, Japan) and an ORP meter (PTS-2019C, TOA DKK, Japan), respectively. Suspended solids (SS) and volatile suspended solids (VSS) were determined using a glass filter (0.4 µm, GB140, ADVANTEC, Japan). The unfiltered samples were used to analyze biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total Kjeldahl nitrogen (TKN). The filtered sample was used to determine filtered COD, ammonium, nitrate, and nitrite. The COD and TKN were analyzed by a HACH water quality analyzer (DR-2500, HACH, US) and nitrogen compounds were detected using HPLC (LC-10A Tvp, Shim-pack IC-C1, IC-A1, Shimadzu, Japan). Other water quality experiments were conducted according to AHPA (1998).

The settled (excess) sludge in the clarifier was sampled during the routine analysis and the SS and VSS were measured. The sludge volume index (SVI) was determined according to the Standard method (AHPA, 1998).

2.4. Calculation of sludge retention time and sludge production rate

The SS_{sum} production from the DHS reactor was defined as the sum of SS volumes in the DHS effluent and the excess sludge settled in the clarifier. The sludge retention

time (SRT) and sludge production rate were determined according to Equations (1) and (2).

$$SRT = \frac{V \times X_{rea}}{Q_w \times X_w + Q \times X_{eff}} \quad (1)$$

$$Y_{obs} = \frac{Q_w \times X_w + Q \times X_{eff}}{Q \times C_{rem}} \quad (2)$$

Where SRT is the sludge retention time (day), V is the DHS reactor volume (sponge media volume) (L), X_{rea} is the retained sludge concentration in the DHS reactor (g SS L⁻¹ sponge), Q_w is the production volume of excess sludge (L day⁻¹), X_w is the SS concentration of excess sludge (g SS L⁻¹), Q is the flow rate (L day⁻¹), X_{eff} is the SS concentration in the DHS effluent (g SS L⁻¹), Y_{obs} is observed yield coefficient, corresponding to the SS_{sum} production rate from the DHS reactor, (g SS g⁻¹ COD removed) and C_{rem} is the removed COD concentration in the DHS reactor (g COD L⁻¹).

2.5. Retained sludge measurements

To determine retained sludge concentration in the DHS reactor, three sponge media were randomly taken from each segment. The sponge media were immersed and squeezed in distilled water to elute the retained sludge until the sponge became clean. The SS and VSS were analyzed in the squeezed sludge samples and calculated based on the sponge media volume.

2.6. Endogenous respiration rate

To measure the endogenous respiration rate, sponge media were taken from segments 1, 4, and 8 on day 624. The sludge samples were washed with phosphate buffer saline (PBS) solution (NaCl 7.6 g L⁻¹, NaH_2PO_4 0.50 g L⁻¹, Na_2HPO_4 1.54 g L⁻¹). The sludge concentration was adjusted to 2–3 g VSS L⁻¹ using PBS solution. The sludge was aerated for 6 h at 25°C to remove the remaining substrates before the experiment. The DO in the sludge with or without substrate was monitored to determine DO decrease rate at 25°C and was measured using an oxygen monitor (5300A, YSI, US) with a detector (5301, YSI, US). The endogenous respiration rate was obtained by the sludge concentration and DO decrease rate.

2.7. Microfauna observation

Sponge media was taken from segments 1, 4, and 8 of the DHS reactor between day 781 and day 785 and sludge samples were taken from it. A sample (10 µL) was used for counting microfauna with a phase contrast microscope (DMBA310, Shimadzu, Japan) and arcellinida, ciliophora, rotifera, nematoda, oligochaeta and cladocera were counted. The microfauna was named according to the New Taxonomy database of the SWISS-PORT group (NEWT; Phan et al., 2003). The average numbers were calculated using triplicate counting results.

3. Results and discussion

3.1. Process performance of the UASB-DHS system

The performance of the UASB-DHS system was evaluated for approximately 850 days. A summary of the water quality is shown in Table 1. The average values were calculated based on one year operation results after the retained sludge concentration became stable (day 446–810). The UASB reactor removed approximately 65%, 70%, and 60% of the influent SS, COD (unfiltered COD), and BOD (unfiltered BOD), respectively. Because the UASB process is anaerobic, the value of TKN did not change. The removal of the remaining organic substances and nitrification were effectively carried out by the following DHS reactor. The final effluent quality was as follows: SS=12 mg L⁻¹, BOD=7 mg L⁻¹, COD=36 mg L⁻¹, and TKN=3 mg L⁻¹ on average. The value of total nitrogen was moderately reduced after the DHS reactor, suggesting occurrence of denitrification. The process performance of the DHS reactor was similar to those in previous studies (Machdar et al., 2000; Tawfik et al., 2006; Tandukar et al., 2006) and was comparable to that of the activated sludge process as found in the previous study by Tandukar et al. (2007).

Time courses of temperature, SS, and BOD for sewage, UASB effluent, and DHS effluent are shown in Fig. 1. The temperature ranged throughout the year from 10 to 28°C. The SS and BOD concentrations in the UASB effluent oscillated during the operational period. In the DHS effluent, the SS concentration tended to increase during the early stage of temperature elevating periods (the beginning of spring), especially in the second year (day 550 to 650). Similar to the SS concentration, the COD concentration increased in this period (Fig. S2). On the other hand, the BOD concentration was maintained at a low level during the operational period, indicating that SS in the temperature elevating periods mainly consisted of low biodegradable organic substances.

The profile analysis of the wastewater stream along the height of the DHS

1 reactor showed that organic substances were removed mainly in the upper portion (Fig.
2 S3–5). The concentration of organic substances in the stream was maintained at a low
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4 level in the middle and lower portions. Nitrification occurred in the middle and lower
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6 portions, and nitrate accumulated in the effluent. The higher organic loading made
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8 preferable environments for heterotrophic bacteria, whereas the lower organic loading
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10 enhanced nitrifier growth because there was less competition for oxygen with
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12 heterotrophs. Several other studies have also presented similar observations with the
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14 UASB-DHS system (Machdar et al., 2000; Araki et al., 1999; Tandukar et al., 2005).
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16 These data suggested that the microorganism community composition, including the
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18 microfauna composition, in the DHS reactor probably differs along the height of the
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27 Despite the UASB effluent (which contains negligible amounts of DO) being
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29 supplied to the DHS reactor, DO concentration quickly increased to 3 mg L⁻¹ after
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31 segment 1 (0.4 m from the inlet). A high DO concentration was maintained throughout
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33 the reactor. The DO concentration of DHS effluent was more than 6 mg L⁻¹ on average.
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35 Oxygen was dissolved into the wastewater stream by a chemical equilibrium reaction
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37 with oxygen in the atmosphere during the wastewater stream trickling down through
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39 the sponge media. Presence of DO at 5 mm inside the sponge surface was confirmed
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41 by a previous microelectrode study (Araki et al., 1999). Abbassi et al. (2000) also
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43 reported that increasing DO concentration from 2 to 6 mg L⁻¹ led to an approximately
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45 25% reduction of mix liquor suspended solids (MLSS) in an activated sludge reactor.
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47 They assumed that deep diffusion of oxygen into flocs enhanced biodegradation of
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49 organic substances derived from dead cells in the flocs. Furthermore, the sludge
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51 degradation by microfauna was also enhanced under DO rich conditions (Hendrickx et
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53 al., 2009). Thus, the high DO concentration in the stream may enhance process
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performance, and also reduce excess sludge production from the DHS reactor.

3.2. SS production from the DHS reactor

The production rate of the excess sludge settled in the clarifier was only 0.09 g SS g⁻¹ COD removed (0.07 g VSS g⁻¹ BOD removed) for one year under the steady state (day 446–810). This rate was much lower than those of other UASB post-treatment processes of 0.37 g TS g⁻¹ COD removed in a submerged aerated biofilter (Gonçalves et al., 1998) and 0.29–0.33 g VSS g⁻¹ BOD removed in a rotating biological contactor (Castillo et al., 1997). The VSS/SS ratio of the excess sludge was 0.68 on average and the value was almost stable during the steady state. The SVI of the excess sludge was a sufficient level of 33 mL g⁻¹ SS, indicating the sludge was well stabilized.

The SS_{sum} (the sum of SS in the DHS effluent and excess sludge) production rate from the DHS reactor was observed at 0.18 g SS g⁻¹ COD removed (0.20 g VSS g⁻¹ BOD removed). The SS_{sum} production rate relied on the operational temperature, i.e., 0.32 g SS g⁻¹ COD removed below 15°C and 0.02 g SS g⁻¹ COD removed above 25°C. In particular, the SS_{sum} production rate increased during the temperature elevating period (between day 550 and day 650), indicating that the SS_{sum} production rate was strongly affected by season.

3.3. Retained sludge in the DHS reactor

The change of retained sludge concentration in the DHS reactor during the entire operational period is shown in Fig. 2. The DHS reactor was initiated using virgin sponge media without inoculums. The retained sludge concentration gradually

increased after the initiation and reached 24.7 g VSS L⁻¹ sponge (38.5 g SS L⁻¹ sponge) on day 446. Although the retained sludge concentrations after day 446 fluctuated, it was assumed that the retained sludge concentration became stable after day 446. The average VSS and SS concentrations under steady state were 26.9 g VSS L⁻¹ sponge and 39.6 g SS L⁻¹ sponge, respectively. The retained sludge concentration in the DHS reactor was about 10 times higher than that in the activated sludge process. Despite the fact that the average volumetric OLR was 0.9 kg COD m⁻³ day⁻¹ based on the sponge media volume in the DHS reactor, this high sludge concentration provided a low COD-VSS loading rate of 0.03 g COD g⁻¹ VSS day⁻¹ on average under steady state. The low food to microorganisms (F/M) ratio can be a main reason for low excess sludge production in DHS reactors. The membrane bioreactor (MBR) with low F/M ratio showed limited sludge production (Chang et al., 2011). Low and Chase (1999) also pointed out that the sludge production in an activated sludge process can be reduced by 44% when a lower F/M ratio was achieved by increasing the biomass concentration from 1.7 to 10.3 g L⁻¹.

Based on the amount of retained sludge and the SS_{sum} production from the DHS reactor, SRT can be calculated as >135 days. Similarly, a long SRT (95–125 days) in the DHS reactor was observed in a previous experiment (Tandukar et al., 2007). SRT is also an important factor for reducing excess sludge production from wastewater treatment processes (Troiani et al., 2011). For instance, the observed yield coefficient (Y_{obs}), corresponding to the SS_{sum} production rate, of activated sludge process with SRT of less than 6 days was 0.4–0.5 g MLSS g⁻¹ COD removed (Yoon et al., 2004), but it can be reduced as low as 0.23–0.32 g MLSS g⁻¹ COD removed in MBR with longer SRT of 20–40 days. The much longer SRT of >135 days in the DHS reactor may contribute to the low Y_{obs} of 0.18 g SS g⁻¹ COD removed. Under long SRT conditions

(namely the endogenous phase in microbial growth curve), incoming energy such as carbon sources and oxygen is used for cell maintenance rather than cell growth (Sun et al., 2007). Furthermore, long SRT conditions are preferred for growth of bigger organisms such as bacterial predators like protozoa and metazoa in wastewater treatment processes (Wei et al., 2003a).

In Fig. 3, the retained sludge concentration along the distance from the inlet is described. The retained sludge gradually developed from the upper portion of the reactor. Interestingly, the retained sludge concentrations at the upper portion were drastically changed after the sludge concentration became stable. Heavily accumulated sludge in the winter season ($30.7 \text{ g VSS L}^{-1}$, day 576) was significantly decreased at the beginning of spring ($24.7 \text{ g VSS L}^{-1}$, day 655). Simultaneously, SS concentration in effluent from the DHS reactor was increased. The retained sludge concentration slightly increased during summer (day 655 to 778). On the contrary, retained sludge concentrations in the lower portion were stable.

The comparison of excess sludge production with conventional processes is shown in Table 2. The results showed that the excess sludge production rate in the DHS reactor was much lower than those of conventional processes such as activated sludge process and other UASB post-treatment processes. The unique feature of the DHS process is that it can achieve a very long SRT with high sludge concentration even under short HRT conditions. Other processes, such as an extended aeration activated sludge process, require a longer HRT to maintain a long SRT, which is not favorable for wastewater treatment in terms of energy consumption and land requirement.

3.4. Endogenous respiration rate of the retained sludge

The endogenous respiration rates of the sludge sampled on day 624 were measured. The endogenous respiration rate at 25°C was 0.179 g O₂ g⁻¹ VSS day⁻¹ at 0.4 m from the inlet (segment 1), 0.029 g O₂ g⁻¹ VSS day⁻¹ at 1.6 m (segment 4), and 0.018 g O₂ g⁻¹ VSS day⁻¹ at 3.2 m (segment 8) (Fig. S6). The endogenous respiration rate decreased toward the outlet of the reactor. This tendency was similar to OLR in the DHS reactor. Thus, the DHS sludge exposed to a higher organic concentration had a greater endogenous respiration rate. It was reported that the endogenous respiration rate was 0.046 to 0.052 g O₂ g⁻¹ VSS day⁻¹ at 22–24°C in a membrane bioreactor (Witzig et al., 2002) and 0.072 to 0.192 g O₂ g⁻¹ VSS day⁻¹ at 20°C in an activated sludge (Kristensen et al., 1992). The endogenous respiration rate of DHS sludge was comparable to those aerobic sludges.

The endogenous respiration rates strongly depended on temperature. Sludge taken from segment 1 especially showed a drastic shift upon temperature. The endogenous respiration rates at 10 and 15°C were only 0.018 and 0.027 g O₂ g⁻¹ VSS day⁻¹, respectively, whereas those at 25 and 35°C were 0.179 and 0.368 g O₂ g⁻¹ VSS day⁻¹, respectively. The endogenous respiration rates of segment 1 at 25 and 35°C were similar to the COD-VSS loading rates of segment 1 (0.26 g COD g⁻¹ VSS day⁻¹).

3.5. Microfauna population in the retained sludge

The numbers of the microfauna in the retained sludge taken from segments 1, 4, and 8 of the DHS reactor are presented in Fig. 4. A number of protozoa and metazoa were found in the DHS sludge. The microfauna population changed along the reactor height

1 because of the different wastewater characteristics. The number of the protozoa in the
2 DHS sludge from segment 1 was $>84,000$ individuals (ind.) mL^{-1} sponge for
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4 arcellinida and $>40,000$ ind. mL^{-1} sponge for ciliophora. The number of ciliophora
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6 decreased from the inlet to the outlet, and was only $19,500$ ind. mL^{-1} sponge in
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8 segment 8. In contrast, the number of arcellinida increased from the inlet to the outlet,
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10 with almost double ($164,900$ ind. mL^{-1} sponge) found in segment 8. It is known that
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12 arcellinida prefer low OLR conditions in the activated sludge. Hence, the lower portion
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14 of the reactor, where the OLR was low, was the preferred environment for arcellinida.
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20 In addition, protozoa in activated sludge treating the same sewage as the
21 UASB-DHS system were counted. The numbers were $1,200$ ind. mL^{-1} for arcellinida
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23 and $4,400$ ind. mL^{-1} for ciliophora. These values fit with the number of key protozoa
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25 found in activated sludge (approximately $4,000$ ind. mL^{-1}) by Zhou et al. (2006).
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27 Comparing the two sludges, the number of protozoa in the DHS sludge is one order of
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29 magnitude greater than that in the activated sludge. However, the population of
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31 protozoa in the DHS sludge based on the sludge weight (ind. g^{-1} SS) is comparable to
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33 that in the activated sludge. The reason for the great number of protozoa in the DHS
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35 reactor is attributed to its higher sludge concentration, which is about 5–10 times
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37 higher than that in activated sludge.
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43 Various metazoa, known as slow growing microfauna, were also present in
44 the DHS sludge. The numbers of metazoa in the DHS sludge in segment 1 were $1,600$
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46 ind. mL^{-1} sponge for rotifera, $1,700$ ind. mL^{-1} sponge for nematoda, 900 ind. mL^{-1}
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48 sponge for oligochaeta, and 400 ind. mL^{-1} sponge for cladocera. In oligochaeta,
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50 *Aeolosoma* sp. and *Nais* sp. were mainly observed. The number of metazoa decreased
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52 from the inlet to the outlet. Metazoa are known predators of bacteria and protozoa, and
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54 are introduced to activated sludge to reduce the excess sludge production (Rensink and
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Rulkens 1997; Hellen et al., 2006; Liang et al., 2006; Huang et al., 2007; Wei et al., 2009; Khursheed and Kazmi, 2011). They are also known to improve sludge settling characteristics (Hellen et al., 2006; Wei et al., 2009). For instance, oligochaeta, which were present in the DHS sludge, are known to be one of the dominant species in the microbial ecosystem in sewage treatment processes (Rensink and Rulkens, 1997). They may contribute to sludge reduction by predation of other species such as bacteria and protozoa. It has been reported that the sludge reduction rates of the members of oligochaeta, *Aeolosoma hemprichi* and *Tubifex tubifex*, were determined as 0.8 mg VSS mg⁻¹ *Aeolosoma* day⁻¹ and 0.54 mg VSS mg⁻¹ *Tubifex* day⁻¹, respectively (Liang et al., 2006). The sludge production in a pilot activated sludge reactor treating settled domestic wastewater decreased from 0.40 to 0.15 g MLSS g⁻¹ COD removed when Tubificidae (oligochaeta) were added to the aeration tank (Rensink and Rulkens, 1997). On the other hand, Luxmy et al. (2001) suggested that metazoa are not effective for reducing sludge production in an aeration tank and Liang et al. (2006) pointed out that the contradictory opinions were related to the lack of effective methods to determine sludge reduction rates caused by microfauna. Therefore, the development of an adequate evaluation method is important.

Worms were not totally counted, but there were many in the DHS sludge (Fig. S7). To reduce the excess sludge by microfauna predation, the use of worms has begun to receive increasing attention (Khursheed and Kazmi, 2011). Wei et al. (2003b) reported that the density of worms was negatively correlated to sludge yield. The operating conditions, such as DO concentration, are also important for sludge degradation by worms. Hendrickx et al. (2009) found that a high DO concentration was required to maintain the maximum sludge consumption rate by worms added to the reactor because a significant decrease in the number of worms under low DO

concentration (below 1 mg L⁻¹) environments was observed. Sufficient DO, supplied through the DHS reactor, enabled the growth of worms in the DHS sludge. In addition, sponge media might be the preferred environments for worms. It is likely that the worms contributed to the reduction of sludge production from the DHS reactor.

4. Conclusion

The DHS reactor showed high effluent quality and only 0.09 g SS g⁻¹ COD removed of excess sludge was discharged. The DO, F/M ratio, SRT, endogenous respiration rate, and microfauna were determined as the important factors for the reduction of excess sludge. The study revealed that, with the excellent oxygen supply system of the DHS configuration, the DHS sludge has sufficient characteristics in terms of high concentration, relatively high endogenous respiration rate, and significantly high density and diversity of microfauna to minimize excess sludge production.

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Table 1. Summary of effluent quality in the system between day 446 and day 810.

	Sewage	UASB eff.	DHS eff.
SS, mg L ⁻¹	95 (25)	33 (21)	12 (12)
VSS, mg L ⁻¹	83 (22)	28 (18)	9 (9)
Unfiltered BOD, mg L ⁻¹	183 (63)	53 (23)	7 (4)
Unfiltered COD _{Cr} , mg L ⁻¹	292 (64)	113 (36)	36 (22)
Filtered COD _{Cr} , mg L ⁻¹	143 (34)	56 (12)	23 (9)
TKN, mg L ⁻¹	31 (4)	30 (4)	3 (3)
NH ₄ -N, mg L ⁻¹	22 (3)	27 (3)	3 (4)
NO ₃ -N, mg L ⁻¹	N.D.	N.D.	18 (4)
NO ₂ -N, mg L ⁻¹	N.D.	N.D.	N.D.
DO, mg L ⁻¹	N.D.	N.D.	6.6 (0.7)

Numbers in parenthesis are standard deviation,

N.D.=Not detectable

Table 2. Comparison of the excess sludge production with conventional treatment processes.

Treatment system	Wastewater	HRT	SRT	Temp.	Sludge concentration	Volumetric OLR	COD-VSS loading rate	Excess sludge production	Reference
		h	day	°C	g VSS L ⁻¹	kg COD m ⁻³ day ⁻¹	kg COD kg ⁻¹ VSS day ⁻¹	g SS g ⁻¹ COD removed	
ASP	Sewage	12	3–5	9–32	1.4	2.3	1.7	0.88	Tandukar et al., 2007
UASB	Sewage	4	45	28	13	3.5	0.27	0.15	Cavalcanti et al., 1999
SMBR	Industrial	8	200	25	12–15	3	0.11	0.115†	Sun et al., 2007
STMBR	Artificial	6	20–40	-	10–15	-	-	0.23–0.32	Yoon et al., 2004
RBC	Sewage (UASB eff.)	0.75	-	18	-	1.36**	-	0.29–0.33††	Castillo et al., 1997
SABF	Sewage (UASB eff.)	0.17	-	-	-	>5.0 (>1.2*)	-	0.37	Goncalves et al., 1998
DHS	Sewage (UASB eff.)	3.2	>135	10–28	27	0.85 (0.43*)	0.03 (0.02***)	0.09 (0.07††)	This study

ASP: Activated sludge process, UASB: Upflow anaerobic sludge blanket, SMBR: Submerged membrane bioreactor, STMBR: Separated type membrane bioreactor, RBC: Rotating biological contactor,

SABF: Submerged aerated biofilter, DHS: Down-flow hanging sponge, *: kg BOD m⁻³ day⁻¹, **: kg COD m⁻² day⁻¹, ***: kg BOD kg⁻¹ VSS day⁻¹, †: g VSS g⁻¹ COD removed, ††: g VSS g⁻¹ BOD

removed. RBC, SABF and DHS are post treatment processes of UASB treating sewage.

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2 **Figure captions**
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6 **Fig. 1.** Time courses of (A) temperature, (B) SS and (C) BOD during the entire
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8 operation period.
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10 **Fig. 2.** Change in the retained sludge concentration during the entire operational period.
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12 The arrows indicate the profile results in Fig. 3.
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15 **Fig. 3.** Profile of the sludge concentration in the DHS reactor.
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18 **Fig. 4.** The numbers of microfauna in the DHS sludge.
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22 *The black and white figure will be supplied for the printed version.
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Fig. 1. Time courses of (A) temperature, (B) SS and (C) BOD of the entire operational period.

Fig. 2. Change in the retained sludge concentration during the entire operational period.

The arrows indicate the dates in which the sludge profile data was obtained as shown in Fig. 3.

Fig. 3. Profile of the sludge concentration in the DHS reactor.

Fig. 4. Numbers of microfauna in the DHS sludge.