Development of a down-flow hanging sponge reactor for the treatment of low strength sewage
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ABSTRACT
The process performance of a down-flow hanging sponge (DHS) reactor for treating low strength sewage (biochemical oxygen demand (BOD) 20–50 mg/L) was investigated in Bangkok, Thailand. The hydraulic retention time (HRT) was set at 4 h during the start-up period and was reduced to 1.5 h in a stepwise manner. Throughout the 300-day operational period, the DHS reactor shows high performance with respect to the removal of total suspended solid (>90% total suspended solid removal efficiency). No clogging of sponge media was observed in response to the self-digestion phenomena of the biofilm. At a HRT of 1.5 h, the BOD removal efficiency was sufficiently high (about 85%). The pathogen Escherichia coli and other coliform bacteria were removed almost completely as well (removal was 99.4% and 98.1%, respectively). Regarding the retained sludge activity measurement, the nitrite oxidation rate was higher than the ammonium oxidation rate (0.031 and 0.022 gram of nitrogen per gram of volatile suspended solids per day, respectively). In the 300 days of operation, the amount of excess sludge production was negligible. Thus, no sludge treatment system is required. Introduction of the DHS system in developing countries is recommended because this system requires a relatively small area, and has low electricity consumption and operation costs.

Key words | DHS, direct treatment, trickling filter, sewage

INTRODUCTION
Energy and environmental issues have gained widespread attention in developing countries. Some countries, however, do not give adequate attention to wastewater treatment because of budget and technological limitations. In particular, the large size of wastewater treatment systems is an obstacle to their use in many developed countries. To promote the adoption of wastewater treatment systems in developing countries, the development of low cost and appropriate wastewater treatment systems is critical. To this end, the development of a techno-economic sewage treatment process adapted for decentralized treatment is necessary.

Recently, attached-growth aerobic treatment systems, such as trickling filter systems, have gained popularity because of features such as low biomass production, low energy consumption, and relatively short hydraulic retention time (HRT) compared with conventional activated sludge processes (Mahmoud et al. 2009; Guo et al. 2010). The down-flow hanging sponge (DHS) system is a type of trickling filter system that was developed decades ago using sponge (polyurethane foam) as a medium (instead of rock). Polyurethane foam has a porosity of up to 90% and a specific surface area of 2,400 m²/m³ (Tandukar et al. 2006a). Aeration is derived from flowing wastewater from the top to the bottom of the sponge along the reactor height.

The DHS system was developed as a post-treatment process for anaerobic reactors (upflow anaerobic sludge blanket (UASB)) for treatment of domestic sewage. The first generation DHS system was a cube type conducted on a laboratory scale (Agrawal et al. 1997); the DHS performed well with respect to removal of organic matter and nitrification, but other aspects of wastewater treatment were not complete. The second generation was a curtain-type DHS; a rectangular prism sponge was arranged similarly to a curtain (Tandukar et al. 2006a, b). The second generation
system was more efficient at removing organic matter than the first generation, but the effectiveness of the nitrification process was reduced. The third generation system contained a random packing type of media that was selected for easy scale-up (Tawfik et al. 2006a). Previous research showed that the DHS reactor is a compact and cost-effective treatment system for post-treatment of domestic sewage because of its simple construction and operation, and minimal maintenance requirements (Machdar et al. 2000; Tawfik et al. 2006b; Mahmoud et al. 2009).

The average biochemical oxygen demand (BOD) concentration of sewage in Bangkok, Thailand, is relatively low (BOD 20–50 mg/L) because of the use of a combined sewer system and the tropical climate. This concentration is approximately the same as that of effluent from UASB reactors for treatment of domestic sewage in Japan (Syutsubo et al. 2011). There are currently no reports on the direct application of the DHS system for domestic sewage treatment. In this study, the DHS system filled with a random packing type of media was applied for sewage treatment in Bangkok. Generally, UASB reactors for sewage treatment are operated for retention time periods (8 to 12 h). Also, the effluent contained some sulfide and soluble methane. These compounds lead to the competition of oxidation processes in the post-treatment system. So, the direct application of the DHS system is expected to be a more feasible method for the treatment of low strength wastewater.

The Bangkok metropolitan area has seven large sewage treatment stations and 14 small sewage treatment stations, which treat only 40% of the discharge produced in the area (Nisita 2012). Thus, construction of new treatment facilities is required. However, large treatment stations are not recommended because of associated high construction costs. In addition, activated sludge processing requires high amounts of energy. Sewage in Thailand is classified as low strength sewage because of the low organic matter content resulting from contamination by rainwater and/or canal water. Also at low influent BOD concentration, BOD removal efficiency based on energy consumption (kgBOD/kWh) is reduced in the present sewage treatment station (Nisita 2012).

Therefore, appropriate treatment technology is required for low strength sewage. Usually, the efficiencies of both biological organic degradation and energy for treatment tend to decrease as the organic strength of the wastewater decreases. The DHS system is useful for the treatment of low strength sewage because of its high energy efficiency. Installation of DHS systems for sewage treatment in communities will reduce the need for the construction of large treatment stations. Currently, there are no reports on the application of DHS systems for direct treatment of domestic sewage. The main objective of this research is to evaluate the process performance of DHS systems for the direct treatment of sewage with low organic matter content.

**METHODS**

**Reactor setup**

A pilot-scale DHS system was set up at the Thungkhru wastewater treatment plant, Bangkok. To properly perform the stable biodegradation process, the total height of the reactor should be 4 to 5 m (Tanaka et al. 2002). However, because of space limitations (ceiling height), the treatment unit was designed to contain two DHS reactors connected in series, each of which was 2.4 m in height, excluding the distributor unit. The schematic diagram of the DHS reactors is shown in Figure 1. The reactor consisted of a sewage distributor, six column segments (A1 to A6, B1 to B6), and a clarifier unit. The operation was conducted at ambient temperature (30–35 °C). The sponge was cylindrical in shape with a diameter of 3.3 cm and a height of 3.3 cm,
and was used as the packing material. The sponge had a void ratio of more than 90% per unit. To avoid compaction, the sponge was inserted into a net ring made from polyethylene and installed in all segments; 300 pieces of sponge media per segment.

The total bulk volume of the sponge media in the DHS reactor was 101.5 L. The packing ratio of the sponge media in each segment was about 53%, based on the volume of the sponge-filled portion of column. The wastewater distribution unit was set up at the top of the DHS to make sewage flow down through the sponge uniformly. There was no sponge media in the clarifier unit, and wastewater sampling for water quality analysis was performed here. The liquid volume of each clarifier was 17.2 L. At a HRT of 1 h, the retention time of the clarifier is only 10 minutes. Excess sludge produced in the first DHS reactor’s clarifier unit was pumped to the second DHS reactor. Because the DHS reactor provided adequate time for self-degradation of attached biomass (sludge), the amount of excess sludge produced was minimal, and that produced in the second DHS reactor’s clarifier unit was negligible. The reactors were initiated by being seeded (fed) with an activated sludge solution (1,500–1,500 mg volatile suspended solids (VSS)/L), harvested from the treatment centre of the Thungkhru wastewater treatment plant, for 10 days. After that, sewage (from household activities in the Thungkhru area) was continuously fed into the DHS reactor by a peristaltic pump at a flow rate 0.42 L/min. Wastewater was added to the top of the reactor via a distributor unit, then flowed from the top to the bottom of the reactor by gravity. As a result, the DHS reactor was operated with a HRT of 4 h (based on the sponge media volume). This HRT was maintained until day 97, at which time the reactor performance was stable. The HRT decreased from 4 h to 2 h, then to 1.5 h, then to 1 h in a stepwise manner. The organic loading rate (OLR) reached up to 1.34 kg COD (chemical oxygen demand)/m³·day based on the sponge media volume. This HRT was maintained until day 97, at which time the reactor performance was stable. The HRT decreased from 4 h to 2 h, then to 1.5 h, then to 1 h in a stepwise manner. The organic loading rate (OLR) reached up to 1.34 kg COD (chemical oxygen demand)/m³·day based on the sponge media volume. The reactor was operated continuously for 300 days.

Sampling and analysis

Both composite samples and grab samples were collected to investigate process performance with respect to water quality in the reactors. Sampling points were: influent, effluent from the first DHS (reactor A), and effluent from the second DHS (reactor B). Water samples were collected for 10 minutes every hour, and stored in a refrigerator. To investigate the performance of the DHS reactor, the COD, BOD (with the addition of allythiourea, which is also referred to as carbonaceous BOD), total suspended solids (TSS), various forms of nitrogen (ammonia, nitrate, nitrite, total nitrogen (TN)), and VSS of both influent and effluent were analysed. Analyses of dissolved oxygen (DO), pH, oxidation reduction potential, and temperature of the water samples were conducted on site twice per week. All analysis procedures followed Standard Methods (APHA 1998). The compact dry ‘Nissui’ EC plate (Nissui Pharmaceutical Co. Ltd, Japan) was used for the analysis of Escherichia coli (E. coli) and total coliforms.

Reactor profile experiment

To measure changes in water quality along the height of the reactor, a water quality profile experiment was conducted occasionally. Samples were collected from the reactor at 0, 0.8, 1.6, 2.4, 3.2, 4.0, and 4.8 m from the inlet. Both sludge concentration and wastewater concentration were analysed on days 59, 165, 226, and 299, at sampling points A1, A3, A5, B1, B3, B5, and BC (Figure 1). The following parameters were measured to investigate the performance of the DHS reactor: BOD, TSS and VSS, and concentrations of TN, ammonia, nitrite and nitrate.

For the analysis of sludge concentration, three sponges were randomly selected from each segment. Because sludge was present inside the sponge as well as on the surface, the sponge was squeezed and washed with distilled water to remove all the sludge. Sludge samples were analysed for TSS and VSS. Sludge samples were taken from positions A1 A3, A5, B1, B3, and B5 (Figure 1).

Nitrification activity of the retained sludge

From the profile experiment, the process performance of the DHS system clearly improved after day 165. Thus, nitrification activity of the retained sludge was measured starting on day 186. Measurement of nitrification activity was carried out on sludge samples harvested from different heights of the DHS reactor (A1, A3, and A5). DHS sludge was kept and cleaned with a buffer solution. Sludge was aerated at 25 °C for 6 h prior to the experiment.

For the experiment, NaHCO₃, chemolithotrophic medium, and buffer solution were added to a 500 mL flask. Sludge was added to the flask in a volume to produce a final sludge concentration of 2,000 to 3,000 mg VSS/L. The entire mixture was stirred and aerated continuously at 25 °C. Subsequently, to measure the actual potential of ammonia oxidation activity, NH₄Cl was added in the absence of organic carbon. Later, NaNO₂ in a concentration
of 10 mg-N/L was added to measure nitrite oxidation. A sample was taken from the flask, which was used for the analysis of ammonia, nitrite, and nitrate concentration every 30 m for at least 5 h.

Oxygen uptake rate measurement

Sludge samples from the measurement of nitrification activity were also used for the oxygen uptake rate (OUR) test. Sludge was mixed with distilled water in a 500 mL flask. Then, the flask was aerated for a few minutes and DO was measured using a DO meter every 30 s, without additional substrate for autolysis. Acetate and ammonia were used as substrates to measure organic removal efficiency and nitrification activity, respectively.

RESULTS AND DISCUSSION

Process performance

The DHS system showed high performance for the removal and trapping of TSS in the sponge media, even though the DHS was continuously fed with TSS/VSS in fluctuating concentrations. There were no problems related to clogging of the sponges because the biofilm on the sponge surface can be self-degraded because of the low sludge OLR. The DHS reactor was found to have high removal efficiency of TSS and VSS (Table 1).

Although the DHS system was operated under a low and fluctuating OLR, the removal efficiency of organic matter was high. This indicates that the water quality of the effluent is appropriate for discharge to reservoirs. From the time course of routine data of the BOD concentration of the DHS effluent, the effluent quality of the DHS was better than that produced by the present activated sludge system in Thungkhrui (Nisita 2012). The DHS system therefore performs better than the conventional activated sludge system.

As shown in Table 1, both total BOD and soluble BOD of the effluent were less than 5 mg/L over the course of the operational period. The removal efficiencies of total BOD and soluble BOD in the first DHS reactor (reactor A) at a HRT of 4 h were 74 and 57%, respectively. In the second DHS reactor (reactor B), the removal efficiencies of total BOD and soluble BOD were 18.9 and 16.1%, respectively. When HRT was reduced to 2 h, the DHS system maintained an adequate performance level.

In the first DHS reactor, the total BOD removal efficiency was 78% and soluble BOD removal efficiency was 62%.

At a HRT of 1.5 h, the removal efficiency followed the same trend as that observed at a HRT of 2 h. After 234 days, the HRT was reduced to 1 h. The DHS system still showed sufficient removal efficiencies for both total BOD and soluble BOD (76 and 64%, respectively, of those of the first DHS).

The average ammonium concentration in influent wastewater was 7.2 mg-N/L. The DHS reactor had a high removal efficiency for ammonium oxidation at all HRTs (Table 1). At a HRT of 4 h, the NH4 concentration of the effluent was 0.1 mg-N/L and ammonia removal efficiency was 98.6%. Also at a HRT of 2 h, NH4 removal efficiency remained at 98.5%. This system produced good quality effluent with low ammonium (0.1 mg-N/L); this is a result of the relatively low nitrogen loading rate of Thai domestic wastewater and the high efficiency aeration of the DHS system (DO of the effluent was 5.2 mg/L). This indicates that the nitrification process occurs to completion.

On day 190, the DHS reactor was operated at a HRT of 1.5 h. It showed high efficiency for the removal of ammonia (95.8% (0.2 mg-N/L) removal). The rainy season occurred from day 204 to day 227; the dilution of sewage by the rainwater caused a low nitrogen loading rate (Figure 2). However, the nitrification process continued to occur at a sufficient level. At a HRT of 1 h, the domestic wastewater concentration in the DHS reactors increased to levels that were equivalent to those before the 204th day. As shown in Table 1, nitrification efficiency of the DHS reactors was high at all HRTs; this indicates that the activity of nitrifying bacteria was not limited by oxygen, because DO in the effluent was high, and the concentration of nitrite is nearly zero.

The average TN concentration in domestic wastewater was 8.6 mg-N/L and soluble nitrogen was 6.8 mg-N/L. The DHS reactor can remove nitrogen through denitrification in the anoxic zone inside the sponge area (Agrawal et al. 1997). The nitrogen removal process continued to occur at a sufficient level. At a HRT of 4 h, the TN removal efficiency was 28.3% (6.0 mg-N/L of effluent) and soluble nitrogen removal efficiency was 15.1% (5.69 mg-N/L of effluent).

Nitrogen removal efficiency increased when the HRT was reduced to 2 h. Removal efficiencies of TN and soluble nitrogen in the DHS reactor were 38.2% and 32.9%, respectively. Under low HRT conditions, the carbon source tended to remain until lower part segments (such as A5). This indicates that the denitrifying bacteria were able to utilize the carbon source for denitrification.
Table 1 | Water quality data for all HRT operations

<table>
<thead>
<tr>
<th></th>
<th>Sewage</th>
<th>HRT 4 h</th>
<th>2nd DHS</th>
<th>Sewage</th>
<th>HRT 2 h</th>
<th>2nd DHS</th>
<th>Sewage</th>
<th>HRT 1.5 h</th>
<th>2nd DHS</th>
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<th>HRT 1 h</th>
<th>2nd DHS</th>
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<td></td>
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<td></td>
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<td>1st DHS</td>
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<td></td>
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<tr>
<td><strong>DO</strong></td>
<td>-</td>
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<td>5.4 (0.7)</td>
<td>-</td>
<td>4.8 (0.3)</td>
<td>5.0</td>
<td>-</td>
<td>5.2 (1.3)</td>
<td>5.3 (0.1)</td>
<td>-</td>
<td>3.6 (1.2)</td>
<td>5.1 (0.9)</td>
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<td><strong>TSS</strong></td>
<td>36 (24.1)</td>
<td>2 (1.5)</td>
<td>1 (0.9)</td>
<td>33 (22.8)</td>
<td>9 (5.3)</td>
<td>1 (0.9)</td>
<td>27 (9.7)</td>
<td>7 (9.0)</td>
<td>1 (0.6)</td>
<td>27 (21.2)</td>
<td>17 (18.2)</td>
<td>15 (27.6)</td>
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<tr>
<td><strong>VSS</strong></td>
<td>24 (13.3)</td>
<td>2 (1.6)</td>
<td>1 (0.6)</td>
<td>17 (8.9)</td>
<td>5 (2.9)</td>
<td>1 (0.6)</td>
<td>7 (4.2)</td>
<td>1 (0.7)</td>
<td>0 (0.1)</td>
<td>15 (8.9)</td>
<td>8 (6.4)</td>
<td>5 (7.5)</td>
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<td><strong>COD total</strong></td>
<td>67 (18.1)</td>
<td>34 (9.2)</td>
<td>22 (10.1)</td>
<td>63 (20.7)</td>
<td>36 (9.3)</td>
<td>25 (9.8)</td>
<td>46 (10.8)</td>
<td>29 (8.9)</td>
<td>18 (7.9)</td>
<td>56 (17.9)</td>
<td>35 (11.6)</td>
<td>24 (16.2)</td>
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<tr>
<td><strong>COD soluble</strong></td>
<td>37 (11.1)</td>
<td>24 (9.3)</td>
<td>15 (7.7)</td>
<td>34 (10.5)</td>
<td>22 (9.0)</td>
<td>17 (8.2)</td>
<td>27 (6.4)</td>
<td>19 (6.4)</td>
<td>14 (5.7)</td>
<td>30 (5.1)</td>
<td>20 (4.8)</td>
<td>15 (4.5)</td>
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<tr>
<td><strong>BOD total</strong></td>
<td>20 (5.5)</td>
<td>5 (0.4)</td>
<td>4 (0.8)</td>
<td>15 (5.5)</td>
<td>3 (1.2)</td>
<td>2 (0.9)</td>
<td>14 (4.6)</td>
<td>2 (0.5)</td>
<td>2 (0.1)</td>
<td>20 (2.9)</td>
<td>5 (2.0)</td>
<td>4 (1.2)</td>
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<tr>
<td><strong>BOD soluble</strong></td>
<td>9 (2.7)</td>
<td>4 (0.9)</td>
<td>3 (0.7)</td>
<td>6 (1.3)</td>
<td>3 (0.9)</td>
<td>2 (0.9)</td>
<td>7 (3.1)</td>
<td>2 (0.6)</td>
<td>2 (0.1)</td>
<td>9 (1.6)</td>
<td>4 (1.2)</td>
<td>3 (1.1)</td>
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<tr>
<td><strong>TN</strong></td>
<td>7 (2.8)</td>
<td>6 (1.7)</td>
<td>7 (2.4)</td>
<td>6.8 (1.2)</td>
<td>5 (1.3)</td>
<td>4.6</td>
<td>6.4 (1.9)</td>
<td>5.4 (1.7)</td>
<td>4.97 (1.6)</td>
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<td>4.9 (1.4)</td>
<td>4.1 (0.6)</td>
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<td><strong>NH₄-N</strong></td>
<td>7 (1.4)</td>
<td>0.1 (1.5)</td>
<td>1 (1.1)</td>
<td>6.9 (0.8)</td>
<td>0.1 (0.1)</td>
<td>0.1</td>
<td>5.7 (2.6)</td>
<td>0.2 (0.1)</td>
<td>0.2 (0.1)</td>
<td>7.4 (1.7)</td>
<td>2.0 (1.8)</td>
<td>0.2 (0.1)</td>
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<tr>
<td><strong>NO₃-N</strong></td>
<td>-</td>
<td>4.8 (1.7)</td>
<td>5.7 (3.1)</td>
<td>-</td>
<td>3.1 (0.7)</td>
<td>2.7</td>
<td>-</td>
<td>2.3 (1.1)</td>
<td>2.4 (1.2)</td>
<td>0.6 (0.2)</td>
<td>2.3 (0.6)</td>
<td>2.7 (0.6)</td>
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<tr>
<td><strong>NO²-N</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.1 (0.1)</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
<td>0.1 (0.1)</td>
<td>0.03 (0.03)</td>
<td>0.2 (0.2)</td>
<td>0.1 (0.1)</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td>1916 (1964)</td>
<td>17 (41)</td>
<td>4 (6)</td>
<td>1425 (718)</td>
<td>14 (17)</td>
<td>0.4 (2)</td>
<td>1282 (505)</td>
<td>65 (100)</td>
<td>8 (15)</td>
<td>826 (528)</td>
<td>72 (69)</td>
<td>19 (28)</td>
</tr>
<tr>
<td><strong>Total coliform</strong></td>
<td>12054 (17457)</td>
<td>289 (350)</td>
<td>90 (146)</td>
<td>13554 (10535)</td>
<td>438 (216)</td>
<td>67 (44)</td>
<td>9438 (2039)</td>
<td>1060 (606)</td>
<td>184 (227)</td>
<td>6779 (3566)</td>
<td>1408 (1683)</td>
<td>611 (13723)</td>
</tr>
</tbody>
</table>

Unit – mg/L except where stated otherwise.
The value in parentheses is standard deviation.
At a HRT of 1.5 h, TN removal efficiency decreased to 23.9% (5.0 mg-N/L of effluent) in the rainy season. At a HRT of 1 h, the treatment efficiency remained high (Figure 2). The TN concentration of the effluent was about 3.8 mg-N/L and the removal efficiency of TN was 42.6%.

Domestic sewage is a source of pathogens, exposure to which may negatively impact human health. In this experiment, the DHS reactor had high removal efficiencies of both E. coli and total coliforms, because maintenance of high DO condition in the DHS prevents growth of E. coli and total coliforms. The microorganisms (such as protozoa and metazoa) present on or inside the sponge surface can also degrade the pathogens. Table 1 shows the efficiency of pathogen removal. At a HRT of 4 h, E. coli removal efficiency was 90.3 and 67.1% in the first and second reactors, respectively. Even when the HRT was reduced to 1 h, the removal efficiency did not change significantly. The trend was the same for total coliforms. Removal efficiencies of both E. coli and total coliforms were sufficient under all HRT conditions.

**Sludge concentration**

Figure 3 shows sludge retention of the DHS reactor. After almost 300 days of operation, there was high accumulation of sludge in the sponge media. Sludge was deposited in the inside of the sponge media. Also, biofilm was formed on the surface of the sponge, especially in the upper portion of the segment. During the first 2 months of operation, the initial sludge concentration was about 12 gVSS/L-sponge in the first segment; the sludge concentration gradually increased to 25 gVSS/L-sponge after almost 300 days of operation. This sludge concentration is about 10 times higher than that of activated sludge processes. Therefore, the DHS system showed superior performance with respect to sewage treatment, compared with activated sludge processes. As shown in Figure 3, the accumulation of sludge was high 1.5 m from the top of the DHS reactor. As a result, most of the biodegradation processes occurred between 0 and 1.5 m from the top of the reactor. Over long-term operation, the sponge media did not require maintenance. Excess sludge production measured in the second DHS clarifier unit was 0.002 kgTSS/m³ at a HRT of 1 h; this is 89% lower than the excess sludge concentration of current activated sludge processes (0.018 kgTSS/m³).

**Nitrification activity**

After the 185th day of operation, retained sludge in the DHS system (reactor A) was subject to sludge activity
measurements (sludge from reactor B was not examined because the sludge concentration in the sponge media was low). In previous research, ammonia oxidation activity of retained sludge from the DHS sponge was 30.5 mg-N/gVSS·day (Machdar et al. 2000). This study showed the superior nitrification efficiency of the DHS reactor; ammonia oxidation activity observed in the sludge obtained from segment A3 and A5 was about 68–95 mg-N/gVSS-day (Figure 4).

**Oxygen uptake rate**

This experiment confirmed the oxygen utilization potential of autotrophs and heterotrophs in the retained sludge. Figure 5(a) shows the OUR at HRTs of 2 h and 1 h. Sludge in the first section (A1) has a higher specific OUR for heterotrophs than the second and third segments because this segment received enough nutrients and organic matter to activate the bacteria. At a HRT of 1 h HRT, OURs increased in all segments. Also, specific OURs varied between segments; heterotrophic OUR was higher in the upper segment (A1) and autotrophic OUR was higher in the lower segment (A5). The OURs of autotrophs are in the range reported by previous studies (0.06–0.13 gO2/gVSS-day) at an operating temperature of 25 °C operation (Tandukar et al. 2006b).

**Electricity consumption**

The DHS system, a type of trickling filter, had a lower electricity consumption than current activated sludge processes in use at Thungkrhu (0.23 kWh/m3). The electricity consumption of the DHS system can be calculated by simulating the Thungkrhu wastewater treatment plant under the following conditions: using 20 m of pump head (including head loss), 65,000 m3/day of water flow rate, and 70% pump efficiency. This provides an electricity consumption of 0.074 kWh/m3 of sewage for the DHS system, which represents a 68% reduction in electricity consumption. Also, the DHS system achieved high efficiency of BOD removal based on energy consumption (0.27 kgBOD/kWh, two to three times that of the activated sludge process).

**CONCLUSION**

The pilot-scale DHS reactors in Bangkok produced high-quality effluent with HRTs of 1–2 h. Organic matter, ammonia, and pathogens were adequately removed. Moreover, the DHS reactor is simple to operate and maintain, and is robust in construction. In addition, a high DO concentration was observed in the effluent, though the system did not require external aeration energy. Therefore, it is possible to use this DHS system for the direct treatment of domestic sewage. Furthermore, the DHS system has the potential to be used for small-scale treatment (at the community level) of sewage in developing countries because of the low energy and area requirements.

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