Treatment Performance of Practical-Scale Down-flow Hanging Sponge Reactor Using Sixth-Generation Hard Sponge Media

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Abstract
A down-flow hanging sponge (DHS) reactor with a lateral partition was filled with sixth-generation sponge media (DHS-G6), polyethylene sponges stiffened with epoxy resin, and third-generation sponge media (DHS-G3), polyethylene sponges wrapped in a plastic net, in a continuous experiment at a sewage treatment plant in India to assess and compare the treatment performances of the two sponge media. No clear differences between the different media were found in removal of biochemical oxygen demand (BOD), ammonium nitrogen and fecal coliform. The best performance was obtained at a hydraulic retention time of 2 h. The concentrations of respective components in the water treated by the DHS-G3 and DHS-G6 were as follows: BOD, 5 mg L⁻¹ and 7 mg L⁻¹; ammonium nitrogen, 4 mg N L⁻¹ and 6 mg N L⁻¹; and fecal coliform, 3.2 × 10⁴ 100 mL⁻¹ and 3.9 × 10⁴ 100 mL⁻¹. Performance levels fully satisfying the Indian discharge standards were obtained for all the above, except for fecal coliforms.

Keywords
Sewage treatment; down-flow hanging sponge; sponge media; removal of organics; nitrification

INTRODUCTION
A down-flow hanging sponge (DHS) reactor was developed as a method for post-treatment of the effluent from an up-flow anaerobic sludge blanket (UASB) reactor and has provided excellent treatment performance, equivalent to that of the activated sludge process, in a 10-year demonstration experiment in India (Okubo et al., 2015; Onodera et al., 2016). Since DHS reactors use a trickling filter-type method, they have several favorable characteristics: although post-treatment of effluent using DHS is an aerobic process, it does not require external aeration; it generates less excess sludge than activated sludge processes; it requires less area than other post-treatment processes for UASB; and maintenance of the reactors is simple (Uemura and Harada, 2010).

The properties of the sponge media at the core of DHS reactors must be improved, especially in terms of their workability to ease construction of large-scale reactors and their treatment performance. Currently, the best packing arrangement with regard to workability is “random packing” employing third-generation sponge (G3) media (Tawfik et al., 2008) and sixth-generation sponge (G6) media (Onodera et al., 2014).

The G3 medium is a soft type made of polyurethane sponge. To prevent compaction of the sponge, the exterior is covered with a cylindrical polyethylene plastic net (Tawfik et al., 2008). In contrast, the G6 medium is a polyethylene sponge stiffened with epoxy resin. The reinforcement with epoxy resin reduces porosity, but this configuration has the advantage of not needing a plastic frame to protect against compaction (Onodera et al., 2014).

We have conducted a demonstration experiment with a DHS reactor at a sewage treatment plant in Karnal, India (Okubo et al., 2015; Onodera et al., 2016; Okubo et al., 2016). This study describes a continuous experiment with a practically sized, re-built DHS reactor. A lateral partition was installed in the reaction zone in an existing DHS reactor, and each side was filled with G3 and G6...
media in a random-packing arrangement. The objective was to compare and evaluate the treatment performance of these sponge media.

**EXPERIMENTAL METHOD**

**DHS reactor**

Fig. 1 shows images and specifications of the G3 and G6 media, and a schematic diagram of the practical-scale DHS reactor used for this study. This reactor was installed in a sewage treatment plant in Karnal, India, that employs UASB reactors. The reaction zone of the DHS reactor consisted of a concrete cylinder (5.5 m in diameter and 5.3 m high), with a reactor tower volume of 126 m$^3$ (Okubo et al., 2015; Onodera et al., 2016). Gaps of 15–28 cm were set between the filled layers to promote oxygen uptake by the water sprayed on the DHS. Ventilation ports were incorporated into the reactor to improve air uptake. To compare the performances of the sponges, a lateral partition was installed in the reaction zone, and the spaces were filled with G3 or G6 media.

**Sponge media**

The G3 medium consists of a soft, cylindrical sponge (32 mm in diameter and 32 mm high) made of polyurethane, and is wrapped in a polyethylene plastic net to prevent compaction (Fig. 1) (Okubo et al., 2016). The porosity of the G3 medium is quite high (98%). A preliminary continuous experiment was conducted in the practical-scale DHS reactor for 491 days using only G3 media (Okubo et al., 2016). Rebuilding the reactor to contain both G3 and G6 media required approximately 2 months, so all the G3 media were temporarily removed from the reactor and stored in a moist environment to prevent drying. Before re-filling the reactor, nine G3 media were randomly selected for determination of sludge weight. The mean sludge concentration was 13.7 grams of volatile suspended solids (gVSS) m$^{-3}$ sponge. A total of 796,000 G3 media were required to fill one side of the reactor. The filling ratio was 32.5%.

The G6 medium, polyethylene sponge coated with epoxy resin, is shaped like a hexagonal prism (32 mm high and 42 mm wide), with an 18 mm diameter hole to increase its surface area (Fig. 1). This design helps maintain aerobic conditions by exposing more of the sponge surface to air (Onodera et al., 2014). The G6 media are hard, which eliminates the need for reinforcing structures to prevent compaction, but the epoxy coating reduces their porosity to 70%. The G6 media were free of sludge when first placed in the reactor. A total of 486,000 G6 media were used to fill the other side of the reactor; the total effective volume was 19.3 m$^3$. The filling ratio was 30.6%. The filling conditions for the two sponge media were nearly identical, allowing comparison of their treatment performances. Hereinafter, the sides of the DHS reactor filled with G3 and G6 media are referred to as DHS-G3 and DHS-G6, respectively.

**Operating conditions**

The DHS reactor was operated under three conditions in this experiment: from the beginning to day 111 (Phase 1), the flow rate was 500 m$^3$ day$^{-1}$ (hydraulic retention time [HRT] based on sponge volume, 1.97 h for DHS-G3, 1.85 h for DHS-G6); from day 112 to day 317 (Phase 2), the flow rate was 1,000 m$^3$ day$^{-1}$ (HRT, 0.98 h for DHS-G3, 0.93 h for DHS-G6); and from day 318 to day 390 (Phase 3), the flow rate was 750 m$^3$ day$^{-1}$ (HRT, 1.31 h for DHS-G3, 1.24 h for DHS-G6).

**Analytical methods**

The analysis was conducted on the sewage and the effluents from UASB, DHS-G3 and DHS-G6. The effluent samples from DHS-G3 and DHS-G6 were taken directly from the bottom layer of each stack. The chemical oxygen demand (COD) was measured using potassium dichromate, and ammonium nitrogen (NH$_4^+$-N) was measured using the salicylic acid method. Both measurements were carried out in a DR-890 Portable Colorimeter (HACH). The biochemical oxygen demand
was analyzed by adding N-allylthiourea (ATU) to prevent the overestimation caused by nitrification (APHA 2005). The most probable number (MPN) of fecal coliform (FC) was determined using Difco-A1 medium (Becton, Dickinson and Company).

**EXPERIMENTAL RESULTS AND DISCUSSION**

**Treatment performance during continuous operation**

Fig. 2(A) shows the daily variation of temperature of the incoming sewage. The temperature fluctuated between approximately 14°C and 33°C throughout the year. The UASB effluent and incoming sewage were about the same temperature, while the DHS effluent was found to be approximately 2°C lower than the sewage or the UASB effluent.

Fig. 2(B) shows the change in BOD with elapsed time. The mean BOD throughout the test period was 153 mg L⁻¹ (standard deviation of ±58 mg L⁻¹) in the sewage and 66 (±17) mg L⁻¹ in the UASB effluent. In comparison, the DHS effluent had a BOD of 5 (±4) mg L⁻¹ from DHS-G3 and 7 (±5) mg L⁻¹ from DHS-G6 in Phase 1, 7 (±3) mg L⁻¹ from DHS-G3 and 7 (±3) mg L⁻¹ from DHS-G6 in Phase 2, and 12 (±7) mg L⁻¹ from DHS-G3 and 11 (±5) mg L⁻¹ from DHS-G6 in Phase 3.

As mentioned above, the G3 media had a certain amount of attached sludge at the beginning of the experiment, but had no contact with wastewater for 2 months. Consequently, the attached sludge was considered to be inactive. Although the continuous operation of DHS-G6 was started with no attached sludge, both DHS-G3 and DHS-G6 reached stable BOD treatment performances quite soon after the start of operation. This is a typical characteristic for DHS at start-up and is probably attributable to the physical elimination of organics such as adsorption and filtering (Okubo et al., 2016). Thereafter, the sludge attached to the G6 media gradually thickened, and the contribution of biodegradation to removal of BOD increased.

The BOD load per sponge was 1.59 (±0.5) kg BOD m⁻³ sponge day⁻¹ in DHS-G3 and 1.69 (±0.5) kg BOD m⁻³ sponge day⁻¹ in the DHS-G6 during Phase 2, and 1.10 (±0.3) kg BOD m⁻³ sponge day⁻¹ in DHS-G3 and 1.17 (±0.3) kg BOD m⁻³ sponge day⁻¹ in DHS-G6 during Phase 3. The effluent BOD concentrations in each DHS were somewhat worse in Phase 3 than Phase 2, although BOD loads were lower in Phase 3 than in Phase 2. One of the reasons for this was probably a reduction in the activity of the attached sludge due to a 13-day stoppage of operation of the DHS from day 323 to day 335 to repair a water pump. Furthermore, ambient temperatures reached high levels during this period. This might cause desiccation of the attached sludge. Nevertheless, the effluents from both DHS-G3 and DHS-G6 throughout the experimental period satisfied the Indian discharge standard for BOD of 30 mg L⁻¹. In terms solely of BOD removal, these results clearly indicate that the discharge standard could be met by operating the reactor at a short HRT of approximately 1 h.

The geometric mean levels of FC during this experiment were 1.9 × 10⁷ MPN 100 mL⁻¹ in sewage, 1.3 × 10⁷ MPN 100 mL⁻¹ in UASB effluent, 3.2 × 10⁴ MPN 100 mL⁻¹ (Phase 1), 3.8 × 10⁴ MPN 100 mL⁻¹ (Phase 2) and 8.2 × 10⁵ MPN 100 mL⁻¹ (Phase 3) in the effluent from DHS-G3 and 3.9 × 10⁴ MPN 100 mL⁻¹ (Phase 1), 4.9 × 10⁴ MPN 100 mL⁻¹ (Phase 2) and 1.9 × 10⁵ MPN 100 mL⁻¹ (Phase 3) in the effluent from DHS-G6. We expected treated levels around 10⁴, but levels satisfying the Indian standard for religious ablutions (1.0 × 10³ MPN 100 mL⁻¹) were not achieved.

Fig. 2(C) shows the variations in NH₄⁺-N with time. The mean NH₄⁺-N levels throughout the experimental period were 24 (±8) mg L⁻¹ for sewage (data not shown) and 26 (±7) mg L⁻¹ for UASB effluent. The NH₄⁺-N in the UASB effluent tended to increase after day 100 when the temperature of sewage decreased. A previous study also showed that NH₄⁺-N tends to increase as sewage temperature decreases and conversely decrease as sewage temperature increases (Onodera et al., 2016). Since NH₄⁺-N in the UASB effluent showed the same pattern of fluctuation, it might have been affected by variations in the temperature of the incoming sewage. While effluents from both DHS-G3 and DHS-G6 during the experimental period showed mean NH₄⁺-N levels around 5 mg L⁻¹ in Phases 1 and 2, these levels increased to around 14 mg L⁻¹ in Phase 3. Focusing on the
start-up period, NH$_4^+$-N levels in the effluents of DHS-G3 and DHS-G6 tended to decrease until day 25 and stabilized thereafter. This indicates that the nitrifying bacteria quickly grew until around day 25, contributing to the stable nitrification performance. This is attributed to the porosity of the sponge media with high void volume, which provides locations for nitrifying bacteria to attach and grow (Onodera et al., 2014). The deterioration in water quality in Phase 3 must also be due to the desiccation of attached sludge while the reactor operation was stopped, and to the inactivity of the nitrifying bacteria. Another potential reason for the decline in nitrification performance is that the nitrifying bacteria were overwhelmed by the proliferation of heterotrophic bacteria due to operation during Phase 2 under high BOD load conditions.

Fig. 3 shows the variation in the NH$_4^+$-N removal with HRT in DHS reactors with various types of sponge media in practical-scale experiments previously conducted in Karnal, India. This figure indicates that improvement of the NH$_4^+$-N removal can be expected if the HRT is lengthened, reaching levels exceeding 80% when the HRT of the DHS is controlled to be longer than approximately 1.5 h.

Moreover, an assessment of the effect of relatively low temperature on nitrification under identical BOD load conditions in Phase 2 (water temperatures in the range 20–35°C) revealed a tendency for the NH$_4^+$-N removal to decrease as the water temperature decreases (Fig. 4). Some decreases in the NH$_4^+$-N removal were also observed even when the water temperature was higher than 30°C, but these seem to have been due to unexpected increases in the concentration of organic compounds or of NH$_4^+$.N.

Changes in water quality parameters in the direction of flow through the DHS
Fig. 5 shows the changes in dissolved oxygen (DO), BOD, NH$_4^+$-N, and NO$_3^-$-N in the direction of flow through DHS-G3 and DHS-G6 between day 116 and day 213. Both DHS-G3 and DHS-G6 showed a similar tendency in all the parameters. On day 116, when the UASB effluent had a relatively high BOD of 60 mg L$^{-1}$, BOD decreased in a nearly linear manner from the DHS influent to the DHS effluent (water from the sixth sponge layer). On day 213, when the incoming water had the relatively low BOD of 38 mg L$^{-1}$, the degradation also tended to decrease linearly through the first and second layers, but the degradation pattern became more moderate in the third layer in which the BOD had decreased below 15 mg L$^{-1}$. The final BOD in the effluent was 5 mg L$^{-1}$. As seen on day 116, low-quality UASB effluent may worsen the quality of DHS effluent. Maintenance and management of the upstream UASB reactor is essential to obtain high-quality effluent by DHS treatment.

Nitrification was promoted as the concentration of organic substances decreased in the downstream direction, as noted in a previous study (Tandukar et al., 2005). The NH$_4^+$-N removal rates of both DHS-G3 and DHS-G6 reached 0.7 kg N m$^{-3}$ sponge day$^{-1}$ on day 116. At the beginning of operation of DHS-G6, the reactor was filled with clean sponge media with no attached sludge, but the profile on day 116 indicated the same level of substrate degradation as in DHS-G3.

Summary of DHS-G3 and DHS-G6 treatment performances
Table 1 shows the results from this study. The listed values for sewage and UASB effluent are averages throughout the test period, while those from DHS-G3 and DHS-G6 are averages for each phase. Except for FC, the effluent quality obtained in both systems well satisfied the Indian discharge standards (BOD ≤ 30 mg L$^{-1}$; NH$_4^+$-N ≤ 50 mg L$^{-1}$; FC ≤ 10$^3$ 100 mL$^{-1}$). The lowest concentrations of F. coli in this study were found under the flow rate condition of 500 m$^3$ day$^{-1}$ (Phase 1); NH$_4^+$-N levels also showed good levels, around 5 mg L$^{-1}$. Therefore, the overall assessment of removal of organics, FC and NH$_4^+$-N, suggests that an HRT of approximately 2 h should be an appropriate operating condition.

Analysis of variance in the effluent quality from DHS-G3 and DHS-G6 did not reveal any significant differences in any of the quality items (critical region, p > 0.05), indicating that DHS-G3
and DHS-G6 have similar treatment performances.

CONCLUSION
The performances of practical-scale DHS-G3 and DHS-G6 for the treatment of municipal sewage in India were evaluated simultaneously. There were no clear differences in removal of organics, F. coli or NH$_4^+$-N between these DHS processes. The best performance was obtained at an HRT of 2 h for both DHS-G3 and DHS-G6, and the quality of the effluent from both well satisfied the Indian discharge standards, except those for F. coli. According to the results obtained in this study, DHS-G6 is a promising technology, not only for treatment of municipal sewage at a large scale, but also for domestic wastewater treatment at a small scale for rural areas in developing countries.

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Figure 1. Images and specifications of the third-generation (G3) and sixth-generation (G6) media, and a schematic diagram of the down-flow hanging sponge (DHS) reactor filled with these media.
Figure 2. Changes in sewage temperature (A), biochemical oxygen demand (BOD) (B), and NH$_4^+$-N (C) during the experimental period.

Figure 3. Relationship between NH$_4^+$-N removal ratio and hydraulic retention time (HRT) obtained in experiments using practical-scale down-flow hanging sponge reactors with various types of
sponge media.

**Figure 4.** Relationship between NH$_4^+$-N removal and sewage temperature during Phase 2 (from day 112 to day 317).

**Figure 5.** Changes in water quality parameters in the downstream direction in third- and sixth-generation down-flow hanging sponge reactors (DHS-G3 and DHS-G6, respectively).
### Table 1. Summary of water quality parameters during a continuous experiment using third- and sixth-generation down-flow hanging sponge reactors (DHS-G3 and DHS-G6, respectively).

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sewage</th>
<th>UASB eff.</th>
<th>G3</th>
<th>G6</th>
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<tr>
<td></td>
<td></td>
<td>Phase1</td>
<td>Phase2</td>
<td>Phase3</td>
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<tr>
<td>Temp. (°C)</td>
<td>26 (5)</td>
<td>19 (5)</td>
<td>26 (4)</td>
<td>28 (1)</td>
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<td>COD_{Cr} (mg L(^{-1}))</td>
<td>402 (139)</td>
<td>25 (13)</td>
<td>32 (9)</td>
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<tr>
<td>BOD (mg L(^{-1}))</td>
<td>153 (58)</td>
<td>5 (4)</td>
<td>7 (3)</td>
<td>12 (7)</td>
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<tr>
<td>FC (MPN 100 mL(^{-1}))</td>
<td>1.9 x 10(^7)</td>
<td>3.2</td>
<td>3.8</td>
<td>8.2</td>
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<tr>
<td>NH(_4^+)-N (mg L(^{-1}))</td>
<td>24 (8)</td>
<td>4 (6)</td>
<td>6 (6)</td>
<td>14 (3)</td>
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<table>
<thead>
<tr>
<th>Removal</th>
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<th>UASB+G6</th>
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<tr>
<td>COD_{Cr} (%)</td>
<td>53 (14)</td>
<td>93 (5)</td>
<td>91 (4)</td>
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<tr>
<td>BOD (%)</td>
<td>54 (15)</td>
<td>96 (4)</td>
<td>95 (3)</td>
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<tr>
<td>FC (log (10))</td>
<td>0.5</td>
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<td>2.2</td>
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<td>NH(_4^+)-N (%)</td>
<td>84 (22)</td>
<td>75 (16)</td>
<td>36 (16)</td>
</tr>
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Numbers in parentheses represent standard deviations.

### REFERENCES


