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Evaluation of Water Distribution and Oxygen Mass Transfer in Sponge Support Media for a Down-flow Hanging Sponge Reactor

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ABSTRACT: A down-flow hanging sponge (DHS) reactor has been developed for sewage treatment, mainly in developing countries. This novel reactor employs polyurethane sponge material as a support medium, which promises a proliferation of a large amount of biomass, offering excellent pollutant removal capability. Three types of sponge medium were evaluated with respect to water distribution and oxygen mass transfer. Water was supplied to the device, which consisted of 40 pieces of sponge media connected in series, and a tracer experiment was carried out. The ratios of actual hydraulic retention time (HRT) to theoretical HRT were in the range of 25-67% depending on the type of support medium. By supplying deoxygenated water from the top of the device, the overall volumetric oxygen transfer coefficient, K_La, was evaluated. Despite the non-aerated conditions, the K_La values of the support media were very high, in the range of 0.56-4.88 (1/min), surpassing those of other mechanically aerated processes. Furthermore, it was found that the suspended solids (SS) concentration in the influent played a role in increasing the actual HRT/theoretical HRT ratio, suggesting that managing the influent SS concentration is prerequisite for preventing clogging problems in the DHS.

Key words: down-flow hanging sponge, water distribution, hydraulic retention time, overall volumetric oxygen transfer coefficient, sponge medium

INTRODUCTION

Uncontrolled urbanization, coupled with a lack of sanitary infrastructure in developing countries, has led to severe pollution of local aquatic bodies. Although there is an urgent need to improve water supply and sanitation services, the high cost of the infrastructure and the scarcity of development funds are major problems. The objectives for selecting a sewage treatment process applicable in most developing countries can be summarized as follows: (1) the cost of the process should be as low as possible, (2) the process should be as simple and as easy to maintain as possible, and (3) the size of the treatment facility should be as compact as possible. Under the current conditions in developing countries, introducing expensive and energy consuming conventional wastewater treatment methods, such as the activated sludge process (ASP), is unrealistic.

With these factors as a background, a down-flow hanging sponge (DHS) reactor has been proposed and investigated as an appropriate sewage treatment process for developing countries. It was found to be very efficient, not only in removing residual COD but also for nitrogen and pathogen removal (Uemura & Harada, 2010). The method uses an attached growth-type treatment process employing polyurethane sponges as support media for the growth of bacteria (Fig. 1). The concept for the reactor is based on a conventional trickling filter. Air dissolves into the wastewater as it flows down the DHS reactor, so there is no need for external aeration. The polyurethane sponges are insoluble, non-biodegradable, inexpensive, and highly mechanically stable. Furthermore, the sponge material has a void volume of more than 98%, which provides many excellent sites for growth and attachment of active biomass, resulting

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in a significant increase in sludge retention time (SRT). Sludge is retained both inside and outside the sponge media. The enormous amount of biomass and very long SRT expedite the treatment process.

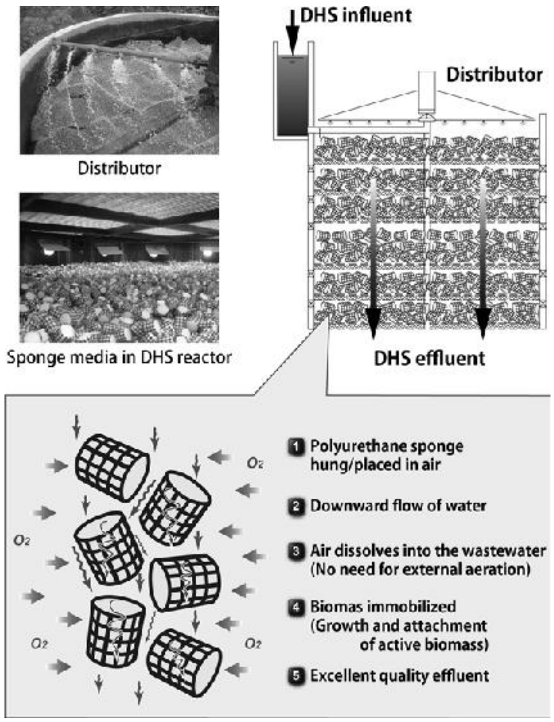

Fig. 1. DHS reactor concept

The objectives for selecting sponge media for a DHS reactor can be summarized as follows: (1) Water should be fully distributed inside the sponge. The performance of a DHS reactor depends upon how uniformly wastewater is distributed in the sponge media. Having the least possible dead volume enhances the contact between the substrate and the microbes. (2) Oxygen mass transfer to water flowing through the sponge media is important in supplying oxygen to microorganisms inhabiting the sponge media. (3) The sponge media should be able to withstand compaction. Because the sponge media absorb water, which increases their weight, the media in the lower part of the reactor must carry that extra force. (4) The sponge material should have a good affinity for microorganisms. (5) The sponge medium should tolerate long-term use.

So far we have accumulated performance data on DHS reactors from pilot to demonstration scales. In these tests, only the shape and method of packing of the sponge media were investigated (Uemura & Harada, 2010). Now, however, DHS reactors have come into wide use in fields other than sewage treatment, from treatment of various kinds of industrial wastewater (Uemura *et al*., 2010; Ikeda *et al*., 2013) to being used as a culture accumulation device for enriching marine microorganisms (Aoki *et al*., 2014). It has now become necessary to pay more attention to the characterization of the sponge media in order to optimize the system's operation in different uses.

Among the desirable traits listed above, previous studies have verified that the sponges perform excellently for characteristics (3) to (5). Improving the outer plastic frame improved the sponges' resistance to compaction (Uemura & Harada, 2010). It has already been confirmed that the sponge medium has a great affinity for microorganisms, retaining 20-30 g of biomass (dry weight) per liter of sponge, which is almost 10 times that of ASP (Onodera *et al.*, 2013 & 2014, Okubo *et al*., 2015). Furthermore, the polyurethane sponge medium we have mainly used in our experiments has been confirmed as being able to endure more than five years of use, according to the results of a demonstration DHS plant at an Indian sewage treatment plant (Okubo *et al*., 2015). Therefore, in this study, we examined (1) water distribution in the sponge media and (2) oxygen mass transfer from the atmosphere to water flowing down the sponge media.In packing-type DHS reactors, wastewater is supplied from the top of the reactor column, which is packed with sponge media as shown in Fig. 1. Adhesion and accumulation of suspended solids (SS) on the sponge media may influence water distribution. Therefore, in this study, we evaluated water distribution in the packing-type DHS reactor with and without SS in the influent.

MATERIALS & METHODS

Sponge support media: The sponge media used for this study are shown in Fig. 2. Sponge media A and B were both polyether-based urethane sponge (cell sizeR″500 µm, porosity = 98%, Sekisui Plastics Co. Ltd). Sponge medium A was made by putting sponge cubes (32 mm x 32 mm) into cylindrical plastic frames (32 mm in diameter, 32 mm tall, with 5.5 mm intervals) to protect them from compacting. The plastic frame was approximately 2.0 mm thick. The volume of one unit of the medium was approximately 19.7 cm^3, with a specific surface area, the ratio of surface area to volume, of 2.05 cm^2/cm^3. Although the basic structure of this type of medium has been altered slightly, it is very similar to that used for previous long-term DHS reactor experiments at pilot to demonstration scales (Uemura & Harada, 2010). Thus, the performance and durability of sponge medium A was guaranteed. Consequently, we compared the other sponge media to sponge medium A.

Sponge medium B was newly developed for use in future full-scale DHS plants, mainly for cost considerations. Therefore, it had never previously been employed in DHS reactor experiments. Sponge medium B was made by putting each cylindrical sponge piece (40 mm in diameter, 44 mm tall) into a cylindrical plastic frame (40 mm in diameter, 44 mm tall, with 20 mm frame

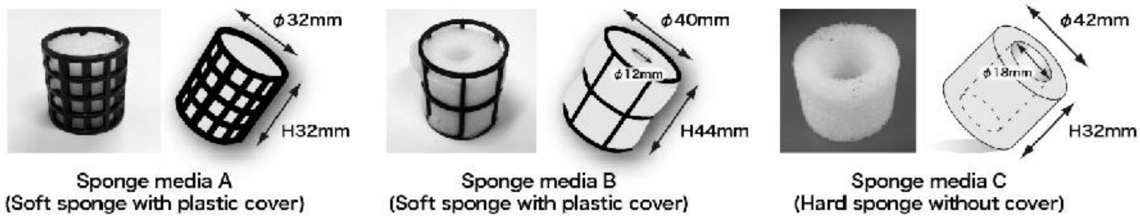

Fig. 2. Sponge support media used in this study

intervals). The thickness of its plastic frame was also approximately 2.0 mm. Because sponge medium B is bigger than sponge medium A, fewer pieces would be needed to fill a DHS reactor, making it cheaper to use. However, the specific surface area was significantly smaller, so we drilled a hole 12 mm in diameter through each sponge from the top surface, creating a small hollow tube. As a result, the specific surface area increased from 1.61 cm^2/cm^3 (without the hole) to 2.17 cm^2/cm^3 (with the hole). The volumes of both media were calculated using the inner space of the plastic frames.

Sponge medium C is a rigid sponge manufactured by copolymerizing polyurethane with epoxy resin for hardening. Its porosity is only 70% but it does not need an outer plastic frame to prevent compaction. The rigid sponge was formed into small hollow tubes that were 32 mm long and had external and internal diameters of 42 mm and 18 mm, respectively. Each sponge has a volume of 28.0 cm^3 and a specific surface area of 2.08 cm^2/cm^3. The average pore size was 1.6 mm, larger than that for the material used for sponge media A and B.

Experimental set-up (sponge hanging method): The experimental device used to evaluate the water distribution and oxygen mass transfer is shown in Fig. 3. The device comprises 40 sponge media linked diagonally using nylon strings, hung from the ceiling of our laboratory. The total sponge volumes of the devices were 788 cm^3 for medium A, 1447 cm^3 for B, and 1120 cm^3 for C. The device was placed in a temperature controlled room set at 25^{o}C unless otherwise stated. This experimental setup is called the sponge hanging method.

Evaluation of water distribution: The ratio of actual hydraulic retention time (HRT) to theoretical HRT was determined by measuring the actual HRT of the sponge media using a tracer, because the ratio was assumed to be a good index to measure the water distribution in the sponge media. The theoretical HRT is given by the following equation.

$$T = V/Q \qquad (1)$$

T: theoretical HRT (min)
V: total sponge void volume (mL), given by total sponge volume x porosity
Q: flow rate (mL/min)

The hydraulic characteristic, which measured the distribution of residence time in the sponge support media, was determined by adding 0.01 mL of saturated NaCl solution to the top of the experimental device. The mean residence times or actual HRTs in the devices with different sponge support media were then calculated from the concentration of the tracer in the effluent over time (JSWA, 2012). The conductivity was measured by an electric conductivity meter (TOADKK CM-201, Tokyo) in a small sedimentation tank (20 mL) set at the lowest part of the device.

Oxygen mass transfer: In this study, we used the oxygen transfer coefficient (K_La) to evaluate the ability of the sponge support media to supply oxygen to the microorganisms. K_La is a coefficient indicating the ability of aeration tanks and devices to transfer oxygen from the gas phase to the liquid phase per time. It has been used often to evaluate aeration tank in activated sludge processes (ASP). K_La is calculated with the following equation (JSWA, 2012):

$$K_La = 1/t \times \ln(C_s/(C_s - C_t)) \qquad (2)$$

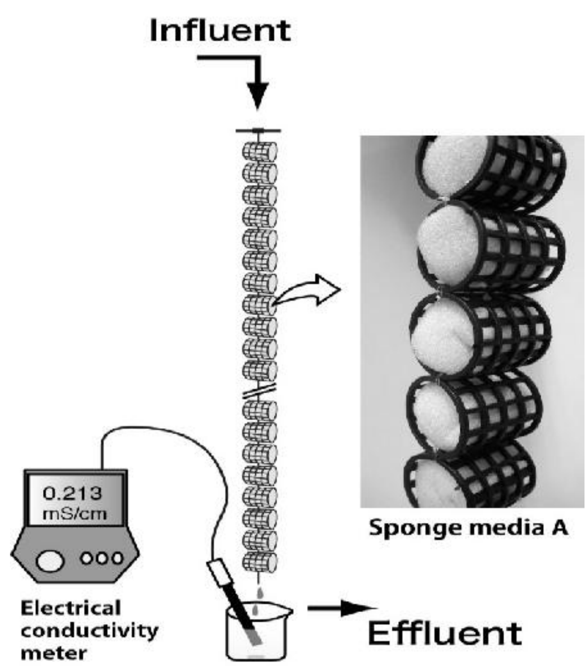

Fig. 3. Experimental hanging sponge setup

C_s: saturated dissolved oxygen concentration (mg/L)
C_t: dissolved oxygen concentration in the effluent at time t (mg/L)

Because Eq. (2) is a function of time, the time (t) that the water has been flowing down at the measurement point can be calculated based on the actual HRT. Ion exchanged water was stored in a 10-L screw cap bottle and aerated with nitrogen gas to remove oxygen, then supplied from the top of the experimental device. To determine the dissolved oxygen (DO) in the stream flowing through the sponge media, Clerk-type DO microelectrodes (OXY meter, UNISENSE Co., Ltd.) were used as in a previous study (Uemura *et al*., 2012). The K_La was then calculated from the measured DO over time. The calculated K_La was corrected for standard conditions (1 atm of pressure and 20°C) using the following equation (JSWA, 2012):

$$K_La\,(20°C) = K_La_{(\theta°C)} / 1.024^{(\theta-20)} \tag{3}$$

θ: actual water temperature (°C)

K_La values were determined using the same method described above for a device made of 40 table tennis balls each 44 mm in diameter (Nittaku Co., Ltd.) to model a material that does not absorb water at all. Furthermore, to ensure the reproducibility of the experiment, all the sponge media in the devices were exchanged 2-3 times during the series of experiments, from tracer examination to K_La measurement.

Experimental setup for evaluating the effect of SS accumulation on water distribution (sponge packing method): The DHS reactor used for the experiment is shown in Fig. 4. The 110 pieces of sponge medium B were packed in a column 25 cm in diameter and 20 cm high as shown in Fig. 4 (total sponge volume = 3680 cm^3). The influent was pumped up from a storage tank and supplied uniformly to the top of the reactor from a sprinkler set at 17 rpm. The reactor was operated at 86.4 min of theoretical HRT based on the sponge volume (flow rate = 61.2 L/d). Prior to supplying the SS, the actual HRT of the reactor was measured using the method described above, but the volume of the saturated NaCl solution was changed to 1 mL. We called this experimental setup the sponge packing method.

After finishing the tracer experiment with clean water, continuous operation was started by feeding influent containing 300 mg-SS/L, which was adjusted by adding sewage sludge from the sewage treatment plant at Sodegaura, Chiba, Japan to tap water (theoretical HRT = 86.4 min). The effluent was circulated to the top of the reactor. The SS concentration was determined 3 times a week. When the SS concentration in the influent dropped to under 50 mg/L, the tracer experiment was carried out to measure the actual HRT. The operation was then restarted with newly prepared influent.

RESULTS & DISCUSSION

Hydraulic characteristics of sponge media (sponge hanging method): As an example of the tracer experiment results, conductivity-duration curve for sponge medium A is shown in Fig. 5. As expected, all the sponge media had a plug flow regime. The relationships between the actual and theoretical HRTs of each sponge medium are shown in Fig. 6. The actual and theoretical HRTs of sponge media A and B showed good correlation (R^2=0.992 for sponge medium A and R^2=0.995 for sponge medium B). The actual HRT/ theoretical HRT ratio was 67% for sponge medium A and 56% for sponge medium B, implying that there is rather more dead volume in sponge medium B than in sponge medium A.

When water flows down the sponge media, part of it infiltrates into the sponge and flows back out with a time lag. Other parts flow down by drifting on the surface of the sponge media. Sponge medium B was made like a small hollow tube to increase its specific surface area so that it would be approximately equal to that of sponge medium A. However, we observed that almost all the water flowed on the outer surface of sponge medium B and only a little flowed into the internal hole during the experiment. If we ignore the internal hole, the specific surface area of sponge medium B is only 1.61 cm^2/cm^3. That could explain why the water distribution was poor in medium B.

The correlation between the actual and theoretical HRTs for sponge medium C was relatively low (R^2=0.500), and the actual HRT/theoretical HRT ratio was only 25% of the values for media A and B. During the experiment, all the sponge media were replaced with new media after experiments with low flow rates (5-20 mL/min). Experiments with high flow rates (44-88 mL/min) were conducted with new sponge media in order to ensure experimental reproducibility. The tendencies of the correlation lines were different for experiments with high and low flow rates (Fig. 6). As noted above, sponge medium C is manufactured by copolymerizing polyurethane with epoxy resin for hardening. A possible reason for this low correlation might that an uneven network structure forms over individual sponges, causing differences in the water distribution. In addition, we believe the reason for the low actual HRT/theoretical HRT ratio, which indicates that there is more dead volume in medium C than in media A and B, is the low porosity of sponge medium C (70%). It could also vary in each medium, however, if processing is unequal.

To date, sponge medium B has not been used for any continuous DHS reactor experiments. However, the actual HRT/theoretical HRT ratio for medium B is much higher than for medium C, which has performed very well in G6 type DHS reactors (Onodera *et al*.,

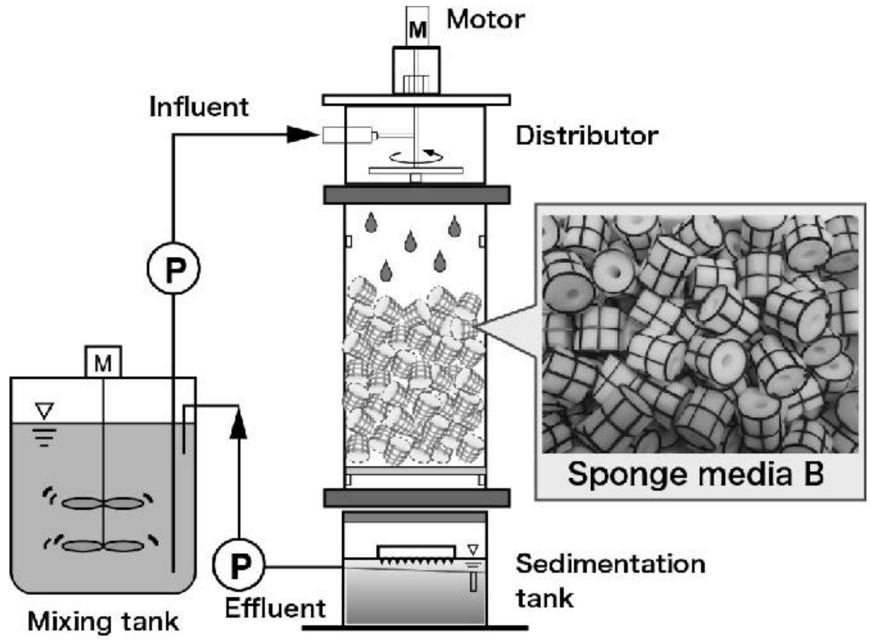

Fig. 4. Experimental packed sponge setup

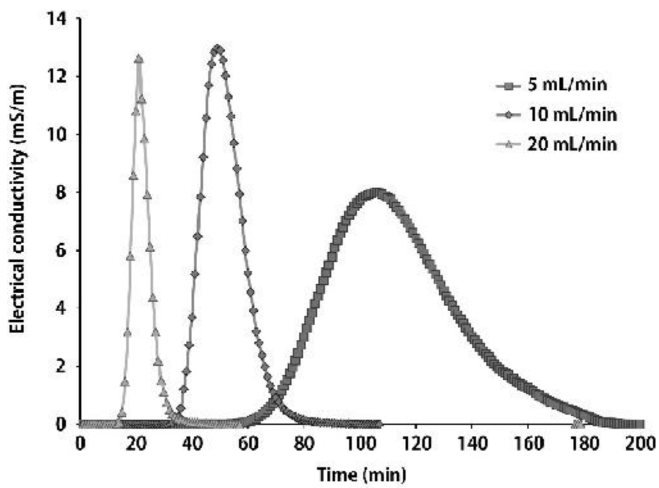

Fig. 5. Relationship between electrical conductivity and elapsed time for sponge medium A

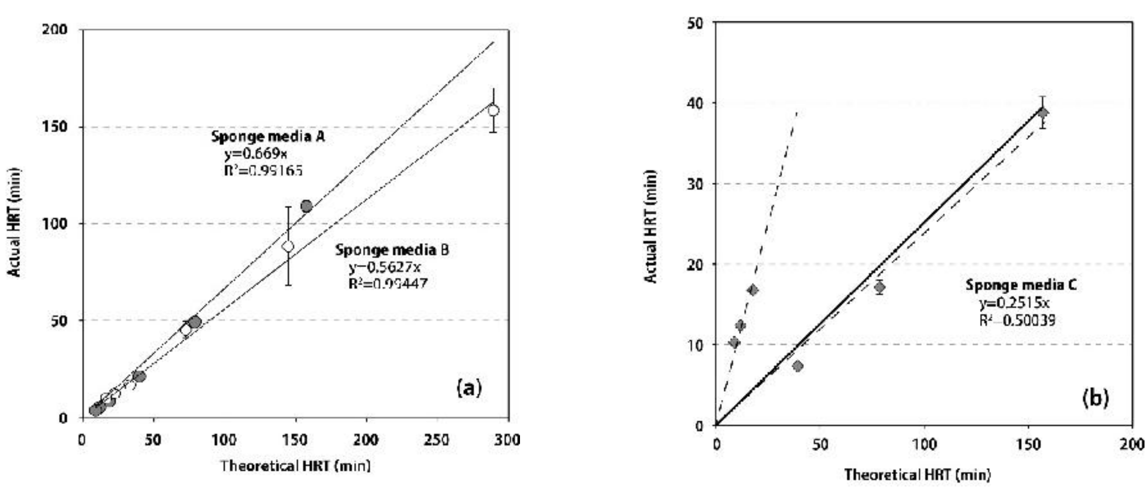

Fig. 6. Relationship between theoretical and actual HRT of sponge media A and B (a) and C (b)

2014). Medium A has also been used in G3 type DHS reactors (Okubo *et al*., 2014). Therefore, medium B's HRT/theoretical HRT ratio is considered to be adequate for practical use.

K_La: Fig 7(s) presents a representative example of the relation between DO and the distance from the top of the device using sponge medium A for flow rates of 5, 10, and 20 mL/min. The figure shows that the DO of the water flowing down the sponge media reached saturation immediately in all the experiments.

We calculated K_La for each sponge medium by exchanging the distance with retention time based on the actual HRT as shown in Fig. 7(b). The DO concentrations before reaching saturation are plotted in the figure. Because the DO concentrations quickly reached saturation and there were insufficient data from experiments having flow rates of more than 44 mL/min, we were unable to calculate the correct K_La precisely. For this reason, we only present results for flow rates of 5, 10, and 20 mL/min in Fig. 8. Up to this point in time, DHS reactors in use have operated at theoretical HRTs in the range from 60 min to 180 min, depending on the type of wastewater targeted. The theoretical HRTs of each sponge medium at flow rates of 5, 10, and 20 mL/min were 39 min to 158 min, 72 min to 289 min, and 39 min to 157 min for sponge media A, B, and C, respectively. These cover the range of theoretical HRTs in use. The value of K_La for each sponge medium tended to increase with increasing flow rate. The difference between the K_La values for sponge media A and B was quite small. Our explanation for this is that the water absorbed within the sponge media takes up little oxygen while oxygen easily dissolves into water drifting near the sponge surface. Therefore, higher values of K_La for higher flow rates suggest that amount of water flowing across the sponge surface increased as the flow rate increased.

In addition, the experiment using table tennis balls as a support medium that does not absorb water produced higher K_La values than the experiments with sponge media A, B, and C at all flow rates. In units of 1/min, these were 6.40 ± 0.95 at 5 mL/min, 8.21 ± 4.12 at 10 mL/min, and 8.79 ± 3.92 at 20 mL/min. As in the experiment with the sponge media, the K_La for the table tennis balls tended to increase with increasing flow rate. However, the reproducibility of the experimental values of K_La for table tennis balls was not good, as can be understood from the relatively large standard deviations (Fig. 8). This might be due to the fact that there was remarkable short-circuiting of the water flowing across the surface.

From the results we see that the K_La values tended to decrease as water infiltrated into the support material. The K_La values for the various media, in units of 1/min, were 6.40-8.79 for table tennis balls, 1.68-4.88 for sponge medium A, 0.78-2.02 for B, and 0.56-1.67 for C. As noted earlier, the water absorbed in the sponge media appears to take up little oxygen while oxygen easily dissolves into the water near the sponge surface. Therefore, oxygen transfer might be quicker for support materials that repel water. Taking into account the oxygen transfer and substrate supply to microbes living inside the sponge, sufficient water should diffuse inside the sponge media. In contrast, the results showed that water flowing across the surface has better oxygen uptake.

Table 1 shows K_La values for various aerated wastewater treatment devices reported as of the time of this study and the sponge media in this study. These include a large-scale (14 m^3) experimental ASP plant, a lab-scale (8.5 L) aeration tank, a stirring tank (2.4 L), and an 18-L rotating biological contactor (RBC). The scales and types of devices differ, but the DHS sponge media have almost the same ability to supply oxygen as the other aeration devices despite needing no external or mechanical aeration. From the viewpoint of oxygen transfer, sponge medium B can supply enough oxygen, and appears to be a practical new medium.

We performed the following calculations using the oxygen uptake rate (OUR) of sludge retained on DHS sponge media that was harvested from an existing demonstration plant in India (Okubo *et al*., 2014) in order to check whether the K_La values of the sponge media can supply sufficient oxygen to the retained biomass. The highest OUR for the retained sludge was 0.319 mL-O_2/g-VSS/min with sewage as the substrate. At that time there were 0.22 g of volatile suspended solids (VSS) per piece of sponge medium (25.7 cm^3) in the sludge. Because this OUR test was conducted when the demonstration DHS plant was performing at its best with fully-grown retained sludge, the oxygen consumption of the retained sludge was considered to be its approximate maximum. The calculations revealed an oxygen consumption of 0.00335 (1/min) per volume of media. Thus, all the sponge media used to evaluate K_La in this study have the ability to supply almost 100 times more oxygen than the retained sludge could actually consume. This extremely high oxygen supply ability is one of the reasons that DHS reactors can guarantee superior performance.

The effect of SS accumulation on water distribution: We first evaluated the water distribution with sponge medium B in a packed sponge configuration. Then we evaluated the effect of SS accumulation (Fig. 9). In Fig. 9, the plot at time 0 shows the actual HRT/theoretical HRT ratio for packed sponge medium B determined with clean water. When the sponge hanging method was used, the ratio was 56% while it decreased to only 14% for the packed sponges. This might be attributed to the fact that water was not sprinkled uniformly on the packed sponge media and some water flowed down the surface of the column wall. Therefore, it will be necessary to reconsider

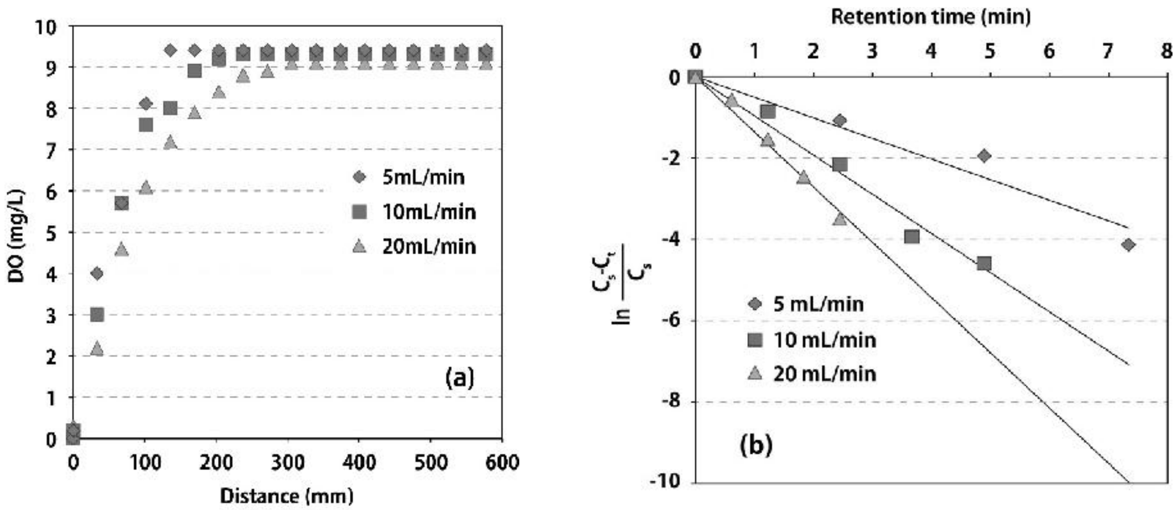

Fig. 7. (a) Change of DO through the hanging sponge media and (b) calculation of K_La for sponge medium A

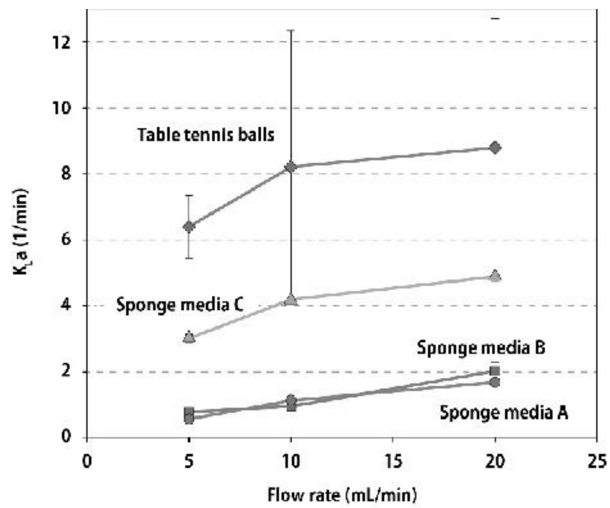

Fig. 8. Changes of K_La with flow rate

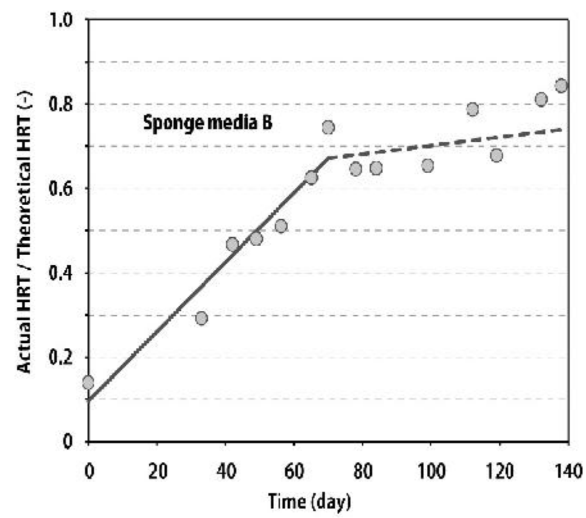

Fig. 9. Change of actual HRT/theoretical HRT with elapsed time

Table 1. Reported K_La values in wastewater treatment processes

Reactor type	K_La (1/min)	Reference
Activated sludge process	0.043-0.577	Shiomi *et al*., 2009
Aerated reactor	0.6-3.6	Scargiali *et al*., 2010
Mixed vessel	0.15	Hill, 2009
Rotating biological contactor	0.011-0.035	Chavan & Mukherji, 2008
DHS sponge media A B C	0.56-1.67 0.78-2.02 1.68-4.88	Present study

improving the sprinkler and adjusting the ratio of the column area to the sponge volume, among other enhancements. In other words, to quantitatively evaluate the water distribution in sponge media, the sponges used in the hanging method express the properties of the sponge medium itself better than those used in the packing method.

The change of the actual HRT/theoretical HRT ratio with elapsed time is shown in Fig. 9. It can be seen that the ratio increased as SS accumulated over time. The polyurethane is so hydrophobic that the sponge repels some of the water, so not all the water can infiltrate into the sponge medium. As a result, the actual HRT was very low at the beginning of the experiment. It increased as the sponge became filled with biomass. This might be because the sponge became more hydrophilic when covered by biomass.

In addition, it seems that the incremental changes in the ratio can be divided into two phases: the first phase, from day 0 to day 65, during which the ratio increased sharply, and the second phase, from day 70 to day 132, during which it increased only slightly. The DHS method provides adequate time for self-degradation of attached biomass, reducing the production of excess sludge from the process (Uemura & Harada, 2010). Therefore, it appears that the biomass attached to the sponge underwent more intensive self-degradation beginning at around day 70. In our experience operating DHS reactors from the lab scale to pilot plants, if the SS concentration of the sewage the DHS reactor receives is under about 150 mg/L, there is no need to worry about SS accumulation, due to sufficient autolysis. However, the results of this experiment indicate that when the SS concentration is high, above 300 mg/L, the actual HRT will likely be over the theoretical HRT, leading to eventual clogging of the sponge media. This indicates the importance of monitoring and management of the influent SS as part of DHS reactor operation.

CONCLUSIONS

From the results of this study, the following conclusions can be drawn:

1. Based on our examination of the performance of hanging sponges versus packed sponges with regard to the water distribution in the sponge media, we found that the properties of the sponge medium were better expressed in the sponge hanging method.
2. From the tracer experiment using hanging sponges, the actual HRT/theoretical HRT ratio was 56% for sponge medium A and 67% for sponge medium B, while K_La was 0.78-2.02 (1/min) for sponge medium A and 0.56-1.67 (1/min) for sponge medium B. Thus, sponge medium B appears to be an appropriate sponge carrier material because it performed very similarly to medium A.
3. The observations suggested that as the SS concentration in the influent becomes larger, there is potential for clogging problems, followed by deterioration of process performance. Therefore, monitoring influent SS will likely be important in managing DHS reactor operations.

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