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Improving the efficiency of small-scale wastewater treatment by pneumatic agitation

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ABSTRACT

Small-scale anaerobic and aerobic systems for wastewater treatment suffer relatively low efficiencies due primarily to a lack of mechanical agitation/mixing. Here, a pneumatic agitation system was designed by installing a U-tube between the anaerobic and anoxic units, pumping air to the closed headspace of the anaerobic unit and releasing the pressurized air through the U-tube to create turbulence of the fluid. Computational Fluid Dynamics (CFD) simulation and fluid tracer trial were used to describe the fluid status in a lab-scale system (13 L). The results demonstrated that a continuous 5-cycle pneumatic agitation achieved a complete mixing of the static fluid. The retention time factor (β) and short-circuiting flow coefficient (t_i/HRT) were increased from 0.93 to 1.14 and 0.02 to 0.27, respectively, indicating that pneumatic agitation significantly reduced dead zone and short-circuiting flow. A prototype at a treatment capacity of 300 L/d was installed in the North-East suburb of Beijing (40.15° N, 116.95° E) to treat rural household wastewater consisting of 630–1200 mg/L chemical oxygen demand and 20–45 mg/L total nitrogen. The field test was monitored in a period of 75 days from September to November 2018. The average removal rate for COD and TN was 96% and 92%, respectively by 10 times/h pneumatic agitation as compared to 49% and 45% without pneumatic agitation. The pneumatic agitation provides a low cost, easy operation and maintenance and efficient means for small-scale domestic wastewater treatment.

1. Introduction

Compact systems typically consisting of anaerobic, anoxic, aerobic and sedimentation units have been developed for small-scale wastewater treatment (Kaneko, 1997; Mažeikiene and Grubliauskas, 2021). An aeration system supplies oxygen for aerobic microorganisms and agitates the aerobic unit to facilitate microorganisms' growth (Fig. 1A). It has been long recognized that a lack of sufficient mixing in the anaerobic unit limits the treatment efficiency (Huang et al., 2018;

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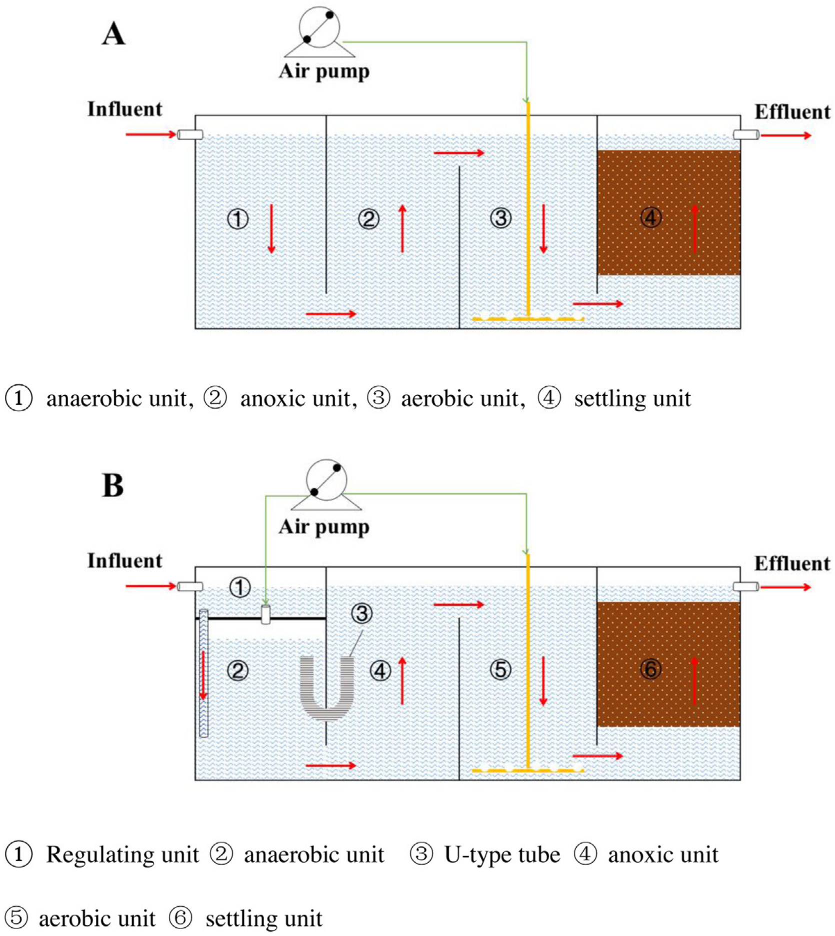

Fig. 1. Schematic illustration of (A) a conventional, small-scale wastewater treatment system and (B) the pneumatic agitated small-scale wastewater treatment system.

Smith et al., 1996). Rodrigues et al. (2003) demonstrated that the removal rate of 500 mg/L chemical oxygen demand (COD) was increased from 55% to 80% when the anaerobic unit was stirred with a mechanical agitator at 50 rpm in a laboratory-scale system (2 L). Foresti et al. (2006) found that the organic matter removal rate was increased by 15% from a stirring speed of 40 rpm to 80 rpm in the anaerobic unit. However, mechanical stirrers for mixing the anaerobic fluid are generally not equipped in small-scale wastewater treatment systems to minimize capital, maintenance, and running costs.

Kobayashi and Li (2011) reported a self-agitation system by accumulating the biogas product in the closed headspace and releasing it through U tubes for small-scale and low-cost anaerobic digesters for the treatment of organic solid wastes and demonstrated that the digestion performance of their self-agitated anaerobic digestor was comparable to that of the completely stirred tank reactor (CSTR). This concept of self-agitation is not applicable for small-scale domestic wastewater treatment because the generation rate of biogas from the anaerobic digestion of wastewater organic matter is far insufficient. Instead, an air pump was proposed to pressurize air in the closed headspace. In consequence, the instant release of the pressurized air through the U tube and the back-flush of the fluid may create disturbance between the anaerobic and anoxic unit (Fig. 1B). The disturbance was obvious in the visual observation and the process was termed here "pneumatic agitation". The major concern regarding this proposal was that the pneumatic agitation might affect the anaerobic environment depending on the frequency of the agitation and therefore, this study was aimed to apply this new concept of pneumatic agitation to small-scale domestic wastewater treatment system (200–500 L/d for a single household wastewater). First, computational fluid dynamics (CFD) was used to simulate the efficiency of pneumatic agitation for the mixing of the fluid and inform the field test design and experimentation. Then a series of laboratory-scale system (13 L) experiments were carried out to investigate the hydraulic status of the fluid in the system using a fluid tracer. Finally, the performance of a prototype system at a treatment capacity of 300 L/d was evaluated for treating domestic wastewater by monitoring the dissolved oxygen level in the anaerobic fluid and the concentrations of COD and total nitrogen (TN) in the influent and effluent.

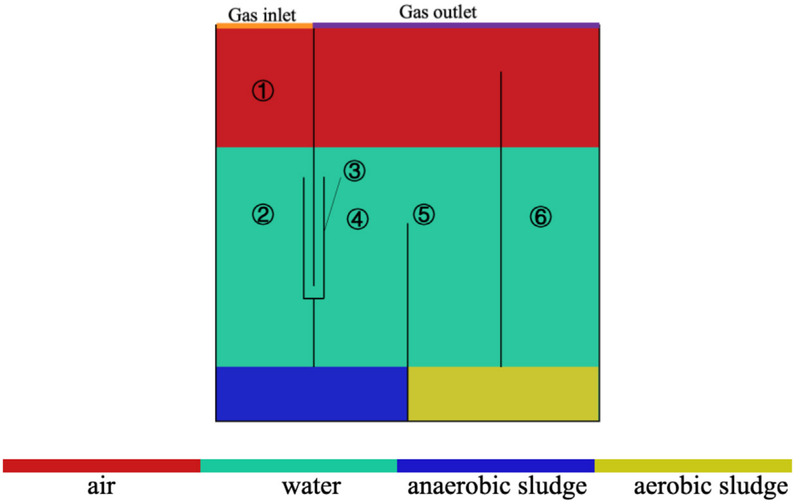

Fig. 2. Simplified 2D simulation model. ① Headspace of the anaerobic unit, ② anaerobic unit, ③ U-tube, ④ anoxic unit, ⑤ aerobic unit, ⑥ settling unit; red is air (gas phase), green is water (liquid phase), blue is the phase of anaerobic sludge, yellow is the phase of aerobic sludge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Materials and methods

2.1. Design of the reactor

In a conventional four-unit treatment system (Fig. 1A), the anaerobic unit was isolated by a plate on which a connection tube was installed to introduce wastewater from the upper part and another tube was connected an air pump to pressure air into the headspace of the lower part (anaerobic unit) (Fig. 1B). A U-tube was installed on the baffle plate between the anaerobic unit and the anoxic unit. The wastewater level in the anaerobic unit was pushed down by the air pump and the pressured air was instantly released to the anoxic unit through the U tube when the wastewater level reached the bottom of the U-tube. As a result, the fluid was concurrently flushed back to the anaerobic unit from the anoxic unit through the channel underneath the U-tube, thus causing the turbulence of the fluid in both units. The anaerobic, anoxic and aerobic units were filled with soft packing materials and the settling unit was filled with 3 mm diameter ceramic grains. The total effective volume of the reactor for laboratory studies is approximately 13 L and the volume ratio of the five units is 1:2:3:3:3. A prototype of the reactor at a treatment capacity of 300L per day was constructed for the field test to treat the wastewater of a rural household (more details in Section 2.4). The volume ratio of the five units and the length, width and height of the prototype reactor were estimated on the baisis of the lab-scale reactor's simulation and flow tracer trails.

2.2. Computational fluid dynamics (CFD) simulation

CFD simulation was used to describe the effect of pneumatic agitation on the mixing of the fluid. These fluid equations, called the Reynolds average Navier–Stokes equations, were nonlinear and cannot be solved analytically in almost all cases. In order to solve the equations, they must be linearized and solved through many small control variables (computational grids). Gambit 2.4.6 was used to build a geometric model and the mesh. The commercial CFD code FLUENT® was used to simulate the two-dimensional flow field. The Volume of Fluid (VOF) model and K-ε model were chosen as solvers (Brannock et al., 2010; Zhang et al., 2014).

The release of the pressurized air through the U-tube and the back-flush of the fluid were instantaneous (1–2 s). The channel underneath the U-tube has the identical width with the treatment tank and the fluid is back-flushed through the channel while the back-flush through the U-tube is nil (the cross-section area of the channel is 500 times greater than that of the U-tube). In this context, the turbulence of the fluid in the anaerobic and anoxic units is caused by the fluid back-flush through the channel and therefore, a 2-D simulation was sufficient to represent the actual situation.

The simulation selection was based on pressure calculation and non-steady-state conditions. The simulation region/model is shown in Fig. 2 where the U-tube is simplified and four phases in different colors are allocated. The input flow is gas. The top of the anaerobic unit was defined as the gas inlet boundary and the top of the anoxic, aerobic and settling units was defined as the boundary of outlet gas (open to air). The boundary condition for the simulation was gas velocity at the inlet of the headspace and atmospheric pressure at the outlet. The initial condition was initialized with the inlet velocity. At t=0, the inlet gas velocity was assumed as 0.02 m/s and other phase velocities were zero. To simplify the calculation and exclude the interference of water flow, we simulated the fluid hydraulics for a static fluid substrate with a density of 1000 g/L and a viscosity of 3 cp without filling materials. The wall is a non-slip interface. The timeframe of a one-cycle of agitation is set at 2.5 min for the laboratory-scale reactor (13 L).

2.3. Fluid tracer trials

2.3.1. Experimental design

Fluid tracer trials are widely employed to investigate the hydraulic characteristics of a fluid in a reactor by injecting a certain amount of tracer at the reactor inlet and measuring the tracer concentration at the outlet (Escotet-Espinoza et al., 2019; Terashima et al., 2013). In general, the flow pattern in a flowing reactor is between an ideal plug flow and perfect mixing flow due to the ubiquity of short-circuiting and dead zone (Partopour and Dixon, 2019). It is described by the residence time distribution (RTD) of the tracer. In this work, the tracer trial was conducted by a pulse input method with tap water containing rhodamine B (Liem et al., 2011). A tracer solution of 100 mL containing 1000 mg/L Rhodamine B was injected into the inlet of the reactor in a certain time interval of 3% of theoretical residence time after water flow was stabilized by a peristaltic pump. Samples were collected at the outlet of the reactor at a certain time interval of every 1/25-1/50 of the theoretical residence time and the concentration of the tracer was determined at 552 nm wavelength by UV–VIS spectrometry (TU-1900, PERSEE).

2.3.2. Determination of hydraulic characteristics in the reactor

The flow phase in the reactor was analyzed and evaluated by measuring the RTD of the tracer (Behin and Aghajari, 2008). To compare RTD curves in different conditions (fluid flow rates, agitation frequency and aeration rate), the tracer concentration and residence time were normalized to C(θ) and θ by Eqs. (1) and (2), respectively. The RTD function E(θ) was used to analyze the flow pattern and calculated by Eq. (4).

$$\mathrm{C}\left(\theta\right)=\frac{C(t)}{C_0}\mathrm{m} \tag{1}$$

$$\theta=\frac{t}{HRT} \tag{2}$$

$$C_0=\frac{M}{V} \tag{3}$$

$$\mathrm{E}\left(\theta\right)=\frac{HRTqC(\theta)}{M} \tag{4}$$

where C(t) is the concentration of outlet tracer (mg/L) at time t (min), V: the total volume of the reactor (L), M: the total amount of tracer (mg), q: the flow rate (L/min) and HRT: the hydraulic retention time of the reactor (min).

The mean residence time (MRT) is the average retention time of the tracer in the reactor (Bhalode et al., 2021). It is defined as the first moment of the RTD by Eq. (5):

$$MRT=\frac{\sum_0^{\propto}tC(t)\Delta t}{M}\times q \tag{5}$$

The variance (σ_θ^2) was obtained according to the second moment to determine the dispersion coefficient (Eq. (6)). For the non-ideal conditions in the reactor, the σ_θ^2 value is between 0 and 1 (Persson et al., 1999).

$$\sigma_\theta^2=\frac{\int_0^\theta(\theta-MRT)^2E(\theta)d_\theta}{\int_0^\theta E(\theta)d_\theta} \tag{6}$$

The retention time factor (β) is used to show the ratio between MRT and theoretical HRT (Eq. (7)). The theoretical β value is 1. The reactor may have a dead zone or short-circuiting flow when the β value is less than 1. Vortex may exist when β is greater than 1 (Nere et al., 2003; Wang et al., 2017).

$$\beta=\frac{MRT}{HRT} \tag{7}$$

The recovery rate of tracer (R r) is used to evaluate the proportion of dead zone. The proportion of the dead zone is inversely proportional to the Re value (Young and Young, 1988).

$$\mathrm{Rr}=\frac{\sum_{i=1}^{n-1}(C_{i+1}+C_i)(t_{i+1}-t_i)}{2*M}*q \tag{8}$$

The degree of short-circuiting is described by the flow coefficient (t_i/HRT) where t_i is the time when the tracer is first detected at the outlet. The t_i/HRT value equals 1, indicating an ideal plug flow, while it is close to zero meaning a strong short-circuiting state (Metcalf and Eddy, 2013).

Fig. 3. Photo of the field treatment system.

2.4. Field test

A prototype system in a capacity of 300 L/d was installed to treat the wastewater from a rural house located in the North-East suburb of Beijing (40.15° N, 116.95° E). The air pump (EDLP600-12 A, Kamoer) was powered by solar photovoltaic (Fig. 3). The air flow for the aerobic unit was set at 3 L/min. The system was seeded with 30 L active sludge obtained from an urban sewage treatment plant. The concentrations of mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) in the active sludges were 7500 mg/L and 6000 mg/L, respectively. The performance of the prototype system was monitored for 75 days between September and November 2018. The household wastewater consisted of 637–1216 mg/L COD and 20–45 mg/L TN. Influent and effluent water samples were collected to measure pH, COD and TN. The dissolved oxygen (DO) level in the anaerobic and aerobic units was measured on the spot using the HANNA HI914 apparatus.

3. Results and discussions

3.1. Computational fluid dynamics (CFD) simulation

The dead zone is usually formed at the corners and side angles within a reactor and it can be minimized by agitation. Fig. 4 shows the status of the fluid within the reactor at different stages in one cycle of the pneumatic agitation simulated by computational fluid dynamics (CFD). Before the agitation, the anaerobic and aerobic sludges are well settled on the bottom of the reactor (Fig. 4A). The air pump pushed the fluid level in the anaerobic unit to decline and moved the anaerobic sludge to the anoxic unit (Fig. 4B). When the fluid level reached the bottom of the U tube, the pressured air was released through the U tube to the anoxic unit and the fluid was instantaneously flushed back to the anaerobic unit through the bottom channel underneath the U-tube (Fig. 4C), causing the turbulence of the whole system (Fig. 4D). Clearly, one cycle of the agitation was not sufficient to achieve a thorough mixing of the fluid in the anaerobic unit (Fig. 4D). If the second agitation was initiated after the agitated sludges were well re-settled back to the original state, the mixing would never reach a complete mixing. Therefore, the frequency of the pneumatic agitation was important to the degree and efficiency of the mixing. The simulation shows that 5 cycles of the agitation achieved a complete mixing of the sludges and fluid (see the animation of the agitation process in the supporting materials).

It should be noted that the anaerobic environment was likely to be constantly disrupted by the pneumatic agitation as air was frequently introduced into the anaerobic unit and anaerobic and aerobic sludges were mixed up. In consequence, the treatment efficiency could be compromised if the frequency of pneumatic agitation was not appropriate. It should also be noted that fluid velocity is another important parameter to affect the hydraulic characteristics of the fluid. To simplify the calculation, we did the CFD simulation for the pneumatic agitation in a static condition. Therefore, the effect of the frequency of pneumatic agitation will be investigated by flow tracer trials under different flow rates and field test of a prototype at a treatment capacity of 300 L/d for rural household wastewater.

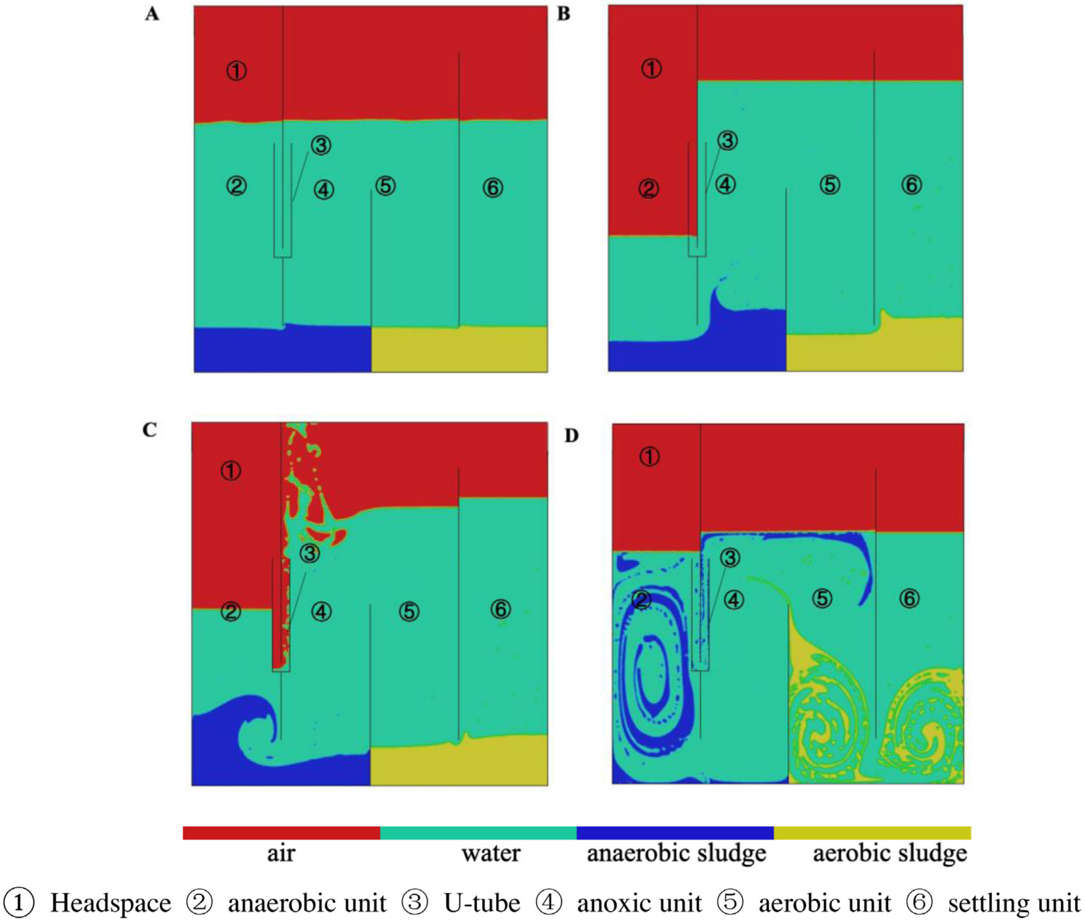

Fig. 4. CFD simulation for a laboratory-scale system (13 L) for the mixing status of the fluid during one cycle of pneumatic agitation. (A) the original state, (B) air is pressurized to push the fluid level down and the anaerobic sludge to the anoxic unit, (C) the fluid level reaches the bottom position of the U-tube, the pressurized air is released from the anaerobic headspace to the anoxic unit through the U-tube and the fluid is flushed back from the anoxic unit to the anaerobic unit through the bottom channel, and (D) the anaerobic fluid level is raised to its original state and the fluid in the reactor is mixed up to a certain extent. The timeframe for one cycle of agitation is set as 2.5 min.

3.2. Flow tracer trials

3.2.1. Effect of fluid flow rate

The flow rate is a critical parameter affecting the hydraulic characteristics of the fluid and therefore, the flow tracer trial was first conducted without pneumatic agitation by examining the fluid flow rates of 18–540 mL/min for the lab-scale reactor. As the aeration of the aerobic unit also causes slight disturbance of the fluid, an aeration rate of 5 L/min in the aerobic unit is set to maintain a DO level of 2 mg/L, which is the requirement for microorganisms' growth (Guo et al., 2013; Sen et al., 1992). The variations in residence time distribution (RTD) curves at different flow rates are shown in Fig. 5 and the corresponding variations regarding hydraulic parameters are presented in Table 1.

All E(θ) values in Fig. 5 present two characteristics: a sharp rise within 0.2θ and a gradual drop with a long tailing. The former is a typical representative of short-circuiting (Brannock et al., 2010) and the latter is a reflection of the dead zone within a reactor (Brannock et al., 2010; Simcik et al., 2012). A positive peak shift of 0.1θ from the flow rate of 18–90 mL/min to 216–540 mL/min implies that increasing the flow rate reduces the short-circuiting. The β values demonstrate that increasing the flow rate from 18 to 540 mL/min reduces both the short-circuiting flow and the dead zone in the reactor. The flow coefficients (t_i/HRT) are close to zero further confirming the short-circuiting. However, the tracer recovery rate (Rr) increased with increasing the flow rate and reached maximum at 216 mL/min. Clearly, the short-circuiting and dead zone are still significant despite that the fluid flowing reduces both the short-circuiting and dead zone.

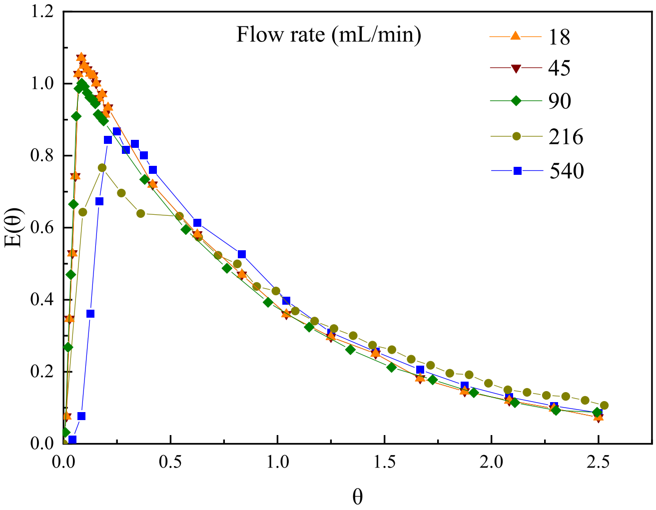

Fig. 5. RTD curves of the lab-scale reactor (13 L) at different flow rates.

Table 1
Hydraulic parameters for the lab-scale reactor (13 L) without pneumatic agitation at different flow rates (aeration rate 5 L/min in the aerobic unit).

Flow rate (mL/min)	β	t_i/HRT	Rr	σ_θ^2
18	0.82	0.01	0.85	0.64
45	0.83	0.01	0.90	0.65
90	0.87	0.01	0.94	0.40
216	0.93	0.02	0.98	0.45
540	0.96	0.07	0.85	0.40

3.2.2. *Effects of pneumatic agitation frequency and aeration rate*

As previously demonstrated by the CFD simulation, the pneumatic agitation significantly improves the fluid mixing in the reactor and the frequency of the agitation is critical to the degree of the mixing. Therefore, the pneumatic agitation frequencies of 0, 5, 10 and 20 times/h were investigated for the lab-scale reactor's tracer trials at the selected fluid flow rate of 216 mL/min (Fig. 6). In considering the effect of aerobic aeration, we conducted the pneumatic agitation experiments with the aeration rates of 5 L/min (Fig. 6A) and 3 L/min (Fig. 6B). Under the aeration rate of 5 L/min in the aerobic unit and a flow rate of 216 L/min, the pneumatic agitation of 0, 5 and 10 times/h did not have a significant influence on the short-circuiting and dead zone (Fig. 6A and Table 2). When the pneumatic agitation was increased to 20 times/h from 10 times/h, the peak of E(θ) was shifted from 0.2 θ to 0.5θ and the values of β, Rr and ti/HRT were substantially increased, indicating a profound improvement in the mixing degree. The slight decrease of β, Rr and ti/HRT values with the 5 times/h pneumatic agitation as compared to without the agitation was likely the result that the effect of pneumatic agitation offset the fluid flow as their flow directions were opposite. It was interesting that the mixing degree of the fluid was enhanced by lower frequencies of pneumatic agitation and there were no significant differences in the mixing degree at an aeration rate of 3 L/min (Fig. 6B and Table 2). This probably indicates that the aeration might have an adverse effect in the case of pneumatic agitation. It was reported that strong turbulence might lead to a larger dead zone and stronger short-circuiting flow (Young and Young, 1988) and therefore, an appropriate turbulence should be considered in the biological treatment of domestic wastewater as too strong turbulence could mix up anaerobic, anoxic and aerobic microorganisms thus destroying their respective growth.

3.3. *The result of field test*

During the period of field test between September and November 2018 (the average temperature was 15 °C), three phases of pneumatic agitation (0, 5 and 10 times per hour) were tested. The system was operated without pneumatic agitation in the first 30 days (Phase I), 5 times (Phase II) and 10 times (Phase III) per hour in the following 45 days. Fig. 7 shows the DO level in the anaerobic and aerobic units and the concentration of COD and TN in the influent and effluent. During the whole investigation period, the DO in the aerobic unit was higher than 3 mg/L and the DO in the anaerobic unit was below 0.2 mg/L under the different pneumatic agitation frequencies. This indicates that the anaerobic environment was well maintained in the anaerobic unit, although the pressurized air was frequently introduced.

During Phase I without the pneumatic agitation, the average removal rates of COD and TN (the average influent concentration 898 mg/L and 27 mg/L) were 49% and 45%, respectively. During Phase II where the agitation frequency

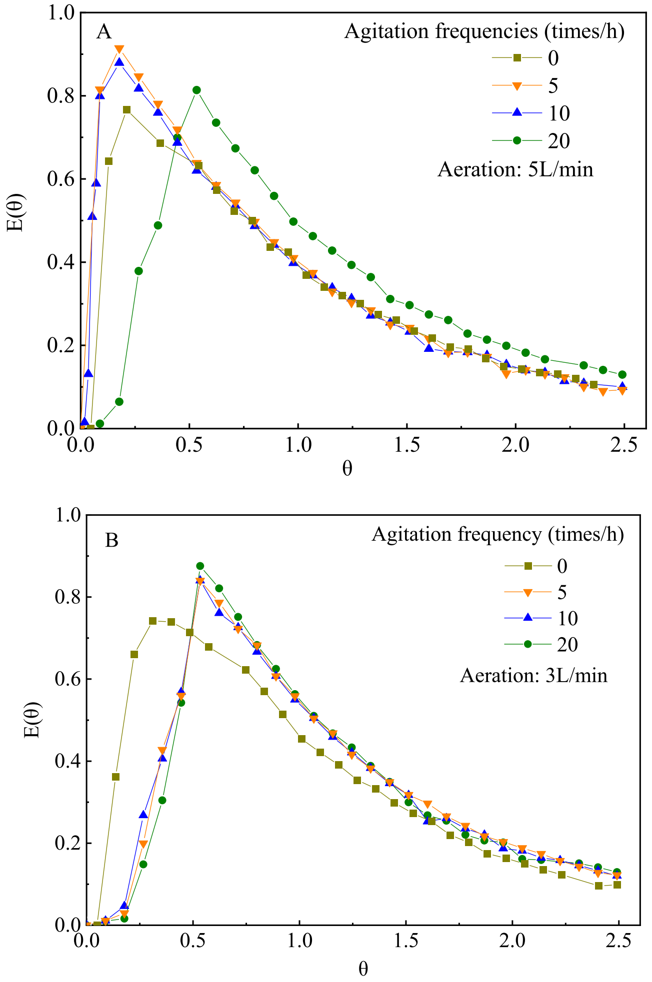

Fig. 6. RTD curves of the lab-scale reactor with different pneumatic agitation frequencies and aeration rates. The agitation frequency 0, 5, 10, 20 times/h and the aerobic aeration (A) 5 L/min, (B) 3 L/min.

Table 2
Hydraulic parameters of the fluid under different aeration rates and pneumatic agitation frequencies in the lab-scale reactor (fluid flow rate 216 mL/min).

Aeration rate (L/min)	Pneumatic agitation frequency (times/h)	β	t_i/HRT	Rr	σ_θ^2
5	0	0.93	0.02	0.98	0.45
	5	0.86	0.02	0.90	0.49
	10	0.88	0.04	0.90	0.49
	20	1.14	0.18	0.99	0.28
3	0	0.94	0.02	0.97	0.40
	5	1.12	0.18	0.98	0.25
	10	1.11	0.18	0.97	0.25
	20	1.13	0.27	0.92	0.24

was set at 5 times/h, the average removal rates of 911 mg/L COD and 23 mg/L TN were 84% and 74%, respectively. Further increasing the pneumatic agitation frequency to 10 times/h (Phase III) resulted in removal rates of COD and TN reaching 96% and 92%, respectively. Clearly, the field test demonstrated that the removal rate of COD and TN was significantly improved by the pneumatic agitation. It was noted that the removal rate of TN in Phase III was significantly improved. In general, the rural household wastewater flow is intermittent and therefore, it was likely that part of the fluid moved back from the aerobic unit to the anoxic unit when the fluid in the anoxic unit was flushed back to the anaerobic unit upon the pneumatic agitation. This process represented nitrification reflux in a convention A/A/O system. In the aerobic unit, the biofilm thickness on the surface of soft packing materials was about 3 mm. In general, the inner layer of the

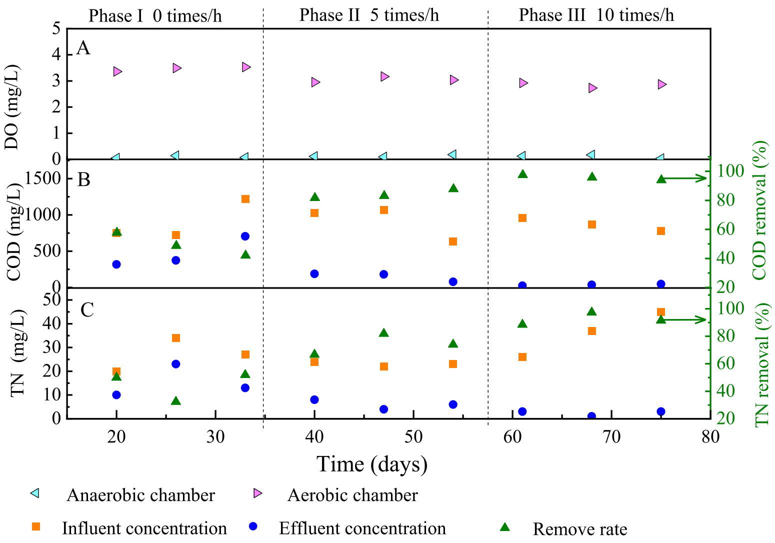

Fig. 7. Field test results of the prototype treatment system (300 L/d) for rural household wastewater. (A) DO concentration in the aerobic and anaerobic units, (B) COD concentration and removal rate, (C) TN concentration and removal rate. Phase I: without pneumatic agitation, Phase II: pneumatic agitation frequency 5 times/h, Phase III: pneumatic agitation frequency 10 times/h. HRT 24 h, the aerobic aeration 3 L/min.

biofilm was an anoxic environment where the denitrification process occurred (Menoud et al., 1999; Xiao et al., 2021). In the settling unit, the ceramsite inside was an anoxic condition, conducive to the denitrification process (Walters et al., 2009). In this context, the pneumatic agitated system may be particularly efficient for the treatment of rural household wastewater.

4. Conclusion

A novel pneumatic agitation system was developed to improve the efficiencies of conventional small-scale domestic wastewater treatment. A U tube was installed between the anaerobic and anoxic units and air was pumped into the anaerobic unit to expel the water into the anoxic unit. When the water level declined to the bottom of the U tube, air was released instantly to the anoxic unit through the U tube and water was flushed back to the anaerobic unit thus causing the disturbance and agitation of both anaerobic and anoxic units. CFD simulation and flow tracer trials showed that the pneumatic agitation significantly reduced the dead zone and short-circuiting flow of the fluid. The frequency of the agitation was important to determine the degree of mixing and affect the treatment efficiency. The field test of the system at a treatment capacity of 300 L/d demonstrated that the pneumatic agitation was particularly efficient to treat high-strength domestic wastewater. The removal rates of 630–1200 mg/L chemical oxygen demand (COD) and 20–45 mg/L total nitrogen (TN) were increased by 46% and 48%, respectively with an agitation frequency of 10 times/h. The system was the ease of maintenance and provided a cost-effective approach for rural household wastewater treatment.

CRediT authorship contribution statement

Shaohua Sun: Methodology, Validation, Formal analysis, Visualization, Writing – original draft. **Yanming Tong:** Methodology, Investigation, Validation. **Aiying Hou:** Methodology, Investigation, Validation. **Lijun Yin:** Software, Methodology, Investigation. **Tong Zheng:** Methodology, Investigation. **Jie Zheng:** Resources. **Jicheng Liu:** Project administration. **Bing Cao:** Review & editing. **Qing Hu:** Review & editing. **Frederic Coulon:** Review & editing. **Xiao Jin Yang:** Conceptualization, Methodology, Resources, Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2021.102220.

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