



## Development of a helical coagulation reactor for harvesting microalgae

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**In this study, an innovative helical coagulation reactor (HCR) was developed for harvesting microalgae by sedimentation with polyaluminium chloride (PAC). The effects of construction and hydrodynamic characteristics on harvesting performance were investigated. Results showed that a higher harvesting efficiency, 96.37%, was achieved for the large and compact flocs generated by the HCR, and the settling rate of flocs was substantially influenced by the velocity gradient ( $G$ ) and the Reynolds number ( $Re$ ). When the Reynolds number closed to the transition between laminar and turbulent flow (4000), the flocs settled faster ( $20.51 \text{ m h}^{-1}$ ), although settling slowed as the Reynolds number increased further because of ruptured flocs. The settling rate of flocs could be further improved to  $23.27 \text{ m h}^{-1}$  by a pulse flow field, mainly due to larger and more compact flocs forming in the plug pipe flow. Furthermore, a comparative investigation of a mechanically agitated vessel and the HCR with the same Camp number ( $Gt$ ) showed that the HCR achieved higher settling rates and a shorter residence time than those with a mechanical agitator. The HCR provided a uniform dissipation of energy and high velocity gradient while avoiding electrical and mechanical energy consumption, suggesting this reactor is an efficient and economic option for microalgae harvesting.**

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**[Key words:** Microalgae harvesting; Helical coagulation reactor; *Scenedesmus dimorphus*; Hydrodynamics; Velocity gradient; Reynolds number]

Microalgal biomass has great potential as a feedstock for the sustainable production of biodiesel (1). However, separating microalgal biomass from dilute liquid suspension remains a major challenge for commercializing microalgal production (2), mainly due to the small size (1–30  $\mu\text{m}$ ), the similar densities of the cells and the culture and low concentration (0.1–5  $\text{g L}^{-1}$ ) (3).

Coagulation is a common method for solid–liquid separations (4). In recent years, sedimentation with coagulation has been widely employed to harvest microalgae in lab-scale studies (5,6). The process of coagulation can be divided into three stages (7): mixing between microalgal cells and coagulants, floc growth, and sedimentation. All three of these stages are directly related to efficient biomass harvesting (8). Generally, these stages are performed in a mechanically stirred vessel for the jar test (9). First, a rapid mixing (200–300 rpm) is applied for the coagulant dispersion (0.5–1 min), and then floc generation occurs (3–5 min) during a slow stir step (30–60 rpm) (10). Finally, the sample is placed statically for gravity sedimentation (30–60 min).

However, coagulation performed in a mechanically stirred vessel presents some deficiencies, such as short circuits, dead zones, asymmetrical stir intensity (high shear near the impeller, but low shear above and below the impeller) and additional mechanical or electrical energy consumption (11). Therefore, new coagulation reactors have been designed and carried out in the water treatment

industry. A pipe flow reactor constituted with an arched plastic tube was used for drinking water treatment, with advantages of simple construction, high kinetic energy dissipation, less short circuits or dead zones, short residence time and more economical (12).

Several authors report that reactors constituted with helical tubes could be employed for coagulation in the treatment of raw water (13), which provide favorable mixing and high particle collision efficiency due to the secondary flow induced by centrifugal forces. According to Gregory (14), hydrodynamic characteristics play an important role in this kind of tubular reactor, and these characteristics are usually described by the velocity gradient ( $G$ ) and the Reynolds number ( $Re$ ). Although a high velocity gradient can promote coagulant dispersion and collision efficiency, intense turbulence may cause more flocs to rupture (15). Furthermore, Carissimi et al. (16) noted that  $\text{Fe}(\text{OH})_3$  flocs formed in a helical pipe reactor had better settling performance and shorter residence time than those generated in a mechanically stirred vessel, and that the settling rate was seriously affected by the hydrodynamic parameters. However, the application of these reactors to harvesting microalgae has not been reported, and the helical pipe reactor may be a great option for harvesting microalgal biomass due to the differences in the biological characteristics of this system compared to the particles found in the water treatment.

Thus, the aim of this study was to develop an innovative coagulation system combining with a jet injector and a helical coagulation reactor (HCR) for microalgal harvesting. The jet injector was employed for coagulant dispersion, and the HCR was used for floc generation and growth. These two processes did not require additional mechanical agitation, which might make microalgal recovery

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more economical. In this study, the effects of reactor construction and hydrodynamic characteristics on HCR performance were investigated and a comparative study evaluated microalgal floc generation in both the HCR and a mechanically agitated vessel.

## MATERIALS AND METHODS

**Microalgae cultivation** The freshwater microalga *Scenedesmus dimorphus* (FACHB-1266) was obtained from the Freshwater Algae Culture Collection at the Institute of Hydrobiology, Chinese Academy of Sciences, and grown in a modified BG11 medium (17). Microalgal culture was maintained in an 80 L photobioreactor at  $25 \pm 1^\circ\text{C}$  under continuous fluorescent illumination with an intensity of  $200 \mu\text{mol m}^{-2} \text{s}^{-1}$ . Filtrated air mixed with carbon dioxide (3%) was continuously supplied at an average rate of  $20 \text{ L min}^{-1}$  to provide a carbon source and mix the culture. The pH was maintained at  $6.5 \pm 0.5$  by adjusting the flow rate of carbon dioxide. Growth of microalgae was terminated at the stationary phase (6 days). The cell dry weight was  $1.53 \text{ g L}^{-1}$ , and the average diameter of *S. dimorphus* cell measured by Mastersizer 3000 (Malvern, Worcestershire, UK) was  $10.75 \mu\text{m}$ .

**Experimental procedure** Harvesting tests were performed using a lab-scale setup (Fig. 1). Initially, a microalgal solution in the stationary phase was introduced into a jet injector by a centrifugal pump. Negative pressure developed in the suction chamber, and the coagulant (polyaluminium chloride, PAC) and pH regulating agent (NaOH or HCl) were injected at the predetermined feeding rate. Reagents were dispersed adequately by jet flow. Subsequently, the microalgal solution containing coagulant was pumped into the HCR for floc generation (Fig. S1). Finally, microalgal flocs were introduced into a sedimentation tank for solid (floc)-liquid separation.

Five different helical coagulation reactors with various lengths were designed and constructed with lucite pipe. The characteristics of the five reactors are shown in Table 1. First, the feed rate was maintained at  $2 \text{ L min}^{-1}$  to evaluate how the reactor construction characteristics effected the floc formation efficiency (harvesting efficiency, size and settling rate).

According to the above tests, a HCR with feed rates ranging from 1 to  $5 \text{ L min}^{-1}$  was selected to investigate the effect of hydrodynamic characteristics on the floc settling rate. Then, the centrifugal pump was replaced by a modified peristaltic pump to study the effect of different flow fields on the flocs.

A mechanically agitated vessel (MY3000-6 J, Meiyu, Wuhan, China) was employed to compare the performance with the HCR system. 800 mL of microalgal suspension was filled in a 1 L beaker. The same amount of coagulant (PAC) was added with a rapid mechanical agitation for 1 min at 200 rpm, and then slow stirring rates ranging from 50 to 90 rpm ( $G \sim 3.3\text{--}8.1 \text{ s}^{-1}$ ) were employed for floc generation, with

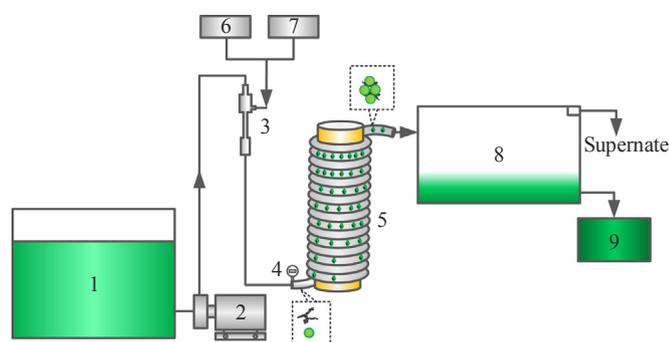


FIG. 1. Experimental setup for harvesting microalgae: 1, microalgae solution tank; 2, centrifugal pump; 3, jet injector; 4, manometer; 5, helical coagulation reactor (HCR); 6, coagulant; 7, pH adjuster; 8, sedimentation tank; 9, concentrated microalgae collector.

TABLE 1. Construction characteristics of the helical coagulation reactors.

Reactor	Length (m)	Tube diameter (mm)	Helical diameter (mm)	Volume (L)	Residence time (s)
HCR1	2	15	100	0.35	10.60
HCR2	4	15	100	0.71	21.20
HCR3	6	15	100	1.06	31.79
HCR4	8	15	100	1.41	42.39
HCR5	10	15	100	1.77	52.99

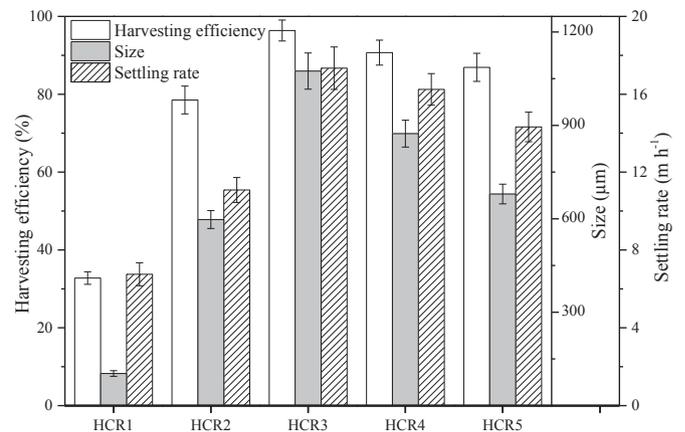


FIG. 2. Effect of construction characteristics on harvesting efficiency, size and settling rate.

a residence time of 5 min. The gradient velocity ( $G$ ) of various stirring rates was calculated similar to the equation reported by Spicer and Pratsinis (18), as shown in Eq. 1. Approximate camp numbers ( $Gt$ ) were obtained in the HCR for different feed rates ( $1\text{--}5 \text{ L min}^{-1}$ ). The performance comparison of flocs was determined through the settling rates effected by the approximate Camp numbers.

$$G = \sqrt{\frac{P_0 N^3 D^5}{\nu V}} \quad (1)$$

where  $P_0$  is the impeller power number,  $N$  is the impeller speed,  $D$  is the impeller diameter,  $\nu$  is the kinematic viscosity of microalgal suspension, and  $V$  is volume of microalgal suspension.

**Analytical methods** The harvesting efficiency was calculated using Eq. 2 reported by Zhang et al. (19), and a modified micrograph analysis was employed to measure the average floc size (Fig. S2) (20). The flocs settling rate was calculated according to the method developed by Oliveira et al. (21).

$$\text{Harvesting efficiency} = \left(1 - \frac{C_A}{C_B}\right) \times 100\% \quad (2)$$

where  $C_B$  and  $C_A$  are the concentration of microalgal biomass (dry weight,  $\text{g L}^{-1}$ ) before and after harvesting, respectively.

The head loss in the HCR was measured using manometers between the inlet and outlet of the HCR to calculate the velocity gradient ( $G$ ) with Eq. 3 (11). Because the solution was discharged in an open sedimentation tank, the pressure at the exit of the HCR could be neglected.

$$G = \sqrt{\frac{\rho g \Delta H}{\mu t}} \quad (3)$$

where  $G$  is the velocity gradient ( $\text{s}^{-1}$ ),  $\rho$  is the medium density ( $\text{kg m}^{-3}$ ),  $g$  is the gravitational acceleration ( $\text{m s}^{-2}$ ),  $\Delta H$  is the head loss of the HCR (m),  $\mu$  is the kinematic viscosity of the solution ( $\text{kg s}^{-1} \cdot \text{m}^{-1}$ ) and  $t$  is residence time (s).

Another significant hydrodynamic parameter is the Reynolds number ( $Re$ ), which can be determined by Eq. 4 (11), where  $\nu$  is the velocity ( $\text{m s}^{-1}$ ) and  $d$  is the tube diameter (m).

$$Re = \frac{\rho \nu d}{\mu} \quad (4)$$

All the experiments were carried out in triplicate, and data analysis was performed in Origin 9. The results below are expressed as the mean of three independent replicates with error bars representing the standard deviation.

## RESULTS AND DISCUSSION

**Effect of construction characteristics on the performance of the HCR** The formation efficiencies of flocs in the five helical coagulation reactors with various construction characteristics are compared using the harvesting efficiency, average size and settling rate, which are depicted in Fig. 2.

Coagulation performances varied significantly for the different tested HCRs. The harvesting efficiency increased promptly as the

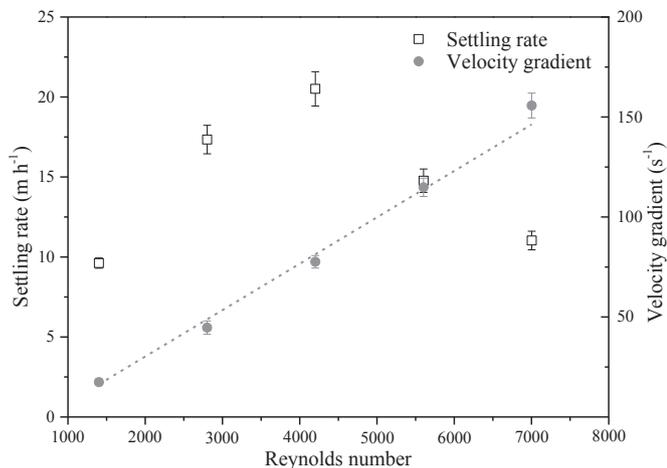


FIG. 3. Effect of Reynolds number ( $Re$ ) and Velocity gradient ( $G$ ) on settling rate.

tube length of the HCR (uncoiled) increased from 2 to 6 m, and an excellent harvesting efficiency of 96.37% was achieved by HCR3 (length: 6 m). When the feed rate was maintained at  $2 \text{ L min}^{-1}$ , a low harvesting efficiency (32.78%) was obtained by HCR1, which had a length of 2 m. This result may be due to the short residence time for floc generation, which resulted in a small size ( $103.22 \mu\text{m}$ ) and a low settling rate ( $6.75 \text{ m h}^{-1}$ ). According to Bo et al. (22), the residence time is one of the most important parameters for floc generation.

As the residence time increased from 10.6 to 31.8 s (the length increased from 2 to 6 m), flocs with an average size of  $1074.37 \mu\text{m}$  and a settling rate of  $17.34 \text{ m h}^{-1}$  were generated in HCR3 due to a sufficient growth period. However, decreased harvesting efficiency and settling rates were observed when the residence time was continuously increased (as the length increased to 10 m), mainly due to flocs breakage caused by the excessive residence time (11). This result was verified by smaller sizes of the flocs generated in HCR4 and HCR5. After reviewing the obtained results, the HCR3 exhibited a very high harvesting efficiency (96.37%) and settling rate ( $17.34 \text{ m h}^{-1}$ ), so this reactor was selected for further investigation.

**Effect of hydrodynamic characteristics on the flocs settling rate** The hydrodynamic characteristics of the HCR for various feed rates ( $1\text{--}5 \text{ L min}^{-1}$ ) were determined in terms of the velocity gradient ( $G$ ) and Reynolds number ( $Re$ ), which were obtained through measurement of the head loss and subsequent calculations. The settling rates of microalgal flocs as a function of the hydrodynamic characteristics of the HCR are shown in Fig. 3.

The velocity gradient ( $G$ ) increased linearly with increasing Reynolds number ( $Re$ ), when the feed rate was increased from 1 to  $5 \text{ L min}^{-1}$ . Moreover, the settling rate of microalgal flocs first increased and then decreased as the  $Re$  increased from 1400.7 to 7003.5. The maximum settling rate ( $20.51 \text{ m h}^{-1}$ ) attained in this study occurred when the  $Re$  was 4202.1 and the  $G$  was  $77.59 \text{ s}^{-1}$  (feed rate  $3 \text{ L min}^{-1}$ ).

According to Galier et al. (23), the flow field is in a transition stage between laminar and turbulent when the value of  $Re$  increased 2300 to 4000, which may increase the settling rate for moderate increases in agitation. However, when the  $Re$  was unduly increased, the rupturing of flocs would have been aggravated by the excessive turbulence, which caused the settling rates to decrease. Those results were also observed by Carissimi et al. (16).

A modified peristaltic pump was employed to compare the settling performance of microalgal flocs in a pulse flow field to that of a constant speed flow field (Fig. 4). The results showed that all the settling rates of flocs formed in the pulse flow field were higher

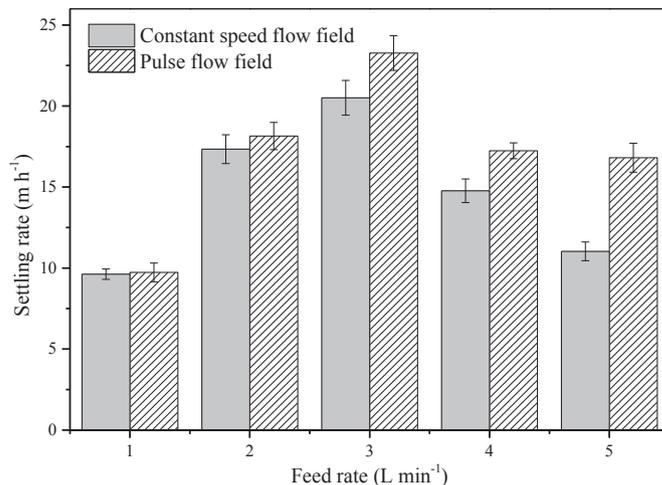


FIG. 4. Effect of feed rate induced by various flow fields on settling rate.

than those produced in the constant speed flow field, especially at a higher feed rate. A superior settling rate of  $23.27 \text{ m h}^{-1}$  was obtained at the feed rate of  $3 \text{ L min}^{-1}$ . The plug pipe flow in the HCR produced by the pulse flow field might have caused smaller clusters or microalgal cells to fill the pores of aggregates, resulting in the larger and more compact flocs. It was similar to coagulation that would be promoted by the gradual shear (24).

**Comparative study of the HCR and a mechanically agitated vessel** The effect of approximate Camp numbers ( $Gt$ ) in the HCR or a mechanically agitated vessel on the settling rate of microalgal flocs is shown in Fig. 5. The settling rate of flocs in the HCR or when a mechanical agitator was present both initially increased for increasing values of  $Gt$ , but this trend later reversed, and these settling rates decreased as the values of  $Gt$  increased further. However, the microalgal flocs generated in the HCR had higher settling rates for all the investigated values of  $Gt$ , and the maximum settling rate in the HCR ( $20.51 \text{ m h}^{-1}$ ) was nearly four times greater than that obtained with a mechanical agitator ( $5.07 \text{ m h}^{-1}$ ).

These higher settling rates may be attributed to the advantages of the uniform plug flow field, high velocity gradient and no dead zones in the helical pipe reactor (11). Conversely, the mechanical agitator causes zones of excessive shear near the impeller edge, which aggravates and breaks flocs. Meanwhile, floc growth is

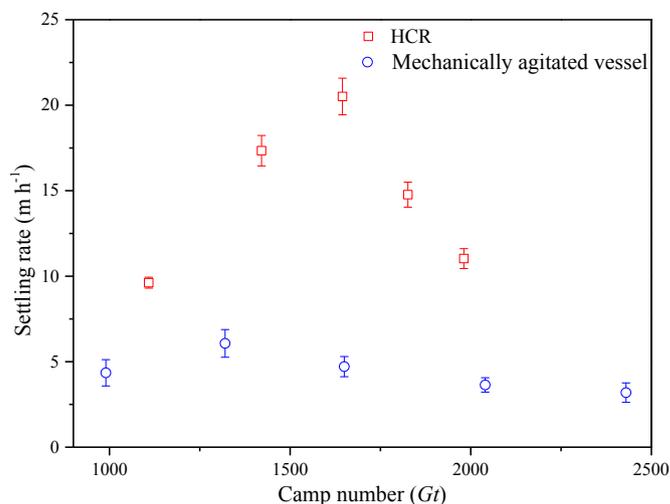


FIG. 5. Effect of Camp number ( $Gt$ ) on settling rate in different reactors.

inhibited in some segregated regions above or below the impeller (16). Thus, low stirring rates (small  $G$ ) are generally employed for most mechanical agitators, which causes a need for a long residence time (approximately 5–10 min) for floc growth (10). Moreover, the HCR system does not require additional mechanical agitation for coagulant dispersion and floc growth, suggesting an efficient and economical method for microalgae harvesting.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jbiosc.2018.09.012>.

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