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Design and Test of Integrated Device for Ammonia Nitrogen Stripping and Recovery of Anaerobic-digested Effluent

Wu Shubiao[1] Xu Xinjie[1] Sun Hao[1] He Keli[1] Wei Xiaoming[2] Dong Renjie[1]

(1. *Key Laboratory of Clean Utilization of Renewable Energy, Ministry of Agriculture, China Agricultural University, Beijing* 100083, *China*
2. *Beijing United Pioneer Environmental Engineering Co., Ltd., Beijing* 100007, *China*)

Abstract: The treatment of anaerobic digestion effluent has become the bottleneck of large-scale biogas station application in China. In order to promote the engineering application of ammonia nitrogen stripping and recovery of anaerobic digestion, an integrated equipment for ammonia stripping and recovery with relative low cost was designed and constructed on-site to demonstrate its efficiency in real biogas plants, decrease lime dosage and control foam. This device mainly consisted of three functional units: pretreatment unit, pH value adjustment unit and ammonia stripping and recovery unit. To reduce the energy consumption, economical reflux circulated stripping method was adopted. A pilot test was carried out by using swine manure anaerobic-digested effluent at a biogas station of Beijing suburbs, the results showed that pH value of anaerobic digestion can be reached 10.5 by adding 22 g lime per liter after four months experiment and optimization, and ammonia removal rate reached 55.8% when the temperature and gas-liquid ratio were 30.7℃ and 960, respectively. Although adding dry lime powder was easily operated, the dissolved efficiency was relatively low. Pre-dissolved lime slurry can effectively avoid the defects and reduce the dosage by 7.5 g/L. Moreover, the effective calcium oxide content of lime from different producers had significant differences. And the performance of lime from different producers in increasing anaerobic digestion effluent pH value was compared and the lime dosage was also analyzed at different temperatures. Finally, higher ammonia removal rate could be attained by using this integrated device under ambient temperature and low air-liquid ratio (0 ~ 1 000).

Key words: anaerobic-digested effluent; ammonia stripping; device design; pilot test

0 Introduction

The anaerobic digestion (AD) technology is one of the most effective ways for the realization of the organic waste reduction, harmlessness and resource utilization, due to its advantages of the clean energy production and the reduction of the greenhouses gases emission. Therefore, AD plays an increasingly significant role in organic waste treatment[1]. Therefore, the application of AD technology in China has developed rapidly in recent years. The number of biogas plants for agricultural waste treatment in China has increased from 11 200 by the end of 2005 to 91 600 in 2012, and the number of middle and large scale biogas projects has grown from 3 500 to 15 400 in the same year[2-3]. However, the growing number and size of biogas projects bring the large amounts of AD effluent, which can not be consumed by the farm land application[4]. As a result, the sustainable development of the biogas project will be restricted if the AD effluent has not been treated effectively[5].

Nitrogen has been widely used in agricultural and industrial production[6]. During the AD process, most of the organic nitrogen in raw materials converted to inorganic nitrogen in the form of ammonia nitrogen remaining in AD effluent[1,6]. Thus, the inadequate utilize of the AD effluent will not only cause an secondary pollution to the environment, for instance, affect the ecological balance, but also waste the nitrogen and phosphorus resources[6-7]. For this reason, the effectively treatment of AD effluent along with the nitrogen recovery can prevent the pollution

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Corresponding author: Dong Renjie, Professor. E-mail: rjdong@cau.edu.cn. Tel: +86-010-62737852.

caused by the AD effluent excessive application or discharge, and realize the efficient resource recycling as well.

Ammonia nitrogen stripping and recovery is an efficient technology designed with relative low cost, simple equipment and convenient operation[8-9]. Currently, there have been many studies focusing on the AD effluent treatment with ammonia nitrogen stripping and recovery[10-13], however, most studies was in laboratory-scale, pilot validation and large-scale application has been rarely reported. Although the laboratory studies are better for the investigation of its mechanism during the implementing process, the pilot scale study is still necessary for the guidance of its on-site application on AD effluent treatment. Since there are a variety of complex factors in engineering application process, which will not appear in the laboratory, such as seasonal temperature changes, added alkaline agent type, process parameters, and so on. Above all, this paper presents an integrated device for ammonia stripping and recovery of AD effluent based on the analysis and comparison of the various stripping technologies and their problems exiting in AD effluent treatment. The pilot scale test and validation experiment was conducted, the alkaline agent dosage and the ammonia nitrogen stripping and removal efficiency factors were analyzed. The results may help to provide the technical reference for nitrogen recovery in AD effluent with ammonia stripping and promote its on-site scale applications.

1 Theory

The ammonia stripping and recovery is a physicochemical process in which a liquid mixture is contacted with carrier gas to remove the free ammonia, by mass transfer from the liquid to the gas phase. The ammonia in the gas phase is absorbed with acid for recycling. During these processes, the pH value and temperature of the liquid mixture are main factors influencing the ammonia dissociation rate in the solution. The amount of ammonia that can be stripped from the liquid is controlled by two thermodynamic equilibrium equations, Henry's law equation and ammonia dissociation equilibrium equation. The equations are as follows[14]:

$$p = K_c c \tag{1}$$

$$\frac{C_{NH_3}}{C_{TNH_3}} = 1 + \frac{10^{-b}}{10^{-(0.090\,18 + 2\,729.92/T)}} \tag{2}$$

Where, p is the partial pressure of the ammonia gas, Pa; K_c is the Henry's law constant, Pa·L/mol; c is moalr concentration in the liquid phase, mol/L; C_{NH_3} is the concentrations of free ammonia, mol/L; C_{TNH_3} is the sum of free ammonia and ammonium ion, mol/L; T is the Kelvin temperature, K; b is the pH value of the liquid.

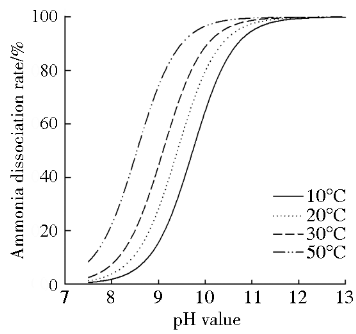

Fig. 1 Ammonia dissociation rate at different pH values and temperatures in solution

The ammonia dissociation rate at different pH value and temperature can be theoretical calculated according to Eq. (2). As shown in Fig. 1, the ammonia dissociation rate increased as well as the liquid's pH value or temperature increasing. However, the liquid temperature increase often consumes a large amount energy, which increases the cost significantly[6, 11]. So, adding alkaline agent often been used to increase the pH value, in case to promote the dissociation of ammonia in solution. In general, the ammonia dissociation rate can be effectively improved with the increasing pH value of the solution at a certain temperature. The ammonia dissociation rate can be 92.5% when the pH value reaches 10.5 at the temperature of 20℃. But, the rate is no longer significantly changed as pH value continued to rise more than 10.5. It indicated that the further improve of pH value above 10.5 has no significant effect on ammonia stripping efficiency[11-12,15].

2 Experimental procedure

2.1 Technological procedure

The integrated device for ammonia stripping and recovery of the AD effluent mainly includes three functional units, the AD effluent high efficient pretreatment unit, pH adjustment unit and ammonia stripping and recovery unit. The whole technological procedure and structural design are shown in Fig. 2 and Fig. 3. The discharged AD effluent from anaerobic digester was transported to the pretreatment unit firstly, followed by the pH adjustment unit and ammonia stripping and recovery unit. These three main functional units of the whole device were automatically controlled by PLC. Sulfuric acid (H_2SO_4, 30%) was used for the absorption of the ammonia as ammonium sulphate ($(NH_4)_2SO_4$).

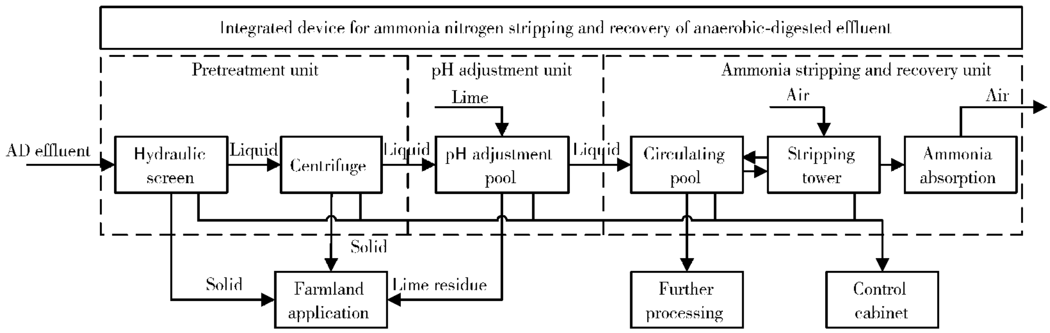

Fig. 2 Technological process of ammonia stripping and recovery

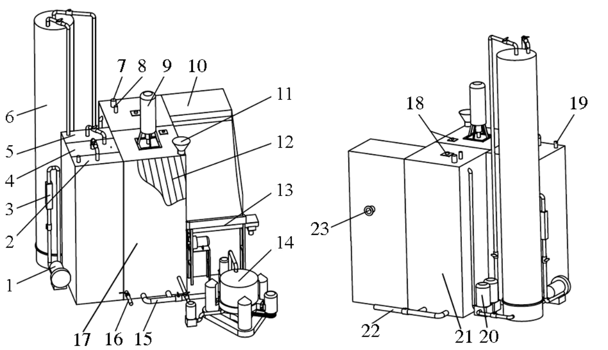
Fig. 3 Constitution figures of integration device for ammonia nitrogen stripping and recovery

1. Fan 2. Exhaust buffer tank 3. Gas flow meter 4. Ammonia absorption tank 5. Absorbing buffer tank 6. Stripping tower 7. Pressure limiting valve 8. Negative pressure valve 9. Stirrer 10. Hydraulic screen 11. Feeding port 12. Inclined tube 13. "U" type screw conveyor 14. Centrifuge 15,22. Discharge pipe 16. Rinse water tube 17. pH adjusting pool 18. pH meter 19. Outlet 20. Circulating pump 21. Cycle stripping pool 23. Feed inlet

2.2 Pretreatment unit

Based on the basic principle of the ammonia stripping and recovery process, it is known to us that improving the initial pH value of the AD effluent to 10.5 and maintaining in this level by adding alkaline agent effectively is the key prerequisites. However, a large amount of suspended solids in the anaerobic digestion solution can reduce the full dissolution of the alkaline agent, which decreased the utilization efficiency of the adding alkaline agent. Therefore, excess dosing alkaline agent usually need to full fill the requirements of the target liquid pH value above 10.5. Thus, the reduction of the suspended solids in AD effluent in order to improve the utilization efficiency of the adding alkaline agent becomes one of key steps for controlling the costs of ammonia stripping and recovery process.

The high efficient pretreatment unit was set to solve the problems mentioned previously in this integrated device. And, the combination of hydraulic screen and centrifugal solid-liquid separator was adopted to reduce alkaline agent consumption factors in the AD effluent and improve the alkaline agent utilization efficiency. Firstly, the large particles in AD effluent can be remove by the hydraulic screen with the help of the hydraulic and gravity. Then, the liquid from the hydraulic screen was transferred to centrifugal solid-liquid separator subsequently. Small particles solids can be further removed effectively under the action of centrifugal filtration. In addition, the buffer capacity of AD effluent was decreased due to the CO_2 emission during the centrifugation process. This is because the low partial pressure of CO_2 in the atmosphere promotes the CO_2 transfer to air.

2.3 The pH adjustment unit

Generally, the alkaline agent used to improve the pH value of the AD effluent include NaOH, $Ca(OH)_2$, and CaO[10-11, 16-17]. In this study, lime was chosen as the external alkaline agent based on the consideration of cost control and the corrosion of equipment[18]. Another advantage of the addition of lime is the reduction of the phosphate, suspended solids and organic matter in AD effluent with the effect of synergistic flocculation[8,10,19]. The sediments in the pH adjustment unit are rich in phosphorus and humus, which can be mixed with the discharged solids from the high efficient pretreatment unit as farmland fertilizer.

Further research is still needed for knowing whether there would be adversely effect on the crops growth with using this kind of fertilizer in relative high pH value.

In addition, the automatic controlled intermittent stirrer was settled in this unit for the reason that the dissolution speed of the adding lime is relatively low and can be easily floating on the liquid surface, which may fouling the inner walls of the equipment and harmful to the device's long-term stable operation. As the same reason, the inclined tube filler was installed in pH adjustment unit to improve the settling characteristics of lime suspension, which avoided the adding lime getting into the subsequent equipment and finally causing an effect on the equipment long-term stable operation.

2.4 Ammonia stripping and recovery unit

The foam can be easily produced in the striping tower while treating anaerobic digested slurry[8, 10], and followed by flooding phenomenon. This will not only have a serious impact on the equipment normal operation, but also affect the stripping efficiency and the purity of consequent recovered ammonia product. The reflux stripping method, has been reported in few studies, can prevent the occurrence of flooding phenomenon[7, 11-12]. However, the reflux stripping process requires a large gas-liquid ratio[12], which remains a high energy consumption level exceeding the tolerance range of the farms and biogas plants in low profit. Accordingly, a reflux circulated stripping method was adopted in the integrated equipment developed in this study on the base of the relevant literatures. With this improvement, the flooding phenomenon can be avoiding and the low power pump with low air flow rate can be used for lower energy consumption relatively.

2.5 Device selection and parameter design

According to LIU's solid-liquid separator sieve selection research[8], total solid content in AD effluent filtrated by 0.5 mm and 0.25 mm sieve have significant differences compared with 0.7 mm sieve, and the treatment effect of 0.25 mm sieve is better than 0.5 mm sieve. The research also showed that the solids removal performance with free settling after sieving is much better, which means the further treatment after sieving is an effective way to remove the solids in AD effluent. Therefore, the hydraulic screen with 0.3 mm grid gap and the three-column centrifuge was chosen in this study. The three-column centrifuge was chosen based on the tabular method[20].

According to the target daily treatment capacity of the device ($1\ m^3/d$), the hydraulic screen dimensions (length × width × height) is 1.5 m × 0.81 m × 1.8 m. The type of centrifuge is SS – 600 with 500 mesh strainer, speed 1 500 r/min. The solid digestate was transported by a "U" type screw conveyer.

The up-flow sedimentation pool installed the inclined tube conducted as pH adjusting pool, whose size is: 1 m × 1 m × 2 m, also designed according to the daily treatment capacity. The flap paddle stirrer has the advantages like simple structure and suitable for operation in situation with solid-liquid suspension[21-22]. Therefore, the flap paddle stirrer was selected based on the experiences, the shape of pH adjustment pool and theory of the solid-liquid suspension system[23]. The stirring speed was 50 r/min, and the stirrer work intermittently at positive and negative direction to prevent solids aggregation in the edges.

The ammonia stripping and recovery unit is mainly composed of circulating stripping tank, circulating pump, stripping tower, etc. (Fig. 3).

The aeration-spray tower was adopted in this study, since a large amount of foam and sediment was easily produced during the stripping process. The aeration started from the bottom of the tower when there is a certain amount of liquid in the tower. Meanwhile, the liquid sprayed from the top of the tower and then reflux recycle stripping process started. The main factor affecting the height of the tower is foam production in stripping process. Accordingly, based on foam production from biogas slurry and the operating mode, the column diameter and height of the tower was $\Phi = 0.6$ m and $h = 3$ m. The liquid circulation flow rate is 80 ~ 100 L/min according to the actual operating condition.

3 Materials and methods

3.1 Materials

After the completion of the device design and experts justification, a pilot demonstration was structured (Fig. 4) in one biogas plant of Beijing suburb and pilot test was conducted during August 2015 to November 2015. The biogas plants, treating pig manure, has two up-flow solids reactors (USR) which had a capacity of 160 m^3. The digestion temperature was maintained at (37 ± 1) ℃ and the hydraulic residence time (HRT) was 40 d. The physical and chemical properties of the AD effluent produced during the experiment are shown in Tab. 1.

Fig. 4 Image of integrated device for ammonia stripping and recovery from anaerobic-digested effluent

Tab. 1 Characterizatics of anaerobic-digested effluent

Parameter	Value
pH value	7.3 ~ 7.9
NH_4^+-N concentration/($mg \cdot L^{-1}$)	800 ~ 1 700
PO_4^{3-} concentration /($mg \cdot L^{-1}$)	5 ~ 18
Mass fraction of total solids/%	0.7 ~ 1.2
Mass fraction of volatile solids/%	0.3 ~ 0.6
Bicarbonate alkalinity (calculated with $CaCO_3$)/($mg \cdot L^{-1}$)	5 000 ~ 8 000
Volatile fatty acids/($mg \cdot L^{-1}$)	600 ~ 1 500

3.2 Experimental procedure

In this paper, the optimization of the alkaline agnet dosage and the ammonia nitrogen removal efficiency were studied. The performance of adding the powdery lime and lime slurry was compared in the pilot test, and we found that the lime dosage is different among different lime manufacturers during the experiment. Therefore, the effective calcium oxide component in lime from different manufacturers was tested, and the performance for pH improvement of AD effluent by adding lime from different manufacturers was analyzed in laboratory. As described before, the gas-liquid ratio (the ratio of gas and liquid flow[11]) and temperature are the key factors influencing the efficiency of the ammonia nitrogen stripping process[8, 11-12, 15]. The gas-liquid ratio can be adjusted by changing the blowing time, since the circulated stripping method was adopted in this study. The influence of gas-liquid ratio on ammonia stripping and removal efficiency was analyzed by adjust the blowing gas flow. Three gas-liquid ratios (640, 800 and 960) were used in this study, and the gas flow was 80 m^3/h, 100 m^3/h and 120 m^3/h, respectively. In addition, The operated temperature changed between 0° and 35℃ in pilot test, and temperature's influence on the ammonia nitrogen removal efficiency in this condition was analyzed.

3.3 Sample collection and analytical methods

During each batch treatment (1 m^3), 50 mL samples were collected from the device inlet, hydraulic screen outlet, centrifuge outlet and the pH adjusting tank, respectively. The physicochemical properties of samples were measured and the addition of alkaline agent in each batch was recorded. During the stripping process, 50 mL samples were taken from circulating pool every hour for the temperature, pH value and ammonia nitrogen concentration measurement. The sampling ports the circulating pool and pH adjusting tank are in the middle. Three repeated experiments were carried out for the same condition.

The glass electrode was used to measure pH value. Total solids and volatile solids content were measured by dry method[24]. The concentration of ammonia nitrogen (NH_4^+-N) and phosphate (PO_4^{3-}) were measured by salicylate – chlorate photometric method and molybdenum antimony anti points spectrophotometric method[25]. Hydrogen carbonate alkalinity (TIC) and total volatile fatty acid (VFA) concentration was determined by Nordmann method[26].

4 Results and discussion

4.1 Alkaline agent dosing optimization

4.1.1 Analysis on the alkaline agent dosing and the increase of pH value

The powdery lime was used at the initial experiment stage for taking the simplicity of the practical application into account. The Fig. 5 shows that an excess of lime addition was required for the first time. Part of the added lime reacts with water rapidly, assembling to spherical, floating on the liquid surface, which can be easily overflow into the circulation stripping pool with the AD effluent from the pH adjusting tank. Thus, adding lime slurry, prepared by adding the lime to clean water for solving in advance, is selected after the first three tests. The lime dosage can reduce 7.5 g/L and remain at 40 g/L during the experiment with the adoption of this method which effectively avoid the defects of adding the powdery lime directly. According to LIU's study[8], the performance is better when the hydrated lime slurry has been used in dealing with the AD effluent, compared with adding dry powder, which reduced 4.49 g/L alkaline agent addition.

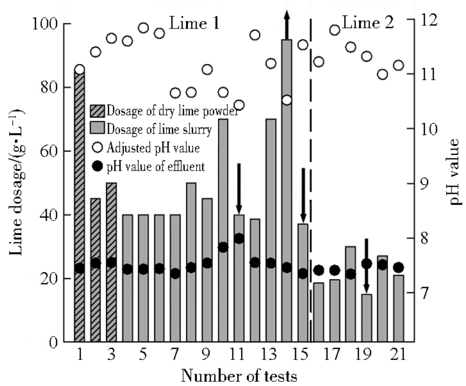

Fig. 5 Lime dosing quantity and adjusted pH values

Although the addition of lime slurry improved alkaline agent utilization rate and reduced the alkaline agent dosage, the sediments in the bottom of poor increased continuously with the accumulation of alkaline agent dosage. As a result, the alkaline agent dosage increased with the increase of sediments. The reason may relate to that the solution mixing was influenced by the sediments, and further influenced the dissolution of the added alkaline agent.

This study shown that discharging 300 L sediments (as symbol ↓ shown in Fig. 5) before adding the alkaline agent can reduce the alkaline agent dosage when the alkaline agent dosage is too high. And if the sediments were not discharge promptly, the dosage will continue to increase (as symbol ↑ shown in Fig. 5). Therefore, cleaning the sediments regularly was suggested in practical application.

The performance of the powdery lime used at the initial experiment stage, purchased from Beijing sewage treatment reagent factory (referred to as the lime 1), was not satisfied due to the low effective calcium oxide content. Thus, the lime purchased near the biogas plant was used as the alkaline agent (referred to as lime 2). The experiment results shown that the alkaline agent dosage maintained at 22 g/L when take lime 2 as the alkaline agent, which has reduced 45% than lime 1.

4.1.2 The performance of the AD effluent's pH increase with lime

The dosage of these two kinds of lime as alkaline agent for increasing the AD effluent's pH value was obviously different in pilot experiment. Therefore, the content of effective calcium oxide and the performance in increasing AD effluent's pH value of these two kinds of lime was further tested and analyzed in laboratory. The effective calcium oxidation content in lime was measured by the "T0811 - 1994 method for the determination of effective calcium oxide in lime", and the results showed the content's difference in two kinds of lime was significant with the mass fraction being (9.05 ± 0.04)%, (54.77 ± 0.31)%, respectively. Also, the performance of using these two kinds of limes to improve the AD effluent's pH value was compared in laboratory at room temperature. The results (as shown in Fig. 6) showed that the performance of lime 2 is much better than lime 1. To improve the AD effluent's pH value above 10.5, adding 43 g/L lime 1 is required while only 19 g/L lime 2 is enough in the same condition. Moreover, the laboratory test results were similar to pilot experiment results.

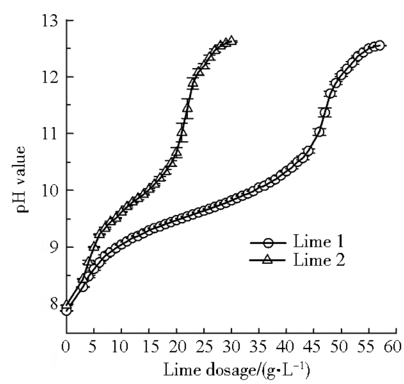

Fig. 6 Performance of lime from different producers increasing anaerobic digestion effluent pH value

The increase of the pH value of AD effluent was to improve the ammonia nitrogen dissociation rate in AD effluent during the stripping process. Generally, the ammonia nitrogen dissociation rate in AD effluent is not only affected by the pH value, but also the temperature (as Eq. (2)). Thus, the practical application performance of this integrated device may be also affected by the environmental temperature in different seasons. Moreover, according to the experimental study on the performance of increasing the AD effluent's pH value by adding these two kinds of lime and ammonia dissociation equation, the lime dosage during the ammonia stripping process of AD effluent with different temperature can be calculated (Tab. 2).

Tab. 2 Lime dosage at different temperatures

Temperature/℃	Lime dosage/($g \cdot L^{-1}$)	
	Lime 1	Lime 2
0 ~ 10	43 ~ 46	23 ~ 26
10 ~ 20	39 ~ 41	20 ~ 23
20 ~ 30	35 ~ 39	17 ~ 20
30 ~ 40	30 ~ 35	13 ~ 16
40 ~ 45	25 ~ 30	10 ~ 12

4.2 Ammonium removal efficiency optimization

The ammonium removal performance and the key factors of this integrated device were analyzed by the on-site pilot-scale demonstration. And, the running performance of the device mainly affected by gas-liquid ratio and AD effluent's temperature.

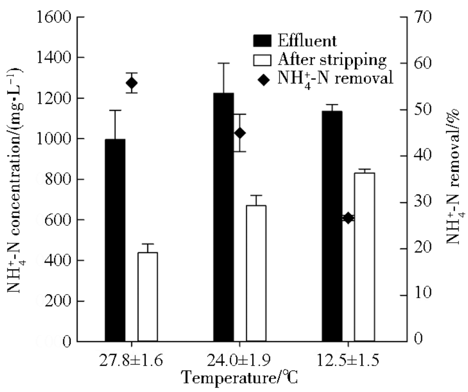

Fig. 7 Effect of temperature on efficiency of ammonia nitrogen removal rate

LI et al.[27] used the stripping technique to remove ammonium from coking wastewater, and found that when the temperature increased from 20℃ to 60℃, the ammonium removal rate improved from 20% to 80%, respectively. The results from the study of CAMPOS et al.[28], who investigated the treatment of leachate by ammonium stripping process, also showed that the temperature has great influence on the ammonium removal rate. The pilot scale experiment was carried out from August to November while the environmental temperature varies from 0℃ to 35℃. So, the ammonium removal rate of this integrated device at different temperatures was investigated in this study, as the results are shown in Fig. 7. The ammonium removal rate is (55.8 ± 2.2)% at (27.8 ± 1.6)℃ and reduced to (26.7 ± 0.56)% at (12.5 ± 1.5)℃ with the same condition (the gas-liquid ratio is 960, and the pH value is 11.4 ± 0.3 at the beginning of the stripping process). The reason is that the higher temperatures aggravated the Brownian motion which promoted the ammonia's desorption and further improved the mass transfer rate of ammonia. So that, the ammonia molecules can be removed more easily[29].

The relatively high gas-liquid ratio is able to maintain greater impetus of the ammonia molecules in the gas-liquid two-phase mass transfer process, which will promote the ammonia molecules transfer to the gas phase, so as to improve the efficiency of ammonia removal. Despite the ammonia concentration in AD effluent varied widely with the change of fermentation material and temperature in biogas plant, the ammonia nitrogen removal efficiency increased with the increasing of gas-liquid ratio (Fig. 8). The ammonia removal efficiency increased from (46.1 ± 5.8)% to (55.8 ± 2.2)% as the gas-liquid ratio increases from 640 to 960 with the same condition (the temperature is (30.7 ± 2.5)℃ and the pH value is 11.5 ± 0.2 at the beginning of the stripping process), respectively.

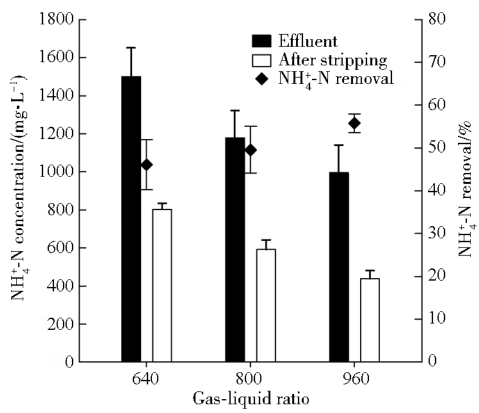

Fig. 8 Effect of gas-liquid ratio on efficiency of ammonia nitrogen removal rate

The treatment of AD effluent has become the bottleneck of large-scale biogas plants application in China[30]. Although the ammonia stripping process is a low cost method for wastewater treatment, which also achieved a relative high efficiency in laboratory studies. However, the cost for AD effluent treatment by the ammonia stripping technology is still high due to the limitation of actual conditions of biogas station and the complex characteristics of AD effluent. Thus, it is still difficult for this technology to be widely used in farms and biogas stations with low profit.

GUŠTIN et al.[12] used packed column for ammonia stripping and recovery in digested slurry of pig manure and found that the removal rate of ammonia reaches 55.3% when the temperature is 50℃, the pH value is 10.5 and the gas-liquid ratio is 412. When the gas-liquid ratio further rises to 1875, the ammonia removal rate increases to 92.8%. Furthermore, SUI et al.[11] found that the ammonia removal rate in digested slurry of pig manure presents 81.8% with the temperature is 30℃ and a similar gas-liquid ratio. Besides, JIANG et al.[7] used an overall ammonia stripping and recovery device for the digested slurry of cow manure treatment and found that the removal rate of ammonia is only 33.9% in lower temperature (25℃, pH value 10.5, gas-liquid ratio 2 429).

From the above studies, it is obviously that both the higher temperature and the higher gas-liquid ratio capable to promote the ammonia removal effectively, and the operating cost increased greatly as well. Thus, in most cases, the ammonia stripping process conducted in room temperature is still the only choice, except the specific biogas plants with the combined heat and power (CHP) which is able to use the waste heat in power generation for liquid temperature enhancement to avoid additional cost. This is also the reason for the investigation of the ammonia stripping and recovery in AD effluent with under room temperature and low gas liquid ratio (0 ~ 1 000) in this study.

After the optimization from the pilot study, the ammonia nitrogen removal rate of this integrated device is (55.8 ± 2.2)% in the condition that the temperature and the gas liquid ratio is (30.7 ± 2.5)℃ and 960, respectively. The ammonia nitrogen removal efficiency in this study was relatively low as compared with previous studies. As described before, the reason may relate to the lower temperature and smaller gas-liquid ratio used in this study, as well as the adoption of the lower-cost empty tower. On the other hand, a positive performance still exists in this study, as the stripping process was carried out under room temperature and low gas liquid ratio (0 ~ 1 000).

Above all, the integrated device for ammonia stripping and recovery in AD effluent can realize the whole process in AD effluent treatment, including the pre-treatment of the AD effluent, pH adjustment and ammonia stripping and recovery. The utilization of the adding alkaline agent improved effectively through the AD effluent's pre-treatment which promote the dissolution of the alkaline agent. The relatively high ammonia removal efficiency was achieved under the condition of room temperature and lower gas-liquid ratio, since the cycling stripping method adopted. This device has good promotional value for ammonia nitrogen stripping and recovery of AD effluent on-site application.

5 Conclusions

(1) An integrated device for ammonia nitrogen stripping and recovery of anaerobic-digested effluent was designed and validated. The integrated device mainly includes three functional units, the AD effluent pretreatment unit, pH adjusting unit and ammonia stripping and recovery unit. The results from the laboratory and pilot scaled studies may provide technical support for the on-site application of the ammonia stripping and recovery technology on the treatment and nutrients recovery in AD effluent.

(2) There are significant differences in the performance of the AD effluent's pH value enhancement with limes from different manufacturers. Thus this factor should be considered in practical application. In addition, alkaline agent dosage should be adjusted according to the environmental temperature change.

(3) The ammonia stripping efficiency increased with the improvement of the gas-liquid ratio and temperature, however, improve the gas-liquid ratio and temperature will also enhance energy consumption. As a result, all these parameters should be considered comprehensively with the combination of costs.

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厌氧消化液氨氮吹脱回收整体处理装置设计与中试试验

吴树彪[1] 徐新洁[1] 孙 昊[1] 何柯立[1] 魏晓明[2] 董仁杰[1]

(1.中国农业大学农业部可再生能源清洁化利用技术重点实验室,北京 100083;
2.北京联合创业环保工程股份有限公司,北京 100007)

摘要:为了促进氨氮吹脱回收工艺处理厌氧消化液的工程化应用,针对投碱量较大、吹脱时易产生泡沫和能耗较高等问题,设计了一套厌氧消化液氨氮吹脱回收整体处理工艺装置。该整体处理装置由高效预处理单元、pH值调节单元及氨氮吹脱与回收单元3个功能单元组成,采用了低耗逆流循环吹脱方法。完成设计后在京郊沼气站进行了中试装置示范搭建,并于2015年8月—11月中旬进行了现场中试试验和工艺优化。结果表明,投加22 g/L生石灰时厌氧消化液pH值可达到运行要求值(10.5以上),并且在水温和气液比分别为(30.7±2.5)℃和960时,氨氮去除率可达(55.8±2.2)%。研究发现虽然投加石灰干粉具有简便性,但是利用率较低,采用投加石灰浆的方法可以有效避免投加干粉的缺陷,可减少7.5 g/L的投加量。同时研究发现不同厂商生石灰中有效氧化钙的含量差别较大,提升厌氧消化液pH值的性能存在较大差异,并分析得出了不同温度下的建议投碱量。该整体处理装置在常温和低气液比(0~1 000)条件下达到了相对稳定的氨氮脱除效率,具有较好的应用推广前景。

关键词:厌氧消化液;氨氮吹脱;装置设计;中试试验

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Design and Test of Integrated Device for Ammonia Nitrogen Stripping and Recovery of Anaerobic-digested Effluent

Wu Shubiao[1] Xu Xinjie[1] Sun Hao[1] He Keli[1] Wei Xiaoming[2] Dong Renjie[1]

(1. *Key Laboratory of Clean Utilization of Renewable Energy*, *Ministry of Agriculture*, *China Agricultural University*, *Beijing* 100083, *China*
2. *Beijing United Pioneer Environmental Engineering Co.*, *Ltd.*, *Beijing* 100007, *China*)

Abstract: The treatment of anaerobic digestion effluent has become the bottleneck of large-scale biogas station application in China. In order to promote the engineering application of ammonia nitrogen stripping and recovery of anaerobic digestion, an integrated equipment for ammonia stripping and recovery with relative low cost was designed and constructed on-site to demonstrate its efficiency in real biogas plants, decrease lime dosage and control foam. This device mainly consisted of three functional units: pretreatment unit, pH value adjustment unit and ammonia stripping and recovery unit. To reduce the energy consumption, economical reflux circulated stripping method was adopted. A pilot test was carried out by using swine manure anaerobic-digested effluent at a biogas station of Beijing suburbs, the results showed that pH value of anaerobic digestion can be reached 10.5 by adding 22 g lime per liter after four months experiment and optimization, and ammonia removal rate reached 55.8% when the temperature and gas-liquid ratio were 30.7℃ and 960, respectively. Although adding dry lime powder was easily operated, the dissolved efficiency was relatively low. Pre-dissolved lime slurry can effectively avoid the defects and reduce the dosage by 7.5 g/L. Moreover, the effective calcium oxide content of lime from

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作者简介:吴树彪(1983—),男,副教授,主要从事废弃物处理与生物质利用研究,E-mail:wushubiao@gmail.com

通信作者:董仁杰(1964—),男,教授,主要从事废弃物处理与生物质利用研究,E-mail:rjdong@cau.edu.cn

different producers had significant differences. And the performance of lime from different producers in increasing anaerobic digestion effluent pH value was compared and the lime dosage was also analyzed at different temperatures. Finally, higher ammonia removal rate could be attained by using this integrated device under ambient temperature and low air-liquid ratio (0 ~ 1 000).

Key words: anaerobic-digested effluent; ammonia stripping; device design; pilot test

引言

厌氧消化技术是实现有机废弃物减量化、无害化和资源化利用的有效途径之一。采用厌氧消化技术处理有机废弃物,不仅可以产生清洁能源——甲烷,而且可以有效缓解有机废弃物对环境造成的负面影响,因此这一技术在处理有机废弃物方面发挥着越来越重要的作用[1]。近年来,厌氧消化技术在我国的应用发展迅速,据统计,我国处理农业废弃物的沼气工程从 2005 年底的 1.12 万处发展到 2012 年的 9.16 万处,其中大中型沼气工程数量从 0.35 万处增长到 1.54 万处[2-3]。沼气工程数量及其规模不断增长的同时也产生了大量沼液,单一的土地消纳往往不能满足沼气工程的发展需要[4],如果这些沼液得不到有效处理将会制约沼气工程的可持续发展[5]。

经过厌氧发酵过程,原料中大部分有机氮被转化为无机氮,以氨氮的形式大量留存在厌氧消化液中[1,6]。而氮素是农业和工业生产广泛应用的原料[6],这些消化液不能充分被利用,不仅容易对环境造成二次污染,影响生态平衡[6-7],更是对氮、磷等资源的浪费。因此,采取有效措施处理厌氧消化液,回收沼液中的氮素,不仅可以有效防止沼液过量施用或排放造成的环境污染,而且可以实现资源的高效回收利用。

氨氮吹脱工艺是一种投资成本较低、设备相对简单、操作简便的高效物化脱氮工艺[8-9]。目前,虽然国内外学者运用这一工艺在处理厌氧消化液方面做了很多相关研究[10-13],但大多停留在实验室规模的小试研究,中试试验及规模化应用鲜有报道。虽然实验室研究可以较好地探讨该工艺实施中的机理问题,但由于实际工程应用时受多种复杂因素(如季节温度变化、添加碱剂类型、操作工艺参数等)的影响,因此非常有必要进行相关中试试验研究,以解决该工艺在实际推广应用中可能遇到的问题。本文基于国内外文献,在分析比较多种吹脱工艺及其在厌氧消化液处理应用过程中可能存在问题的基础上,设计一套厌氧消化液氨氮吹脱回收整体处理装置,并通过现场中试试验测试其运行性能并研究投碱量和氨氮吹脱效率的影响因素,以期为推动氨氮吹脱工艺在回收厌氧消化液中氨氮的规模化应用中提供技术参考。

1 理论基础

氨氮吹脱工艺即通过提高液体的 pH 值或温度,提高液体中氨氮的离解率,使液体中氨的气体分压升高,然后通过一定方式使液体与载气充分接触,在分压差的作用下液体中游离态氨分子发生解吸并进入载气,然后随载气流动带出容器,而载气中的氨分子采用酸吸收等方式进行回收,达到废水中氨氮脱除回收的目的。氨氮吹脱工艺依据 2 个热力学平衡方程,亨利定律方程和氨离解平衡方程[14],公式分别为

$$p = K_c c \tag{1}$$

$$\frac{C_{NH_3}}{C_{TNH_3}} = 1 + \frac{10^{-b}}{10^{-(0.090\,18\ +2\,729.92/T)}} \tag{2}$$

式中 p——游离氨的气体分压,Pa

K_c——亨利常数,Pa·L/mol

c——溶液中游离氨的物质的量浓度,mol/L

C_{NH_3}——溶液中游离氨的浓度,mol/L

C_{TNH_3}——游离氨和氨根离子总浓度,mol/L

T——热力学温度,K

b——液体的 pH 值

根据式(2)可求得不同 pH 值和温度条件下氨根的离解率(图 1)。由图 1 可以看出,提高溶液的 pH 值和温度都有利于提高溶液中氨氮的离解率,在实际应用中考虑到提高温度的能耗较大,处理成本较高[6,11],因此常采用投加碱剂提高 pH 值来促进溶液中氨的离解。当温度一定时,提高溶液的

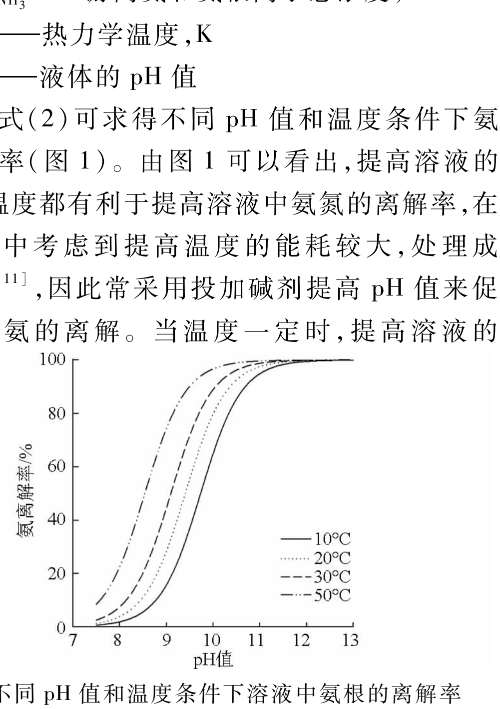

图 1 不同 pH 值和温度条件下溶液中氨根的离解率

Fig. 1 Ammonia dissociation rate at different pH values and temperatures in solution pH 值可有效提高溶液中氨的离解率。在温度为 20℃条件下，pH 值升高到 10.5 时溶液中氨的离解率已经达到 92.5%，pH 值继续升高，氨氮的离解率变化不再显著，即对氨氮吹脱效率没有显著作用[11-12, 15]。

2　工艺流程及装置结构

2.1　工艺流程

该厌氧消化液氨氮吹脱回收整体处理装置主要由 3 个功能单元组成：高效预处理单元、pH 值调节单元及氨氮吹脱与回收单元。其整体工艺流程和构造设计分别如图 2 和图 3 所示。厌氧消化液首先由沼气池排出后被输送至高效预处理单元，随后依次进入 pH 值调节和氨氮吹脱回收单元，完成厌氧消化液氨氮吹脱与回收整体工艺流程。整体装置 3 个主要功能单元的运行均由 PLC 控制器自动控制。吹脱出来的氨采用质量分数为 30% 的硫酸溶液进行回收。

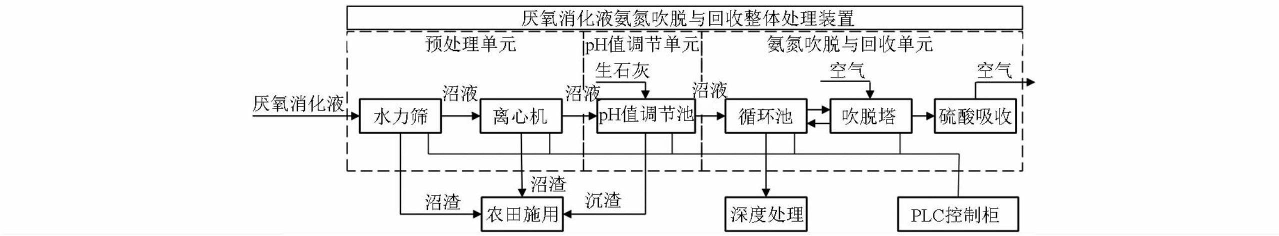

图 2　厌氧消化液氨氮吹脱回收整体处理工艺流程

Fig. 2　Technological process of ammonia stripping and recovery

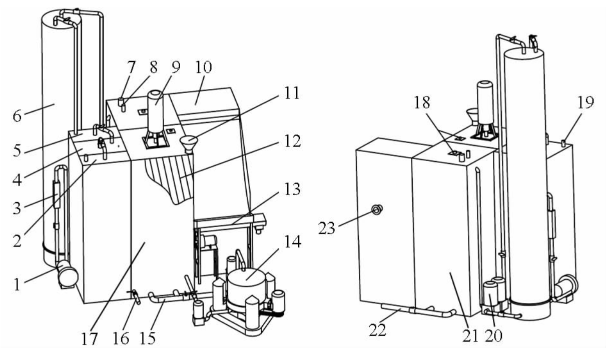

图 3　厌氧消化液氨氮吹脱回收整体处理装置结构图

Fig. 3　Constitution figures of integration device for ammonia nitrogen stripping and recovery

1. 风机　2. 排气缓冲罐　3. 气体流量计　4. 氨吸收罐　5. 吸收缓冲罐　6. 吹脱塔　7. 限压阀　8. 负压阀　9. 搅拌器　10. 水力筛　11. 投药口　12. 斜管填料　13.“U”型螺旋输送器　14. 离心机　15、22. 排渣管　16. 冲洗水管　17. pH 值调节池　18. pH 计　19. 排气口　20. 循环泵　21. 循环吹脱池　23. 进料口

2.2　高效预处理单元

由氨氮吹脱回收工艺的基本原理可知，如何有效利用碱剂提高厌氧消化液的初始 pH 值并较为稳定地维持 pH 值在 10.5 以上是吹脱工艺的关键前提条件。然而厌氧消化液中含有的大量固体悬浮物会降低碱剂投加后在厌氧消化液中的充分溶解，使得投加的外源碱剂利用效率较低。因此，在最终吹脱目标液体 pH 值 10.5 的控制要求下，往往需要投加过量的外源碱剂。如何降低厌氧消化液中固体悬浮物以提高碱剂利用效率及降低投碱量成为控制吹脱工艺运行成本的关键步骤。

针对上述问题，在本厌氧消化液氨氮吹脱回收整体处理装置中首先设置了高效厌氧消化液预处理单元，探讨利用水力筛和离心式固液分离机组合工艺，降低厌氧消化液中耗碱因素的影响，提高碱剂利用率。其中水力筛在水力和重力作用下通过栅网去除厌氧消化液中的大颗粒固形物。水力筛出液进入后续的离心式固液分离机，一方面在离心过滤作用下，较小颗粒固形物得以进一步有效去除，同时由于大气中二氧化碳分压较低，使得厌氧消化液中二氧化碳向空气中转移，打破了厌氧消化液原有的缓冲体系，降低了厌氧消化液的缓冲能力。

2.3　pH 值调节单元

用于提升厌氧消化液 pH 值的碱剂一般包括 NaOH、$Ca(OH)_2$和 CaO 等[10-11, 16-17]。本研究中选用生石灰作为外源碱剂，一方面是考虑成本控制，另一方面是因为生石灰对设备的腐蚀性相对较小[18]，且生石灰的投加还有协同絮凝去除厌氧消化液中磷酸盐、悬浮性固体及有机物的效果[8, 10, 19]。pH 值调节后的沉渣中由于富含磷和腐殖质等厌氧消化液中的营养物质，可与高效预处理单元排出的沼渣混合作为农田肥料，但是较高的 pH 值是否会对农作物生长产生不利影响需进一步研究。

由于生石灰投加后溶解相对较慢，投加后容易在液体表面漂浮和设备内壁结垢，影响设备的长期稳定运行。因此本整体装置中不仅设置了可自动控制的间歇搅拌器，同时在 pH 值调节单元中安装了斜管填料以提高悬浮石灰的沉降性能，避免流入后续吹脱回收单元影响设备的稳定运行。

2.4　氨氮吹脱与回收单元

采用氨氮吹脱工艺处理厌氧消化液时，吹脱过

程中吹脱塔内极易产生泡沫[8, 10]，发生液泛现象，不仅严重影响设备的正常运行，同时会影响吹脱效率及后续氨回收产品的纯度。虽然文献报道吹脱塔采用逆流吹脱的方式[7, 11-12]可相对防止液泛现象的发生，但该过程仍需要较大的气液比[12]，使得吹脱过程能耗仍居高不下，低利润的养殖场和沼气工程点仍难以接受。在参照相关文献的基础上，本研究中开发的整体装置采用了低耗逆流循环吹脱工艺，不仅可以避免泡沫导致的液泛现象，而且可以采用低气流量的小功率气泵，相对降低吹脱能耗。

2.5　装置参数设计及选型

根据刘良[8]的固液分离机筛网选型研究，过 0.5 mm 和 0.25 mm 筛的厌氧消化液筛滤液总固体物含量相对于 0.7 mm 筛差异显著，并且过 0.25 mm 筛的处理效果优于 0.5 mm，同时其研究还表明筛滤后进行自由沉降固形物去除效果更明显，说明过筛后再进一步处理可有效去除厌氧消化液中的固形物。因此，本研究中选用了栅网间隙为 0.3 mm 的水力筛，并采用表格法[20]选用了三足式离心机对筛滤后的滤液进行深度处理。根据本装置设计日处理量（1 m^3），水力筛外形尺寸设置（长 × 宽 × 高，下同）为：1.5 m × 0.81 m × 1.8 m，离心机为 SS-600 型，转速为 1 500 r/min，滤网为 500 目。沼渣输送装置为“U”型螺旋输送装置。

pH 值调节池为上流式斜管沉降池，根据装置的设计日处理量确定其尺寸为：1 m × 1 m × 2 m。折叶桨式搅拌器结构简单，加工容易，适用于固液悬浊操作[21-22]，因此，本研究选用了折叶桨式搅拌器，根据试验经验、调节池形式及固-液悬浮系统理论[23]，搅拌转速设定为 50 r/min，并且为防止固体物在棱角聚集，搅拌器进行间歇正反方向搅拌。

氨氮吹脱与回收单元主要由循环吹脱池、循环泵、吹脱塔、风机、缓冲罐及吸收罐等组成（图 3）。由于吹脱时沼液易产生大量泡沫，并且易结垢，本研究中选用了曝气喷淋塔，运行时，底部持有一定量液体进行曝气，上部进行喷淋，进行循环逆流吹脱。在吹脱处理厌氧消化液时影响塔高的主要因素为泡沫产生量，根据沼液泡沫产生量及操作形式确定塔径和塔高分别为 $\Phi = 0.6$ m、$h = 3$ m。液体循环流量根据实际操作控制为 80 ~ 100 L/min。

3　试验分析

3.1　试验材料

完成装置设计和专家论证后，在北京郊区某沼气站进行了中试装置示范搭建（图 4），并于 2015 年 8 月—11 月中旬进行了现场中试试验。该沼气站以猪粪为原料，中温发酵（37℃），采用升流式固体厌氧反应器（USR）工艺，发酵容积为 2（座）× 160 m^3，水力停留时间为 40 d。试验过程中该沼气站产生的厌氧消化液理化性质如表 1 所示。

图 4　厌氧消化液氨氮吹脱回收整体处理装置

Fig. 4　Image of integrated device for ammonia stripping and recovery from anaerobic-digested effluent

表 1　厌氧消化液理化性质

Tab. 1　Characteristics of anaerobic-digested effluent

参数	数值
pH 值	7.3 ~ 7.9
NH_4^+-N 质量浓度/(mg·L^{-1})	800 ~ 1 700
PO_4^{3-} 质量浓度/(mg·L^{-1})	5 ~ 18
总固形物质量分数/%	0.7 ~ 1.2
挥发性固形物质量分数/%	0.3 ~ 0.6
碳酸氢盐碱度（以 $CaCO_3$ 计）/(mg·L^{-1})	5 000 ~ 8 000
挥发性有机酸质量浓度/(mg·L^{-1})	600 ~ 1 500

3.2　试验设计

本文分别对碱剂投加和氨氮吹脱效率进行了优化研究。在现场中试试验中对比分析了投加石灰干粉和投加石灰浆的效果，试验过程中发现不同厂商的生石灰投加量存在较大差异，因此在实验室对其有效氧化钙成分进行了测定并分析了不同厂商生石灰提升厌氧消化液 pH 值性能的差异。在厌氧消化液氨氮吹脱过程中，气液比和温度是影响吹脱效率的关键因素[8, 11-12, 15]。气液比是气体流量与液体流量的比值[11]，本研究中采用循环吹脱方法，可以通过改变吹脱时间相对改变气液比。本文通过调节吹脱气流量，分析对比了气液比对氨氮吹脱效率的影响（试验设定了 3 种气流量：80、100、120 m^3/h，其相应的气液比为 640、800、960），并且现场中试试验运行期间环境温度在 0 ~ 35℃ 之间变化，通过在不同环境温度下运行该装置分析了温度对氨氮吹脱效率的影响。

3.3　样品采集及测定方法

每批次处理（1 m^3）试验运行过程中分别在设备进水端、水力筛出水端、离心机出水端及 pH 值调节池取样口取样 50 mL，分别测定其理化性质，并记录每批次试验的投碱量。吹脱过程中每吹脱 1 h 在循

环吹脱池取样口取样 50 mL,测定沼液温度、pH 值及氨氮含量的变化。其中,pH 值调节池的取样口及循环吹脱池取样口都设置在箱体中部。每个相同吹脱条件的试验进行 3 次重复试验。

pH 值采用玻璃电极法测定;总固形物质量分数和挥发性固形物质量分数采用干燥法测定[24];氨氮(NH_4^+-N)质量浓度和磷酸根(PO_4^{3-})质量浓度分别采用水杨酸-次氯酸盐光度法和钼锑抗分光光度法测定[25]。碳酸氢盐碱度(TIC)和总挥发性脂肪酸(VFA)质量浓度采用 Nordmann 联合滴定法测定[26]。

4　结果与分析

4.1　碱剂投加优化

4.1.1　投碱量及 pH 值提升分析

考虑到实际应用操作的简便性,在试验初期采用投加石灰干粉的方法,图 5 所示的试验结果表明首次需要投加过量生石灰,并且在试验过程中观察到投加石灰干粉后部分生石灰会被与水快速反应的生石灰包裹,集结为球状,浮上液体表面,并容易随沼液在 pH 值调节池溢流进入循环吹脱池。因此,在前 3 次试验后又选用了投加石灰浆的方法,即将生石灰预先用清水调制后再进行投加。采用投加石灰浆的方法可以有效避免投加石灰干粉的缺陷,减少 7.5 g/L 投加量,使投加量稳定在 40 g/L。在刘良[8]的研究中采用熟石灰浆处理厌氧消化液也取得了较好的效果,比投加干粉减少 4.49 g/L 投碱量。

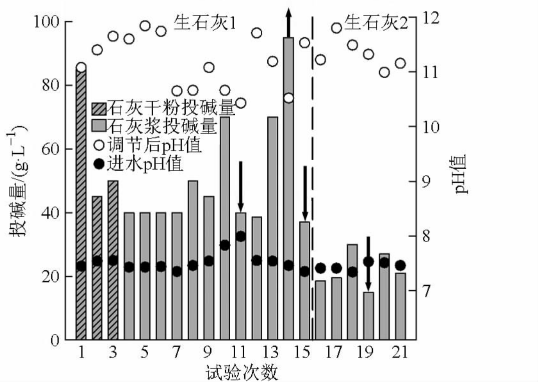

图 5　生石灰投加量及调节后的 pH 值

Fig. 5　Lime dosing quantity and adjusted pH values

虽然投加石灰浆可以提高碱剂的利用率,减少投碱量,但是随着投碱量的累积,池底沉渣不断增加,由于沉降后沉渣密度较大,影响搅拌的进行,投加的碱剂也难以有效溶解,使投碱量增加。试验表明,当投加量过高时投加碱剂前排渣 300 L(图 5 中符号↓所示)可减少投碱量,若不及时进行排渣投加量继续提高(图 5 中符号↑所示)。因此,建议实际应用时定期进行沉渣清理。

试验初期采用的生石灰粉购置于北京某污水处理试剂厂(以下称为生石灰 1),由于其使用效果较差,考虑到有效氧化钙成分含量可能较低,在沼气站附近购置了生石灰块作为外源碱剂,使用前在水中浸泡至微发热后取出消化为粉末后使用(以下称为生石灰 2),计重按消化前重量计。经试验发现当生石灰 2 作为外源碱剂时,其投加量可稳定在 22 g/L,比生石灰 1 减少 45% 的投加量。

4.1.2　生石灰提升厌氧消化液 pH 值的性能

通过现场中试试验发现试验用 2 种生石灰提升厌氧消化液 pH 值的投加量存在较大差异,因此通过实验室试验进行进一步分析研究,测试分析了 2 种生石灰中有效氧化钙的含量和提升厌氧消化液 pH 值性能的差异。根据 T0811—1994《石灰有效氧化钙测定方法》测定生石灰 1、2 有效氧化钙质量分数分别为:$(9.05\pm0.04)\%$、$(54.77\pm0.31)\%$,2 种生石灰有效氧化钙含量存在较大差异。通过实验室室温条件下试验对比分析 2 种生石灰提升厌氧消化液 pH 值的性能发现生石灰 2 提升厌氧消化液 pH 值的性能远好于生石灰 1,投加 43 g/L 生石灰 1 厌氧消化液的 pH 提升至 10.5 以上,而相应生石灰 2 的投加量仅需 19 g/L(图 6)。该试验结果与现场中试试验结果相似。

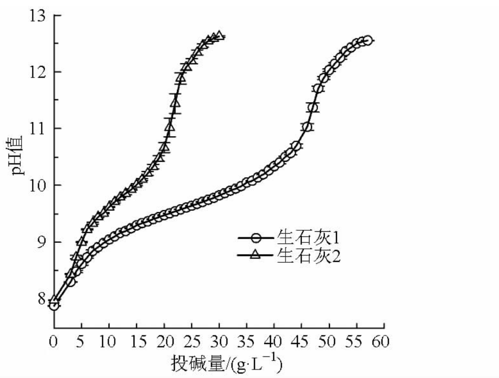

图 6　不同厂商生石灰提升厌氧消化液 pH 值的性能

Fig. 6　Performance of lime from different producers in increasing anaerobic digestion effluent pH value

氨氮吹脱过程中提高厌氧消化液 pH 值的目的是提高厌氧消化液中氨氮的离解率,而氨氮的离解率不仅受 pH 值的影响,还与温度有关(式(2)),因此在实际工程应用中,装置的运行效果可能会受到不同季节环境温度的影响。根据本研究实验测定的 2 种不同厂商生石灰提升厌氧消化液 pH 值的性能(图 6)以及氨离解方程式,可以计算得出北方地区不同温度下 2 种生石灰在厌氧消化液氨吹脱过程中的投加量,如表 2 所示。

表 2　不同温度条件下投碱量建议值

Tab. 2　Lime dosage at different temperatures

温度/℃	投碱量/(g·L⁻¹)	
	生石灰 1	生石灰 2
0 ~ 10	43 ~ 46	23 ~ 26
10 ~ 20	39 ~ 41	20 ~ 23
20 ~ 30	35 ~ 39	17 ~ 20
30 ~ 40	30 ~ 35	13 ~ 16
40 ~ 45	25 ~ 30	10 ~ 12

4.2　氨氮脱除效率优化

通过现场中试示范测试运行，分析了该装置的氨氮吹脱效果及关键影响因素。该装置的运行效果受气液比和厌氧消化液温度的影响。

李瑞华等[27]采用氨氮吹脱工艺去除焦化废水中氨氮的研究发现，当温度从 20℃ 升高到 60℃ 时，氨氮去除率相应地从 20% 提高到了 80% 左右；CAMPOS 等[28]在采用氨氮吹脱工艺处理垃圾渗滤液的研究结果也表明温度对氨氮去除率有较大的影响。本研究中试试验在 8 月—11 月中旬进行，环境温度在 0 ~ 35℃ 之间变化，因此通过不同环境温度下运行该试验装置得出了不同吹脱温度时氨氮的吹脱效率（图 7）。在气液比 960、吹脱起始 pH 值 11.4 ± 0.3 吹脱条件下，沼液温度为(27.8 ± 1.6)℃时，氨氮去除率为(55.8 ± 2.2)%，而当温度在(12.5 ± 1.5)℃时，去除效率仅为(26.7 ± 0.56)%，这是因为较高的温度会加剧布朗运动，促进氨的解吸[29]，提高氨的传质速率，使氨分子更易脱除。

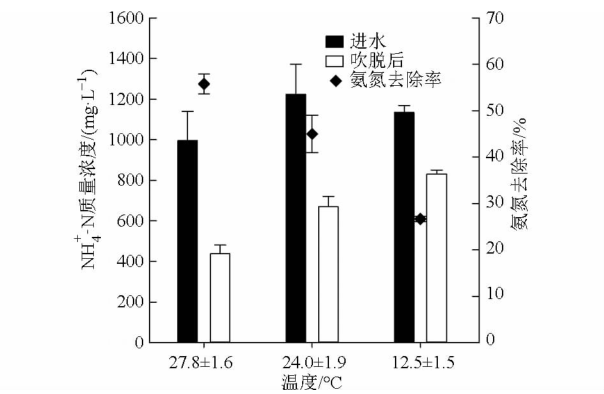

图 7　温度对氨氮去除率的影响

Fig. 7　Effect of temperature on efficiency of ammonia nitrogen removal rate

较高的气液比能够维持氨分子在气液两相的传质过程中有较大的推动力，促进氨分子向气相中转移，从而提高氨氮的脱除效率。由于沼气站发酵原料及发酵温度的变化，使得厌氧消化液氨氮浓度有较大的变化，但是可以看出氨氮的脱除效率随气液比的提高而升高（图 8）。在(30.7 ± 2.5)℃、吹脱起始 pH 值 11.5 ± 0.2 条件下，当气液比由 640 提高至 960 时，氨氮去除率相应地由(46.1 ± 5.8)% 提高到(55.8 ± 2.2)%。

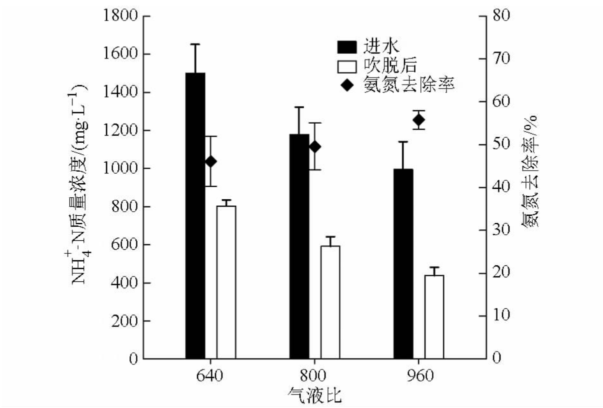

图 8　气液比对氨氮脱除效率的影响

Fig. 8　Effect of gas-liquid ratio on efficiency of ammonia nitrogen removal rate

规模化沼气工程的沼液处理问题已经制约其可持续发展[30]，虽然氨氮吹脱工艺是一种成本较低的污水处理工艺，而且在实验室研究中取得了较高的处理效率，但是受厌氧消化液特性和沼气站实际条件的限制，其在处理厌氧消化液时的成本也较高，难以在低利润的养殖场和沼气站广泛应用。

GUŠTIN 等[12]在采用填料塔对猪粪厌氧消化液中的氨氮进行吹脱回收时发现，在温度、pH 值和气液比分别为 50℃、10.5 和 412 条件下，氨氮的去除率为 55.3%，但当气液比升高至 1 875 时，氨氮去除率也相应升高至 92.8%。然而隋倩雯等[11]在采用相似的气液比对猪粪厌氧消化液进行氨氮吹脱回收时却发现，在吹脱温度为 30℃ 时，氨氮去除率为 81.8%。同时 JIANG 等[7]在相对更低的吹脱温度下(25℃，pH 值 10.5，气液比 2 429)利用整体氨氮吹脱与回收装置处理牛粪厌氧消化液时发现，氨氮去除率仅为 33.9%。

上述研究结果表明吹脱过程中采用较高的吹脱温度和气液比可以有效促进氨氮的脱除，但较高的温度和较大的气液比都会大大增加系统的运行成本。除了在特定的热电联产规模化沼气工程点可以利用不增加额外处理成本的发电余热提升吹脱液温度外，多数情况下仍只能采用常温吹脱工艺。这也是本研究探讨常温、低气液比(0 ~ 1 000)条件下氨氮吹脱规律的主要原因。

经试验优化，本研究中设计的中试装置，在厌氧消化液温度、气液比分别为(30.7 ± 2.5)℃、960 时，氨氮的去除率为(55.8 ± 2.2)%。与其他学者的实验室研究结果相比本研究中优化后氨氮的脱除效率较低，由以上分析得出其原因可能是与实验室研究相比本研究中采用的温度较低、气液比较小，而且本

研究采用了成本较低的空塔操作。但是相对比较本研究在常温、低气液比(0～1 000)条件下取得了较好的处理效果。

本研究中设计的厌氧消化液氨氮吹脱回收整体处理设备能够实现厌氧消化液的预处理、pH调节和氨氮吹脱与回收整体流程,通过预处理能够有效促进碱剂的溶解,提高碱剂的利用率;采用低耗逆流循环吹脱的方法,在常温和低气液比条件下取得了相对较高的氨氮脱除效率,因此在厌氧消化液氨氮吹脱回收方面具有较好的推广价值。

5 结论

(1)为了实现厌氧消化液中氨氮的脱除回收,设计了厌氧消化液氨氮吹脱回收整体处理装置,能够实现厌氧消化液的预处理、pH值调节和氨氮吹脱与回收整体流程,促进氨氮吹脱回收工艺在回收厌氧消化液中氮素的实际应用,并且通过中试试验及实验室研究,在碱剂投加和提高氨氮吹脱效率方面为氨氮吹脱工艺回收厌氧消化液养分的实际工程应用提供了技术指导。

(2)使用2种不同厂商的生石灰提升厌氧消化液pH值的性能存在明显差异,在实际应用时应该考虑该因素的影响。此外,分析得出,当环境温度变化时,可适当调整投碱量。

(3)通过研究气液比和温度对氨氮吹脱效率的影响得出,适当提高气液比和温度可以提高氨氮吹脱效率,但是气液比和温度的提高会增加能耗,因此,需结合成本投入进行综合设计。

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